



# Oregon Climate Assessment Report

**December 2010**

Oregon Climate Change Research Institute





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**Recommended citation:**

Oregon Climate Change Research Institute (2010), Oregon Climate Assessment Report, K.D. Dello and P.W. Mote (eds). College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, OR

available at: [www.occri.net/OCAR](http://www.occri.net/OCAR)

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## **Acknowledgements**

The Oregon Climate Change Research Institute is grateful for the assistance of all those involved in the development and production of this report, especially: the Blue Ribbon Panel for outline development and guidance throughout the process, the lead authors for their hard work and dedication, all contributors for their submissions, the peer reviewers for their useful and thoughtful comments and the publishing office in the College of Oceanic and Atmospheric Science at Oregon State University for assistance in proofreading and production.

## **About the Oregon Climate Change Research Institute**

The Oregon Climate Change Research Institute (OCCRI) is a network of over 100 researchers across the Oregon University System and affiliated state and federal labs. OCCRI was established in 2007 by the Oregon State Legislature to foster climate change research across the Oregon University System.

OCCRI is housed in the College of Oceanic and Atmospheric Science at Oregon State University

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# Oregon Climate Assessment Report

## Legislative Summary



Earth's climate has changed in the past, though the recent magnitude and pace of changes are unprecedented in human existence. Recent decades have been warmer than at any time in roughly 120,000 years. Most of this warming can be attributed to human activity, primarily burning fossil fuels (coal, oil and natural gas) for energy. Burning fossil fuels releases carbon dioxide and other heat trapping gases, also known as greenhouse gases, into the atmosphere. This warming cannot be ascribed to natural causes (volcanic and solar) alone. It can be said that human activities are primarily responsible for the observed 1.5 °F increase in 20th century temperatures in the Pacific Northwest. A warmer climate will affect this state substantially.

### **Future regional climate changes in Oregon include:**

#### **Increases in temperature around 0.2-1°F per decade**

Average annual air temperatures will increase through the 21st century. The amount of warming depends partly on the rate of greenhouse gas emissions.

#### **Warmer and drier summers**

Seasonal changes of climate are typically more relevant for decision makers and for studying impacts. The most consistent changes in global climate models show a regional warming and drying in the summer. The multi-model average decrease for summer precipitation is 14% by the 2080s.

#### **There is some evidence that extreme precipitation will increase in the future**

Though trends in extreme daily precipitation over the 20th century have been ambiguous in Oregon, there is some indication that such events will increase in the 21st century.

#### **Sea level rise**

It is near certain that global mean sea level will increase, possibly by 2-4 feet by 2100. By the mid 21st century, the rate of sea level rise will exceed vertical land movement on the Oregon Coast. Submerged areas will experience erosion and flooding impacts.

#### **Key findings:**

**Summer water supply will decrease as a result of reduced snowpack and summer precipitation.** The presence of a winter snowpack is crucial for summertime water supply in much of Oregon. A viable water supply is needed for irrigation, residential and commercial water use, fish propagation and survival and overall ecosystem health. Snowpack in the Pacific Northwest is particularly sensitive to warming. By mid-century, Cascade snowpacks are projected to be less than half of what they were in the 20th century, with lower elevation snowpacks being the most vulnerable. Water demands are projected to increase throughout the 21st century, particularly in urban areas, posing an additional stressor to water availability.

**Availability, quality and cost of water will likely be the most limiting factor for agricultural production systems under a warmer climate.** Many Oregon irrigation systems are fed by snowmelt and stored in reservoirs. With an increase in temperature irrigation demands will be greater. There may be new opportunities for agriculture in a warmer climate: the growing season may be extended and yields may be more plentiful. A potential opportunity exists for a longer growing season and yields may be greater. Oregon's wine regions have seen the length of the frost-free period increase from 17 to 35 days. However, more research is needed on irrigation technologies and new crop adapta-

tions. Associated management of new invasive plant pathogens, insects and weeds is needed.

**Wildfire is projected to increase in all Oregon forest types in the coming decades.** Warmer and drier summers leave forests more vulnerable to the stresses from fire danger west of the Cascades. Wildfire in forests east of the Cascades is mainly influenced by vegetation growth in the winters that provides fuel for future fires. An increase in fire activity is expected for all major forest types in the state under climate change. Large fires could become more common in western Oregon forests.

**Frequency and magnitude of coastal flooding events may continue to increase.** Storminess and extreme storm events have been increasing, leaving coastal areas vulnerable to flooding and erosion. North Pacific winter storm track is projected to shift northward in the 21st century, meaning slightly fewer, but more intense storms.

**Many plant and animal species on land, in freshwater, and in the sea have and will shift their distributions and become less or more abundant.** In a warmer climate, plant and animal species may have to shift upward or northward on land, and deeper or northward at sea. Rare or endangered species may become less abundant or extinct; insect pests, invasive species and harmful algal blooms may become more abundant.

**Changes to the marine environment including increasing water temperatures.** Substantial increases in water temperatures in the ocean are likely and will exceed natural variability. The ocean also absorbs carbon dioxide (CO<sub>2</sub>) from the atmosphere, which forms carbonic acid and is making waters corrosive to certain species.

**Oregon's economy, like many other states, is likely to be affected by a changing climate and by policies addressing projected changes.** There is still much work to be done in developing a complete assessment on the economic impacts of climate change in Oregon. However, the work to date suggests that climate change poses economic risks to the state. The magnitude of the impact will depend on the rate of physical change, the willingness of humans to alter their behaviors, and the resilience of our ecosystems.

**The important drivers of greenhouse gas emissions are population, consumption, and the emission intensity of the economy** (e.g. tons of equivalent carbon dioxide per unit of economic output).

**We are already experiencing the impacts of climate change in Oregon.** Given these observed and anticipated impacts, prudent measures to adapt should be taken now. Resilience needs to be built into human communities and fostered in natural communities to deal with the adverse impacts on of climate change. The State of Oregon has undertaken a substantial adaptation planning effort drawing heavily from the conclusions regarding the state of climate science found in this report.

The full report can be obtained by calling Julie Cope at the Oregon Climate Change Research Institute at 541-737-5705 and is available for download at [www.occri.net/ocar](http://www.occri.net/ocar).

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# Executive Summary

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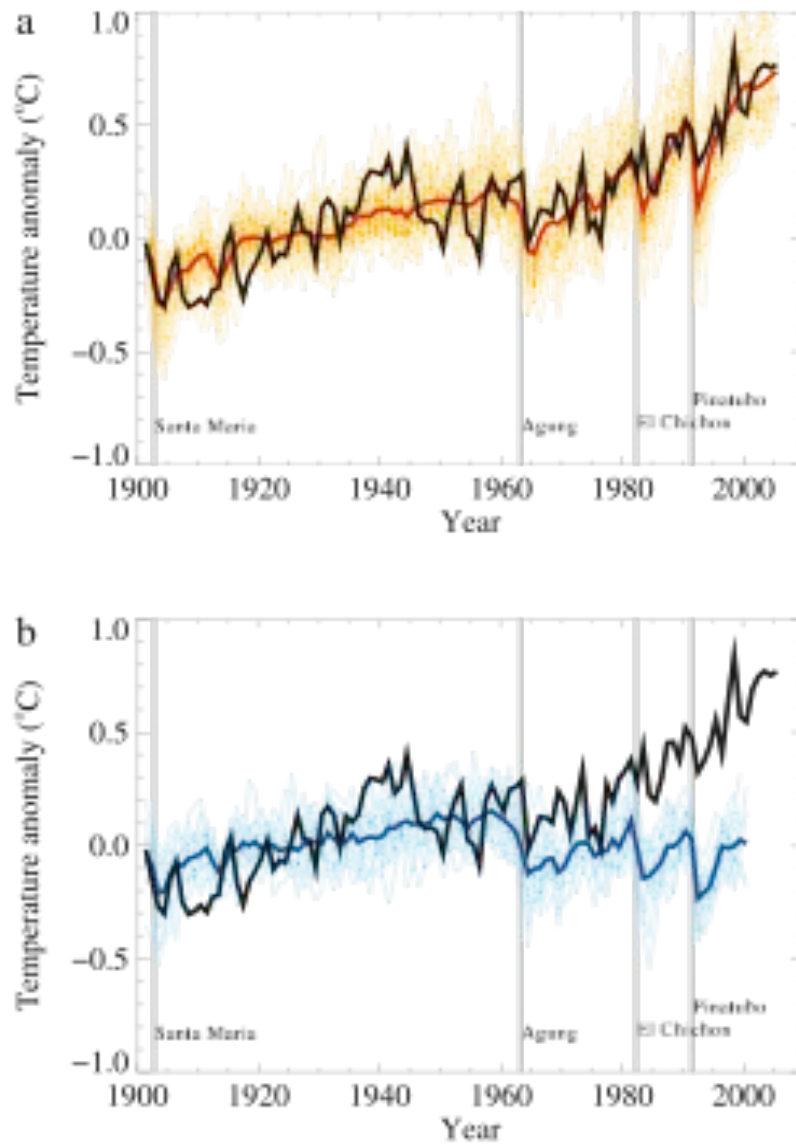
The group of scientists that make up the Intergovernmental Panel on Climate Change found in 2007 that the warming of Earth's climate is unequivocal and largely due to human activity. Earth's climate has changed in the past, though the recent magnitude and pace of changes are unprecedented in human existence. Recent decades have been warmer than at any time in roughly 120,000 years. Most of this warming can be attributed to anthropogenic activity, primarily burning fossil fuels (coal, oil and natural gas) for energy. Burning fossil fuels releases carbon dioxide and other heat trapping gases, also known as greenhouse gases, into the atmosphere. This warming cannot be explained by natural causes (volcanic and solar) alone. It can be said with confidence that human activities are primarily responsible for the observed 1.5 °F increase in 20th century temperatures in the Pacific Northwest. A warmer climate will affect this state substantially.

In 2007, the Oregon State Legislature charged the Oregon Climate Change Research Institute, via HB 3543, with assessing the state of climate change science including biological, physical and social science as it relates to Oregon and the likely effects of climate change on the state. This inaugural assessment report is meant to act as a compendium of the relevant research on climate change and its impacts on the state of Oregon. This report draws on a large body of work on climate change impacts in the western US from the Climate Impacts Group at the University of Washington and the California Climate Action Team. In this report, we also identify knowledge gaps, where we acknowledge the need for more research in certain areas. We hope this report will serve as a useful resource for decision-makers, stakeholders, researchers and all Oregonians. The following chapters address key sectors that fall within the biological, physical and social sciences in the state of Oregon.

## **Chapter 1 - Climate change in Oregon's land and marine environments**

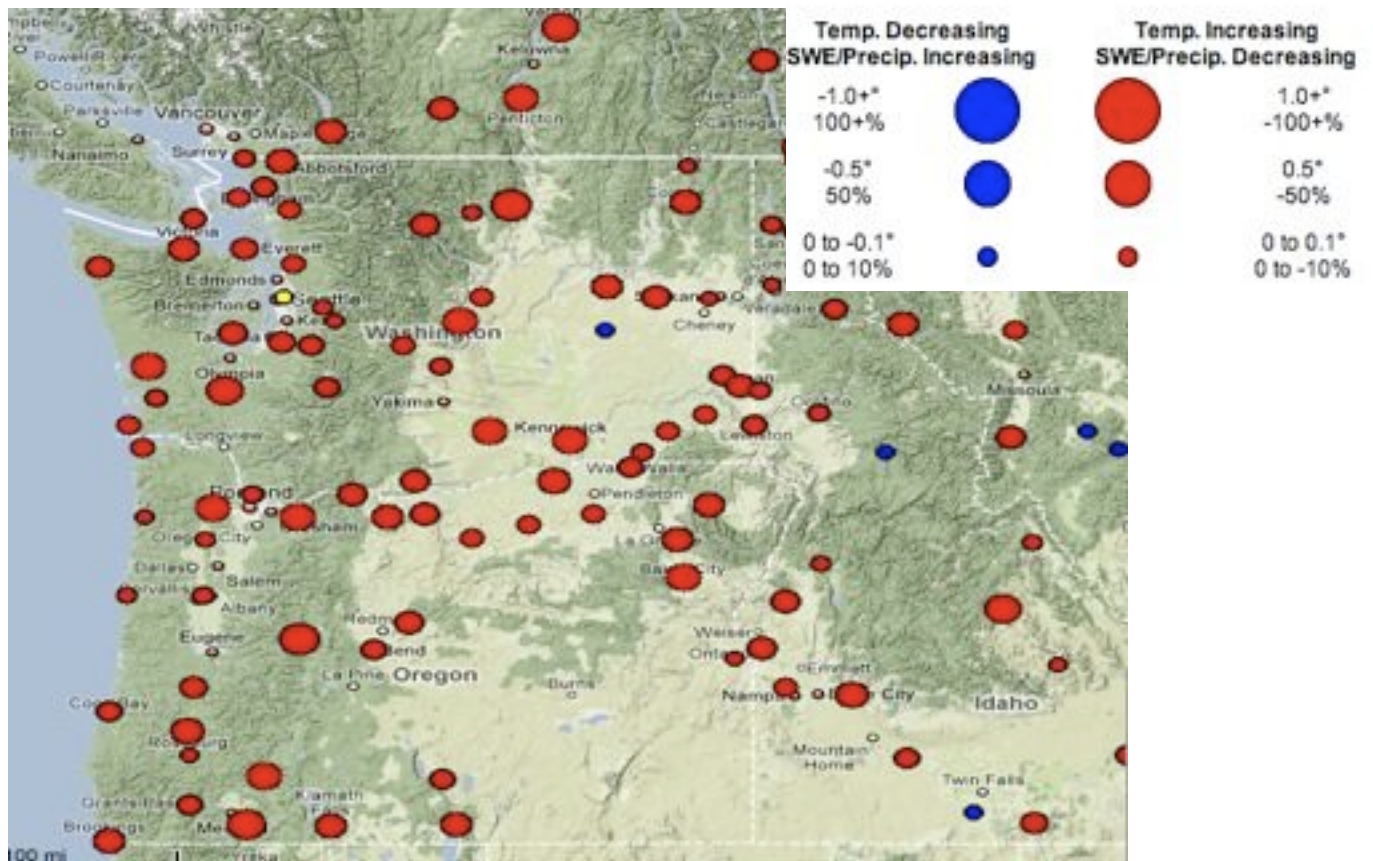
Earth's climate has changed in the past, though the recent magnitude and pace of changes are unprecedented in human existence. Recent decades have been warmer than at any time in roughly 120,000 years. Most of the recent warming can be attributed to human activity - primarily burning fossil fuels (coal, oil and natural gas) for energy. Burning fossil fuels releases carbon dioxide and other heat trapping gases, also known as greenhouse gases, into the the atmosphere. The warming cannot be described by natural causes (volcanic and solar) alone. To confirm this, scientists can perform simulations of past and present climate using GCMs. They run these simulations using both natural and human influences (top panel, figure 1) and compare them to the observed temperature record (black line, figure 1). Running the simulation with only natural forcing (bottom panel, figure 1) does not replicate the observed temperature record; there are marked differences after 1960. Major volcanic eruptions are marked on each plot. These eruptions can cool the earth for one to two years, as demonstrated by the short-term dips in the observed temperature on the plot. The other major natural forcing on climate, solar activity, has not increased over the last 32 years. There are other, empirical methods that do not use global climate models that attribute the warming of the past few decades to human influences as well. The climate system has responded in ways that would be expected with an ob-

served warming: global sea levels rose, the oceans have gotten warmer, and the amount of water vapor in the atmosphere has increased (warmer air can hold more water vapor).



**Figure 1.** Comparison between global mean surface temperature anomalies (°C) from observations (black) and AOGCM simulations forced with (a) both anthropogenic and natural forcings and (b) natural forcings only. All data are shown as global mean temperature anomalies relative to the period 1901 to 1950, as observed and, in (a) as obtained from 58 simulations produced by 14 models with both anthropogenic and natural forcings. The multi-model ensemble mean is shown as a thick red curve and individual simulations are shown as thin yellow curves. Vertical grey lines indicate the timing of major volcanic events. The simulated global mean temperature anomalies in (b) are from 19 simulations produced by five models with natural forcings only. The multi-model ensemble mean is shown as a thick blue curve and individual simulations are shown as thin blue curves. From IPCC (Hegerl et al. 2007), Figure 9.5.

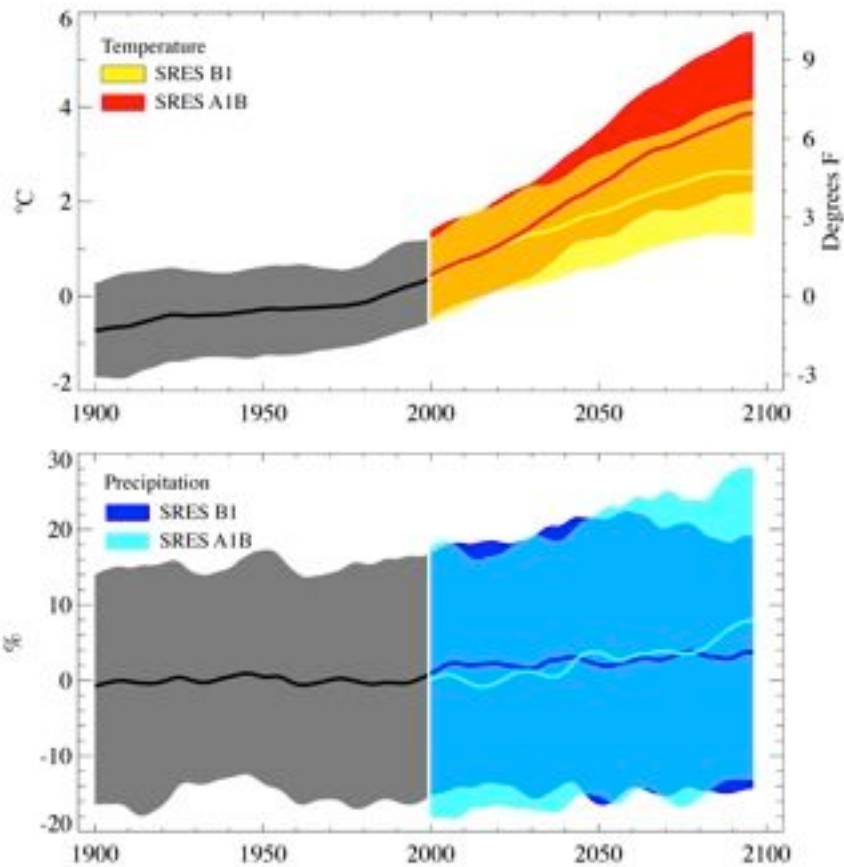




**Figure 2.** Linear trends in annual mean temperature at US Historical Climate Network stations in the Northwest. Red means warming, blue cooling, yellow no trend; size proportional to warming trend (°F/decade). Figures created using a utility at the Office of Washington State Climatologist, [climate.washington.edu](http://climate.washington.edu).

Oregon's climate can be defined as moderate, though varied with four distinct seasons. Mountain ranges dominate spatial patterns of climate in state. The Cascade range is the most influential, dividing the state roughly into two: the wetter west side, and more arid east side. The smaller, yet still significant Coast and Blue-Wallowa ranges also play a role. Most of the precipitation in the state falls between October and March. The coldest day of the year tends to fall around January 1 and the warmest on July 1. Temporal patterns of climate variability in Oregon are primarily influenced by the Pacific Ocean, namely ENSO (El Niño/Southern Oscillation).

Despite the spatial and temporal variability associated with the state's climate, the overall upward temperature trend over the last century is consistent with global carbon emissions; Oregon's climate is already changing. The observed 1.5 °F increase in the Pacific Northwest (1920-2003) is primarily due to human activities. Only a very small percentage of that temperature increase can be attributed to natural (Pacific) variability. Every station in the United States Historical Climatology Network in Oregon showed an increase in annual mean temperature over the 20th century (figure 2). While the increase in regional temperature is consistent with rising greenhouse gas concentrations, regionally averaged precipitation has fluctuated substantially. Additionally, trends in extreme precipitation are ambiguous and have received less attention from researchers.



**Figure 3** Smoothed traces in temperature (top) and precipitation (bottom) for the 20th and 21st century model simulations for the PNW, relative to the 1970-99 mean. The heavy smooth curve for each scenario is the weighted multi-model mean value, calculated for each year and then smoothed. The top and bottom bounds of the shaded area are the 5th and 95th percentiles of annual values (in a running 10-year window) from the ~20 simulations, smoothed in the same manner as the mean value. Mean warming rates for the 21st century differ substantially between the two SRES scenarios after 2020, whereas for precipitation the range is much wider than the trend and there is little difference between scenarios. From Mote and Salathé (2010).

Temperatures will continue to increase in Oregon through the 21st century. Projected temperatures for the next century are largely dependent on overall global carbon emissions. Without a substantial reduction in the activities that produce greenhouse gases, future regional change will likely be marked by increases in temperature around 0.5 °F per decade. The models suggest a warming of 3 °F (figure 2, yellow, b1 carbon emissions) to 10 °F (figure 3, red, continued aggressive carbon emissions). There is a range associated with these projections, but the Pacific Northwest, and Oregon can expect at least some warming through the end of this century. There is a much larger range of uncertainty with annual precipitation. The models do not show a clear trend in annual precipitation for the region over the next century. Seasonal changes of climate tend to be of greater interest for decision makers and resource managers. Climate models point to hotter, drier summers.

Oregon’s marine environment is also influenced by natural variability. There are strong spatial variations, both vertically and horizontally. Temporal variability ranges from winds and tides to heating and cooling. Despite the ocean’s inherently dynamic nature, there is evidence that Oregon’s marine environment is changing. Some of these changes can be linked to global warming. Oregon State University oceanographers have studied the coastal waters for over 50 years and have observed significant changes over this time, including a warming consistent

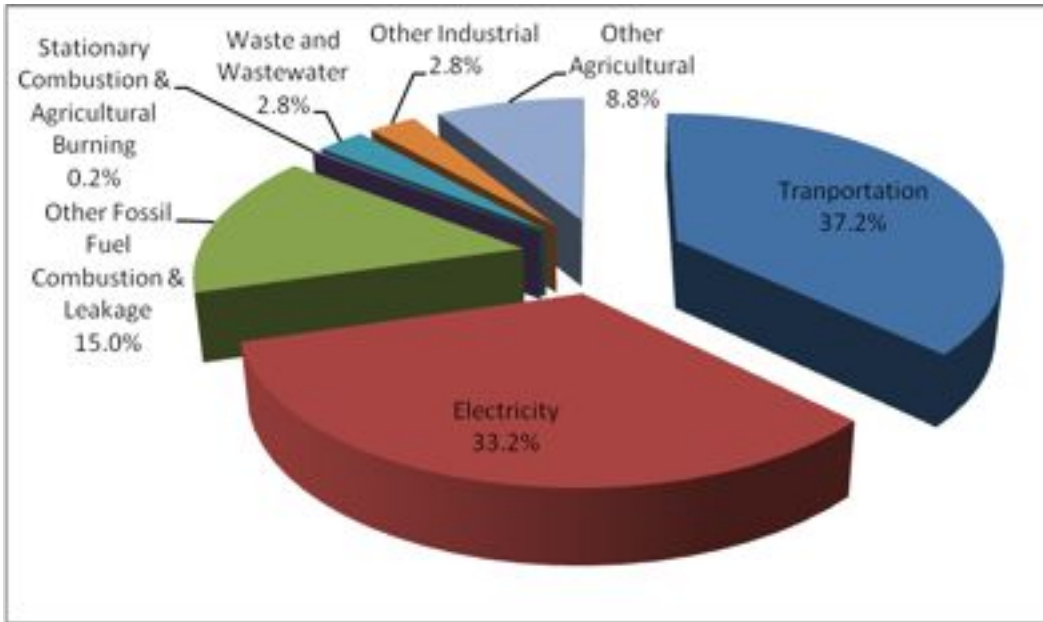
with rising air temperature, a freshening of the surface layer, and declines in dissolved oxygen. Given the year to year nature of the coastal ocean, there is still much work to be done in attributing changes to human or natural activity. Future changes will likely include substantial increases in ocean temperatures that far exceed natural variability.

## **Chapter 2 - Climate change in Oregon - Defining the problem and its causes**

Human activities are driving most the recent global warming, largely through carbon emissions. Oregon has a relatively small population (28th in the US) and implies that its total greenhouse gas emissions are small compared to larger states. Oregon's total carbon emissions are 1% of US national emissions and 0.2% of global emissions. In light of this, per capita (or average per person) emissions should be used to compare Oregon against other states in the country. In terms of per capita emissions, Oregon's are the eleventh lowest in the country (about 20% lower than the national average). In comparing Oregon to other developed countries, its emissions rank much higher. The state's emissions are nearly double the European Community average and almost three times higher than the global average. One reason for the relatively small emissions from the European countries is high population density (also true in the United States). As urbanization increases, carbon intensity (or, amount of greenhouse gas per one dollar of gross state product produced) decreases. This is likely due to shorter commutes and the accessibility of mass transit. Oregon is the eleventh least carbon intensive economy in the country, but is the most carbon intensive of the contiguous West Coast states.

Oregon's contribution to global carbon emissions comes mostly through energy use - electricity consumption and transportation (figure 4). Most of Oregon's electricity comes from coal and hydropower. Transportation has been one of the single largest sources of greenhouse gases in Oregon over the last twenty years. In Oregon, the transportation sector accounts for 37% of greenhouse gas emissions. This is higher than the national average, in part, because Oregon's energy sector includes hydropower, which does not result in greenhouse gas emissions and reduces emissions from sectors other than transportation.

While transportation remains the largest source of greenhouse gas emissions in Oregon, driving habits have changed in recent years. Vehicle Miles Traveled (VMT) have been growing at a slower rate than the national average in Oregon and motor fuel consumption increased at a much smaller rate (.25%) than that of population growth (10.4 %). In Portland, the state's largest city, VMT started to decline in the mid-1990s. Improvements to mass transit also reduce greenhouse gases. Aside from electricity and transportation, waste management, agriculture and industrial sources all contribute to greenhouse gas emissions in Oregon, but in smaller amounts.



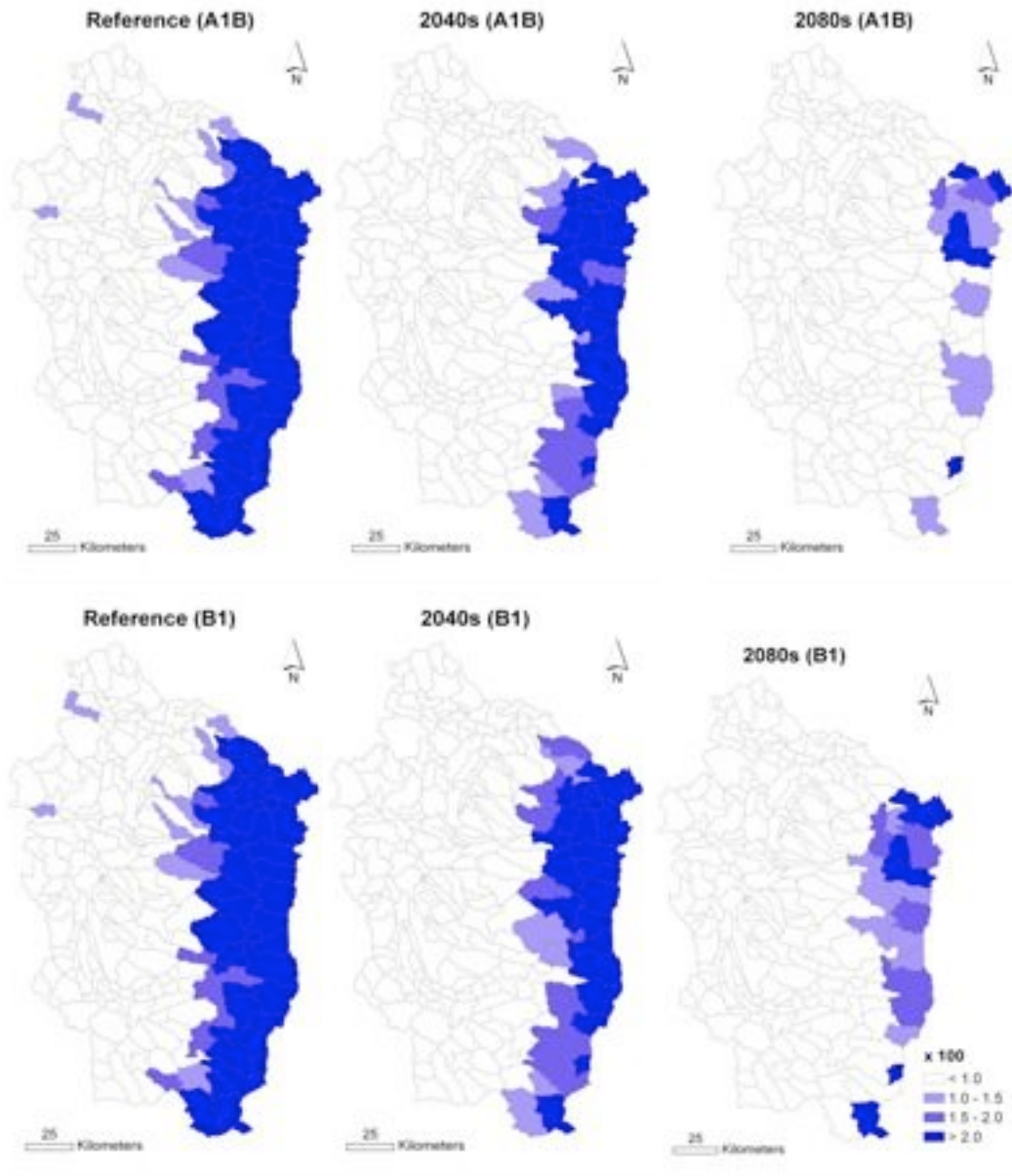
**Fig. 4:** Sources of greenhouse gases in Oregon. Data is averaged over 2003-2007, Oregon Greenhouse Gas Inventory, 2010.

The magnitude and impacts of climate change in the state are dependent on global carbon emissions. As a consequence, Oregon could not by itself reduce the impacts of climate change: policies will need to be enacted on the national and global scale to reduce the impacts of climate change. Since climate does not rapidly respond to year by year changes of emissions, a ten year aggregate emissions goal could be set. Lastly, given the disparity in per capita versus total emissions, state goals should be set to per capita emissions. This would reward states that make reductions in emissions while attracting economic growth and inward migration as opposed to states that reduce emissions by outward migration or economic downturn. Oregon’s population is projected to grow by 13% by 2020, and it is estimated that 63% of that will be due to net migration into the state. If each state adopted this metric, national inventories could still be met and it would allow for a more equitable policy that does not hinder or discourage economic growth.

### Chapter 3 - Climate Change and Freshwater Resources in Oregon

Water resources in Oregon and the western US have always been climate sensitive. The state receives most of its precipitation from October to March, meaning that it must rely on water storage in mountain snowpack to provide sufficient surface water resources in the summer months. The presence of a robust winter snowpack is crucial for summertime water supply. The amount and seasonality of water supply is projected to shift with seasonal changes in temperature and precipitation. It is important to note that not all past trends in streamflow can be attributed to global climate change; there is some interannual variability at play. Recent low flow years, particularly 2001 and 2005, stemmed from low winter precipitation. Snowmelt-related hydrologic variables already show a decline - earlier peak flow, lower summer flow, lower spring snowpack.

In the future, as winter temperatures warm, mountain snowpacks will diminish and summer water supply will likely decline. Earlier spring snowmelt will shift the timing of peak flows; some streams will peak earlier in the year. A decrease in summer precipitation is also likely in the future, which means the small amount of precipitation that the state receives in the summer will be even less in the future.



**Figure 5** Ensemble mean changes (averaged over eight global climate models) in snow water equivalent in the Willamette River basin for historical (reference), the 2040s, and the 2080s by GHG emission scenario. The ratio is multiplied by 100 for representation (Source: Chang and Jung 2010).

A viable water supply is needed for irrigation, residential and commercial water use, fish propagation and survival and overall ecosystem health. With a (1.8 °F) 1 °C rise in temperature,

irrigation demands are projected to increase 10 percent. Transient rain-snow basins, such as those in the Western Cascade basins, are projected to be sensitive to these changes in precipitation and temperature. Cascade snowpacks are projected to be less than half of what they are today by mid-century with lower elevation snowpacks being the most vulnerable. Through the end of the 21st century, April 1 snow water equivalent is projected to decrease in the Willamette River Basin (figure 5) in two emissions scenarios - a1b (carbon intensive) or b1 (more renewables, less carbon intensive). Water demands are projected to increase throughout the 21st century, particularly in urban areas, adding an additional stress to water availability.

Other factors such as increased demand will pose an additional stressor to water availability. Water demands are projected to increase throughout the 21st century, particularly in urban areas. Part of the increased demand will likely be due to summer temperatures, and some of the demand can be attributed to overall population growth of the state. Data from Portland Water Bureau shows that there is a relationship between annual average water consumption and annual average temperature. While demand during winter months is expected to remain constant, research on urban water demand suggests that temperature is the most influential climate variable on water consumption, particularly among single family residential households. These impacts are also evident at multiple scales, including the household, neighborhood, and region.

Water quality is also likely to be impacted with rising air temperature and seasonal shifts in flow availability. Water temperatures are expected to rise as air temperature increases in the 21st century, particularly in urban streams where natural riparian vegetation is typically lacking. A decline in summer stream flow will exacerbate water temperature increases, because the low volume of water will absorb the sun's rays more than during times with larger instream flows. However, an increase in air temperature alone does not lead to major changes in stream temperature. Changes in riparian vegetation (either land use changes or climate-related) will influence streamflow and water temperature. Changes in water temperature can have significant implications for stream ecology and salmon habitat. Smaller streams in transient rain-snow basins and in eastern Oregon will be the most vulnerable to increasing summer air temperature and diminished low flows. There is little research on long term trends in water temperature in undisturbed watersheds; sites with long term data are rare. Sediment and phosphorus loads, which are a detriment to water quality, are expected to increase in winter as winter flow is projected to rise. It will be important for water resource managers statewide to include considerations for climate change in future planning.

## **Chapter 4 - Climate Change and Agriculture in Oregon**

Oregon's agriculture has long been a part of the state's history and a backbone of the economy. The moderate, yet varied climate and fertile topsoil from glacial floods create some of the best growing conditions for a many of crops and commodities. An incredible amount of land statewide is devoted to agriculture. In 2008, Oregon had around 38,600 farms on 16.4 million acres of land. Oregon's agriculture is also of national importance; the state is the top producer of fifteen commodities. In 2008, Oregon exported \$1.6 billion in agricultural commodities. The diversity of agriculture in this state creates an economic strength. That economic strength means that ag-

riculture is especially vulnerable to climate change. Oregonians involved in agricultural practices have long been adaptable to short to long term changes in climate, though the projected rate and magnitude of increase in temperature in Oregon will exceed anything that they have faced in the past.

Agriculture is an inherently climate sensitive sector. Availability, quality and cost of water will likely be the most limiting factor for agricultural production systems under a warmer climate. Warming temperatures will lead to greater irrigation demands. For a 1.8 °F rise in temperature, irrigation demands are projected to increase by ten percent. Many irrigation systems in the state are fed by snowmelt and stored in reservoirs. Drought and heat waves are both costly natural disasters; even short term events can damage crop quality and reduce yields. Livestock are particularly sensitive to higher temperatures in the summer. Crops will be vulnerable to invasion by pests and diseases that thrive in a warmer climate, creating additional stress on the plant. Additionally, warmer winter temperatures will allow insects to survive over the winter or produce multiple generations within one season

Many crops have been optimized to fit a narrow temperature niche - one that may no longer be optimal under a warmer climate. The projected warming in Oregon is expected to displace current agriculture zones, with likely movements toward the coast and higher in elevation. However, much of this work is speculative - in that if a crop exists in today's climate thresholds, that a warmer climate would push them outside a suitable range. There is a need for more research on individual crops and commodities, their optimum climate, and variability thresholds for economic sustainability. Perennial crops are more vulnerable to climate variability and change than annual systems; annual crops may be easier to replace.

In Oregon, winegrapes are an excellent example of an important perennial crop that has a narrow climate range for both quality and economically sustainable production. Pinot noir is considered to be the state's marquee winegrape. It grows well in cooler climates with an average growing season temperature of 57 °F to 61 °F, such as the Willamette Valley. Prior to 1950, the Willamette Valley was in a marginal climate for growing the Pinot Noir grape (< 57 °F), but the warming of the past few decades have brought this region into optimal wine growing range. With continued increases in temperature that are projected through the 21st century, most of the Willamette Valley will not be viable for growing the pinot noir winegrape. Producers will have to replant a grape that grows in a different, warmer climate or to move to higher elevations or further north in latitude, both costly options.

There is evidence that points to a lengthening of the growing season worldwide. The growing season, or dates from first frost in the spring to last frost, has also lengthened across the country. In Oregon, wine regions have seen the length of the frost free period increase by 17 to 35 days. This change in growing season can have mixed benefits. On one hand, lengthening the growing season may allow for increased production. A longer growing season translates into an increased need for irrigation, though this may be mitigated somewhat by increased CO<sub>2</sub> fertilization.

Carbon dioxide is essential for plant growth. There are some benefits for crops with rising carbon dioxide levels. Increased CO<sub>2</sub> in the atmosphere may lead to increased yields and plant

growth. It may also mitigate drought stress by allowing the plants to partially close their stomates, or take in less water. Negative impacts include a decline in nutritional quality and decreased efficiency of some pesticides. However, the benefits of increasing CO<sub>2</sub> on plants are not substantial enough to offset the negative impacts of increased greenhouse gases in the atmosphere and other climate change impacts to agriculture.

Agriculture also contributes to the climate change problem; Chapter 2 states that agriculture makes up about 9% of Oregon's greenhouse gas emissions. There are some opportunities for greenhouse gas mitigation in agriculture - including reductions of nitrous oxide and methane emissions and reduction of energy consumption.

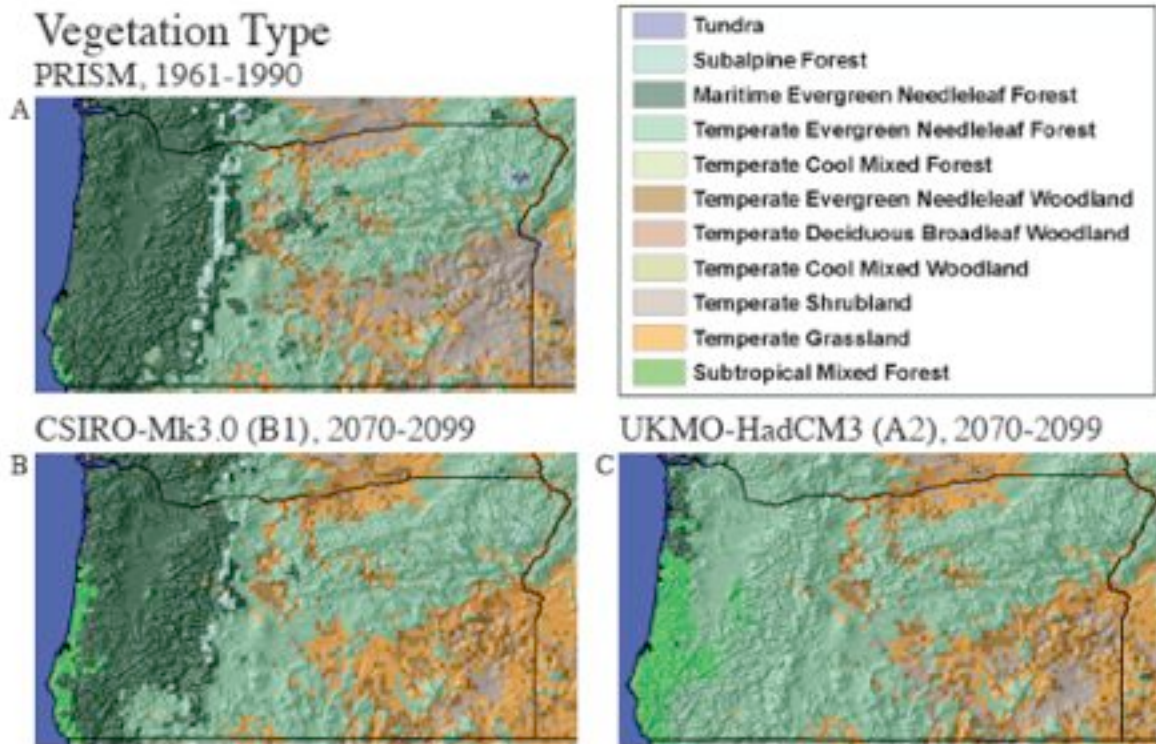
## **Chapter 5 - The potential effects of climate change on Oregon's vegetation**

Oregon vegetation is varied across the state and heavily influenced by the interactions of climate and topography. Given the interaction between vegetation and climate in this state, it is likely that future climate change will affect the plant species in Oregon. Currently, undeveloped areas of Western Oregon are predominantly forested and agricultural while much of Eastern Oregon is shrub/sagebrush with patches of forests, agriculture, juniper and grassland. There is clear evidence that vegetation has responded to changes in climate over the distant and recent past, with large rapid changes since the mid-1970s, coinciding with the accelerated warming of the past few decades. Understanding how vegetation has changed in the past is important for understanding how Oregon's vegetation may respond to future climate changes. Adaptive management may help in creating resiliency, but the challenge lies with the slow life cycle of many Oregon plants versus the rapid rate of warming.

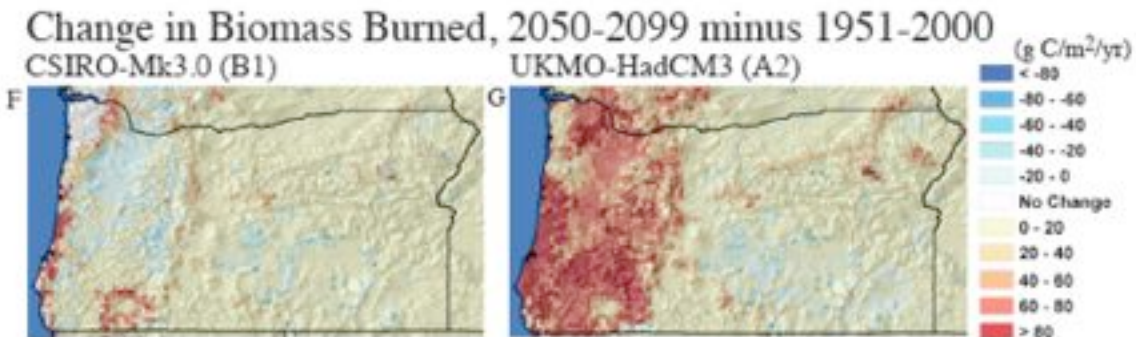
Vegetation types will shift statewide as a result of a changing climate. Vegetation models show that areas of subalpine forest and tundra are projected to decrease as temperatures increase at higher elevations. Areas of shrubland in the eastern part of the state are projected to decrease. These changes in vegetation will threaten the habitat for species of management concern. An expansion of forest and woodland is projected into parts of eastern Oregon currently dominated by grassland and shrubland. On the coast, areas of mixed evergreen and subtropical mixed forest are projected to expand, marking a major transition from temperate to subtropical species (figure 7).

Wildfire will likely increase in all Oregon forest types in the coming decades. Warmer and drier summers leave forests more vulnerable to the stresses from fire danger west of the Cascades. Wildfire in forests east of the Cascades is mainly influenced by vegetation growth in the winters prior to the fire. An increase in fire activity is expected for all major forest types in the state under climate change. Large fires could become more common in Western Oregon forests (figure 8). Estimate increases in regional forest area burned ranges between 180% and 300% by the end of the century, depending on the climate scenario and estimation method examined.





**Figure 7.** Vegetation types simulated by MC1 (MAPSS Group, contact: R.P. Neilson) on an 8-km grid for (A) 1961-1990 using PRISM climate data (Daly et al., 2000) and for 2070-2099 using climate data simulated (B) by CSIRO-Mk3.0 under the B1 emissions scenario and (C) by UKMO-HadCM3 under the A2 emissions scenario



**Figure 8.** Future changes in biomass burned calculated as 2050-2099 values minus 1951-2000 values (F, G) were also simulated by MC1.

Pests and diseases will continue to expand northward into Oregon affecting forest species. Mountain pine beetle occurrence has been increasing over the last eight years and will likely continue to increase in a warmer climate. Drought also acts as an additional stressor in increasing vulnerability to the pest. Other pests and diseases, including sudden oak death, have been spreading northward from California into southwestern Oregon since the beginning of the century. In the case of sudden oak death, extreme precipitation events help infect more trees, which

then become vulnerable to mortality during droughts. Generally, insects and diseases will expand northward in latitude, toward the coast and upward in elevation in a warming climate.

## Chapter 6 - Impacts of climate change on Oregon's coasts and estuaries

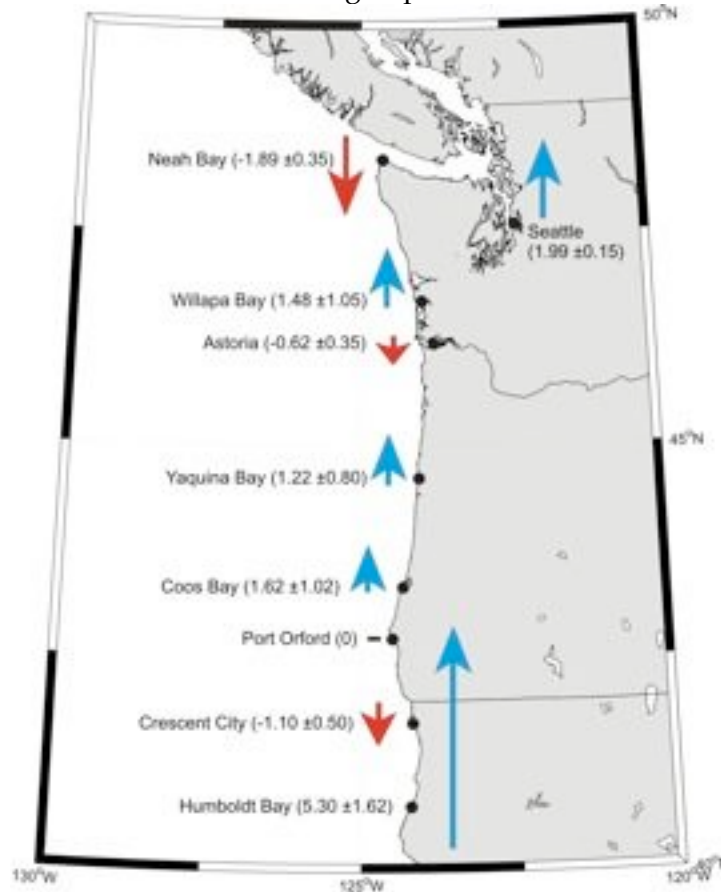
The changing climate will likely have significant impacts along the coast and estuarine shorelines of Oregon. Changes associated with global climate change include rising sea levels, storminess, rising water temperatures and ocean acidification. The impacts of these changes include increased erosion, inundation of low lying areas and wetland loss and decreased estuarine water quality. Impacts from coastal erosion and flooding are already affecting the Oregon Coast (figure 9), and are an analogue for future climate change impacts. Beach elevations have been lowered as a result of extreme waves, and many beaches have seen little post-storm recovery in the intervening years. Coastal infrastructure will be under increased risk of inundation and damage under a changing climate with impacted sectors including transportation and navigation, shore protection and coastal flood structures, water supply and waste and storm water systems, and recreation, travel and hospitality.



**Figure 9.** Ongoing shoreline retreat over the past decade in the Rockaway cell and localized hotspot erosion effects have resulted in substantial sections of the shore having to be rip-rapped in order to safeguard property. SLR expected over the next century and enhanced storms will almost certainly increase the risk of failure of such structures and the potential loss of homes and important infrastructure backing the beach (Photo courtesy of Mr. Don Best, 2009).

Globally averaged sea level has risen through the 20th century, coincident with warming. In the Pacific Northwest, actual sea level rise varies along the coast, as a result of geologic uplift (or vertical land movement). In some spots along the coast (figure 10) The upward movement of land is exceeding actual sea level rise and have been relatively immune to sea level rise impacts thus far (blue arrow). It is nearly certain that global mean sea level will increase, by 2-4 feet (1

meter) by 2100. Coastal areas that are uplifting geologically have been relatively immune to sea level rise impacts thus far. However, by the mid 21st century, the rate of sea level rise will probably exceed vertical land movement on all stretches of the Oregon Coast. Submerged areas will experience significant erosion and flooding impacts.



**Figure 10** Analysis of NOAA tide gauges to assess changing sea levels along the coast of the PNW. Colored arrows represent the rates of change in relative sea levels (mm/yr), along with their uncertainty, generated using summer data only (see Section 6.2.2 for details). (After Komar et al., in press).

The Oregon Coast has been historically prone to severe winter storms, which are the dominant factor for flooding and erosion on the coast. Storminess has been increasing, and consequently the frequency and magnitude of these coastal flooding events will probably continue to increase. All significant wave heights measured during the winter have been increasing at a rate of 0.023 m/year, but extreme waves generated by the strongest storms are increasing at higher rates than the winter averages (0.095 m/year). The maximum has increased from about 9 meters in the late 1970s to 12 meters in 2005. This is a significant increase, though we do not yet know if this is a climate change related trend or natural variability. Therefore, we have limited ability to predict future trends in wave heights or coastal storms, but if the trend continues, impacts will be substantial. Storminess and extreme storm events have already been increasing very rapidly, leaving unarmored coastal areas vulnerable to flooding and erosion. The North Pacific winter storm track is projected to shift northward, meaning slightly fewer, but more intense storms.

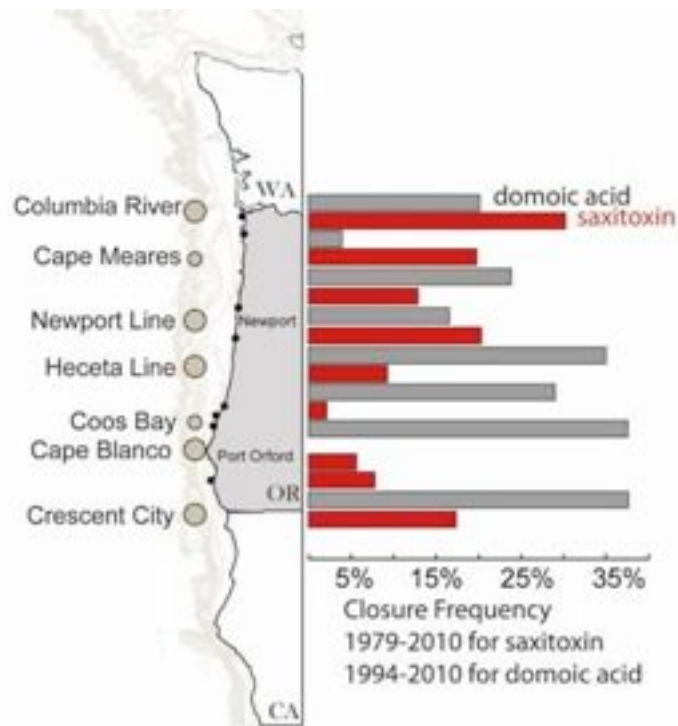
The estimated long term rate of coastal wetland loss is greater for the Pacific Coast than any other areas of the US. It is likely that regional coastal climate change may result in more changes in the near-coastal and estuarine habitats. This includes changes in the intensity and timing of coastal upwelling, increased fog and onshore winds, shifts in temperatures and chemistry of nearshore waters. The combination of these climate and nearshore ocean changes will exert stress on the communities of near-coastal and estuarine organisms. The range of species responses to the climate change stressors may include elevational shifts in the distribution of submerged aquatic vegetation, disruption of shell formation for calcifying organisms, alteration of the phenology of phytoplankton blooms, shoreward migration of tidal marshes, and increased colonization by non-indigenous aquatic species.

## **Chapter 7 - Oregon's fish and wildlife in a changing climate**

Oregon's fish and wildlife include animals on land, fish and other species in rivers and lakes, and various kinds of sea life in estuaries and coastal ocean. Oregon is one of the most ecologically diverse states in the country. The state's robust biodiversity, some of which is already threatened or endangered -- inhabits complex and dynamic ecosystems that we have only begun to understand, let alone examine in terms of climate change. It is clear that the abundance and distribution of species are shifting already and will shift more rapidly as habitats on land, in freshwater, and in the sea are altered due to increasing temperatures and related environmental changes. It remains to be seen if past changes are all tied to global climate change or if they are a result of some other variability, but they represent a proxy for how species may shift in a warmer climate.

Among the observed species changes: Insects are moving in from the south of Oregon, frogs are reproducing earlier in the year and land birds are shifting their distributions northward and migrating earlier. Freshwater fish are losing their cool-water habitats. In the marine environment, algal blooms have increased (figure 11) and the highly predatory Humboldt squid have shifted their distribution from subtropical and tropical regions, making an appearance off the coast of Oregon in the last few years.

In a warmer climate, plant and animal species may have to shift upward or northward on land or deeper at sea for survival. Rare or endangered species may become less abundant or extinct; insect pests, invasive species and harmful algal blooms may become more abundant. Declines in the abundance of species may be caused directly by physiological stress related to changes in temperature, water availability, and other environmental shifts, and/or indirectly by habitat degradation and negative interactions with species that are benefited by climate change (diseases, parasites, predators, and competitors).



**Figure 11** Left: Current sites in the Oregon surf zone (dots) and offshore sampling lines (circles) sampled for harmful algal blooms relative to ocean depth contours (gray lines). Regions near the Columbia River outflow, Heceta Bank and Cape Blanco are sites of strong summer phytoplankton blooms. Right: The percentage of positive samples exceeding shellfish fishery closure limits are shown as bars for domoic acid (grey) and saxitoxin (red) at different latitudes along the coast

Understanding the responses of Oregon’s fish and wildlife to climate change will require a better understanding of smaller organisms and insects and ocean species. Knowledge of ecological interactions will be crucial for understanding the related effects of climate change (increased predation or competition, for example). Management and natural resource polices that protect intact ecosystems are a tool for adaptation; native species can live and migrate to these safe refugia.

## Chapter 8 - Toward assessing the economic impacts of climate change on Oregon

Oregon’s economy, like many other states, is likely to be affected by a changing climate and by policies addressing projected changes. There is still much work to be done in developing a complete assessment on the economic impacts of climate change in Oregon. The work to date suggests that climate change poses economic risks to the state. The magnitude of the impact will depend on the rate of physical change, the willingness of humans to alter their behaviors, and the resilience of our ecosystems. It is not possible, at this time, to provide a comprehensive economic assessment of the impacts of climate change in this state.

Quantifying the economic impacts of the previously discussed sectors in this report requires models that predict behaviors as well as changes in climate variables and changes in economic variables. Some studies utilize a business as usual scenario - in that society and behaviors continue in the same manner and people do not take steps to mitigate greenhouse gases, adapt to climate change or different economic scenarios.

The magnitude of economic impact is dependent on the magnitude and rate of future climate and economic changes. There are projects in place at Oregon State University and other institutions that are examining how agricultural sectors may fare under a cap and trade or other incentive based policies. Quantifying the cost of inaction is controversial because it requires a connection between changes in climate and human responses. Many models suggest that the costs of inaction in climate change would be 2% of the world's gross domestic product (GDP), but the Stern study in 2006 suggests the costs could be substantially greater (5-20% of world GDP).

Agriculture is one of the most important sectors of the state's economy and is highly sensitive to climate. Farms and ranches are the largest group of owners and managers of land impacting ecosystem services, such as greenhouse gas mitigation, water quality and quantity regulation, and wildlife habitat and biodiversity conservation. Consequently, the impacts of climate change on agriculture, the impact of policies designed to reduce greenhouse gas emissions, and agriculture's ability to adapt to and mitigate the impacts of climate change are critical issues for to consider. Water availability will be the primary factor in agricultural production in the future. Both California and Washington projected negative economic impacts with the loss of irrigated water by the end of the century. Oregon could experience similar impacts if water for irrigation becomes scarce, but additional research is required to quantify the economic impact of climate change on water availability for irrigation.

Climate change will have multiple and sometimes conflicting impacts on Oregon's economy. There is still much uncertainty of the full economic impacts of climate change. An understanding of physical climate impacts and improvements in measuring and valuing economic change continues to evolve. Climate change projections tend to be at a spatial scale that is too large to be relevant for smaller systems, like the agricultural sector. Research should continue in quantifying the costs and benefits of action: both adaptation and mitigation.

## **Chapter 9 - Human dimensions of climate change: public knowledge, attitudes, and barriers to change; impacts on cultural and built environment; and potential public health impacts**

This report discusses the impacts of climate change on land and in the ocean in significant detail, but it offers much less insight on the human dimensions of climate change, beyond the anthropogenic contribution to the problem. Undoubtedly, climate change will impact Oregonians directly. Climate change in Oregon will likely have an impact on our built environment - that is, things that are man-made (roads, airports, infrastructure) - and on public health. The attitudes of Oregonians toward climate change are somewhat unknown, but small-scale surveys indicate that many residents of our state would consider it a problem worth attention by policymakers.

Also, very little Oregon-specific research on the impacts of climate change on public, or human health have been performed. This does not mean that the state is immune to an increase or emergence of vector-borne diseases that harm humans in a warming climate, but rather that specific research needs to be performed on specific diseases using regional climate projections for Oregon. Disease is discussed in Agriculture (chapter 4), Vegetation (chapter 5) and Fish and Wildlife (chapter 7). It can be speculated that human disease will also act in a manner similar to those that impact both plant and other animals, but there is room for more research in this area.

There have been a few small studies that survey groups understanding of climate change and general acceptance of the problem. A study of more than 1500 Oregon households about the role of renewable energy revealed that almost two-thirds view climate change as a moderate or serious problem requiring policy changes regarding renewable energy. These initial and small-scale studies suggest that Oregonians know something about climate change and many are likely to perceive it as a problem although they may not know all the scientific details. There are barriers needing to be addressed if expect individuals or groups to change behaviors for either mitigating or adapting to climate change, although there appears to be general acceptance of, and desire for, government policies to direct such behavioral change.

There may be impacts to areas of cultural importance to Oregonians. Native tribes may be vulnerable to climate change, with the potential loss of iconic species or shifts in ecosystems that are a significant part of their culture. Coastal tribes risk inundation and loss from impacts to Oregon's coastline. All Oregonians face impacts to areas of cultural value, such as two important Oregon icons - Mt. Hood and Crater Lake. Aside from aesthetics with potential snowpack loss, climate may change species and forest composition.

# 1. Climate change in Oregon's land and marine environments

**Philip W. Mote<sup>1</sup>, Daniel Gavin<sup>2</sup>, and Adriana Huyer<sup>3</sup>**

Contributing authors: Jack A. Barth<sup>3</sup>, Dudley B. Chelton<sup>3</sup>, Michael Fortune<sup>4</sup>, Burke Hales<sup>3</sup>, P. Michael Kosro<sup>3</sup>, Stephen D. Pierce<sup>3</sup>, Roger Samelson<sup>3</sup>, Kipp Shearman<sup>3</sup>, Robert L. Smith<sup>3</sup>, P. Ted Strub<sup>3</sup>

## Summary and Knowledge Gaps

The human race is profoundly altering the composition of Earth's atmosphere, chiefly by burning fossil fuels, and there is strong evidence that these changes are responsible for much of the global increase in temperature since the mid-20th century. A recent (2001-2009) leveling off of global temperature trends can be understood as an interaction between continuing increases of greenhouse gases and a slight decline in solar output connected with the 11-year solar cycle, and does not indicate that global warming has ceased permanently.

Attribution - that is, formally understanding causes - of changes in regional climate is difficult owing to the large variability, relative to the signal, on such spatial scales. Nonetheless, the warming observed in the Pacific Northwest during the 20th century (1.5°F, 0.8°C) is roughly the same as that expected with rising greenhouse gases.

Future regional climate change will likely be marked by:

- Increases in temperature of around 0.3°C (0.5°F) per decade, which could be lower if global greenhouse gas emissions are lower than expected
- An accentuated warming and drying in summer
- Increased frequency of extreme daily precipitation
- A northward shift in the storm track and slightly fewer but more intense storms

There is little indication yet from global models that patterns of climate variability such as El Niño-Southern Oscillation or North Pacific variability will change substantially in the future.

Oregon's relatively well-monitored coastal waters have exhibited increases in wind-driven coastal upwelling since 1948. Since subsurface monitoring began in the 1960s, scientists have observed a warming and freshening of subsurface waters over the continental shelf, the continental slope, and offshore, contributing 3 cm (1.2") of sea level rise. Since 1975, the concentration of subsurface dissolved oxygen along the Oregon coast has decreased and during some recent summers, oxygen concentrations near the coastal ocean floor have sometimes been nearly or fully depleted. Links between these observed changes and human influences on the climate system have not been established.

Future changes in Oregon's coastal ocean are likely to include substantial increases in water temperatures, far surpassing natural variability. Although most work indicates negligible

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future changes in the strength of coastal upwelling, the acidity of freshly upwelled waters will continue to increase as it has in recent decades. This increase in corrosive effects will likely impact some estuarine shellfish species in the next few decades.

## 1.1 Overview of Global Climate Change

Climate on Earth has changed profoundly during the planet's history, but the pace, scope, and cause of recent changes are unprecedented during the period of human existence. Furthermore, these changes arrive at a time when a burgeoning human population has built infrastructure and expectations around the climate of the past. In this section we examine natural climate changes in the remote and the recent past, and contrast it with the current, human-caused changes of the past few decades.

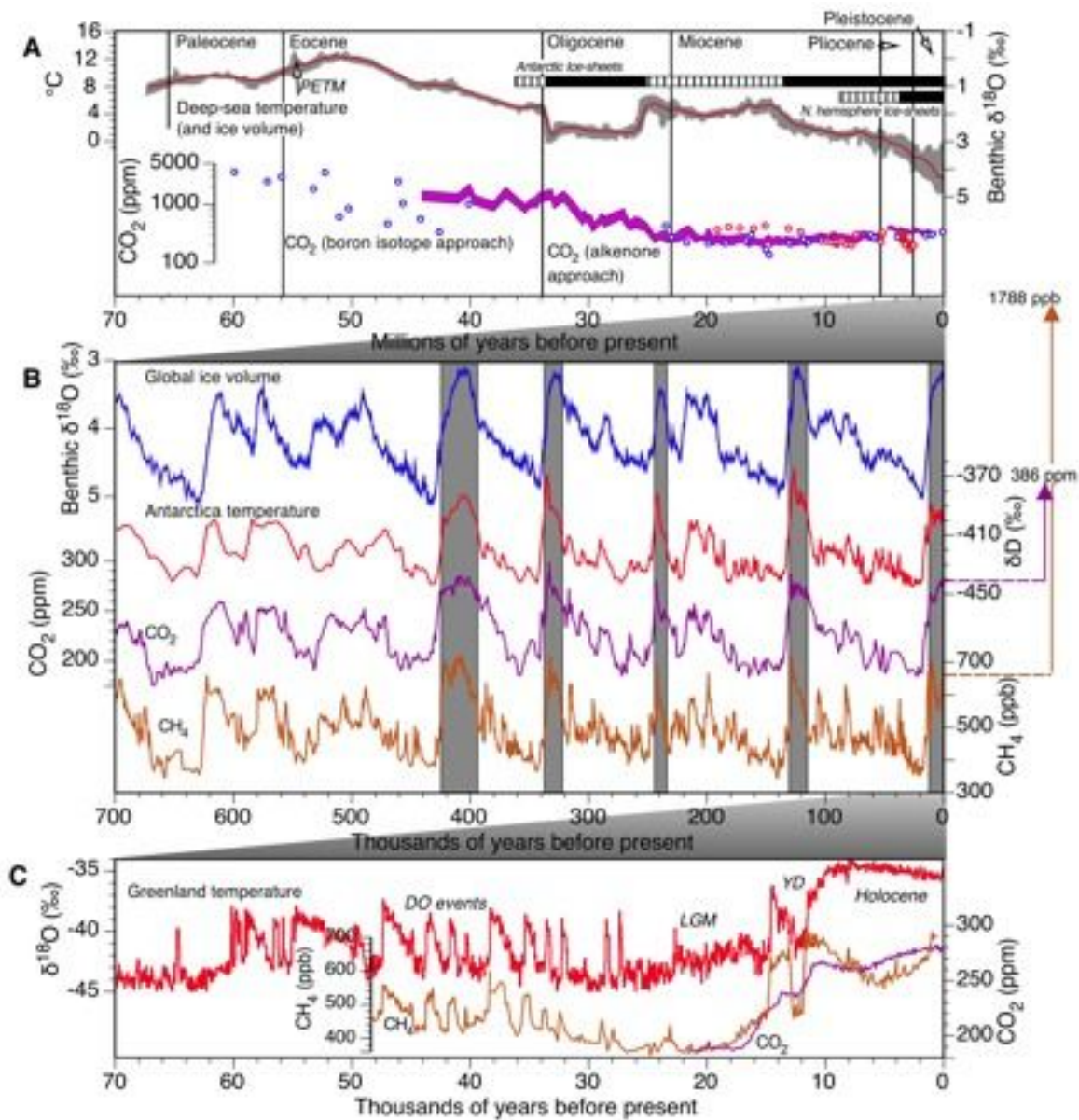
### 1.1.1 Climate Change in the Distant and Recent Past

#### 1.1.1.1 Before 2.6 million years ago

Over geologic time scales, Earth's climate has ranged from much warmer than today to much cooler. At one extreme, during the latter part of the Proterozoic (around 700 million years ago), ice sheets may have extended to near the equator (MacDonald 2010). At the other extreme, during the Cretaceous (100 million years ago), frost-sensitive plants occurred within the Arctic Circle. These extremes resulted from complex interactions between a changing geography (the location, extent, and topography of continents and oceans), atmospheric composition, orbital geometry (for example, the tilt of Earth's axis and the eccentricity of its orbit), and solar luminosity. Earth scientists understand this climate history and the various mechanisms operating in the climate system with decreasing detail the further back in time this history is studied. This summary will be limited to the Cenozoic era, the most recent 65.5 million years that follows the catastrophic extinctions that are linked to a meteor impact.

The temperature record of the Cenozoic was constructed by compiling records of oxygen isotopes measured on carbonate organisms in ocean sediment cores (Figure 1.1; Zachos et al., 2001). The values of these isotopes reflect the deep-sea temperature, but during times of continental glaciations the record mainly reflects the volume of ice sheets on land. The early Cenozoic is marked by deep-sea temperatures of at least 12°C warmer than today, peaking in the early Eocene. At 55 million years ago, a "brief" several-thousand year period of higher temperatures (Paleocene-Eocene Thermal Maximum) is marked by significant changes in the distribution of species and marks the beginning of many mammal lineages (Gingerich, 2006). Current evidence points to a large release of methane from ocean sediments as the cause of this warmth. Other greenhouse gases clearly were important for maintaining the overall warmth of the early Cenozoic. While it is difficult to reconstruct atmospheric CO<sub>2</sub> concentration from ocean-sediment evidence, the most recent studies show broad agreement between two approaches. These studies suggest CO<sub>2</sub> concentrations were as much as 15 times higher than pre-industrial concentrations.

After 50 million years ago, the Cenozoic is marked by a long-term global cooling trend that was interrupted by several distinct events (Figure 1.1A). Two leading hypotheses for this cooling are establishment of gateways in oceanic circulation that isolated Antarctica in its southern position and the drawdown of CO<sub>2</sub>. The first hypothesis is supported by the timing of the onset of cooling and glaciation in the Oligocene. The second hypothesis is supported by recent reconstructions of CO<sub>2</sub> (Figure 1.1A), especially declines in CO<sub>2</sub> at the start of the Pleistocene (Jansen et al., 2007). Weathering of silicate rocks consumes carbonic acids that are derived from



**Figure 1.1** Global climate and greenhouse gas records over three time scales. **A.** Deep-sea temperature over the Cenozoic determined from stable oxygen isotope measurements from several ocean sediment cores (Zachos et al. 2001). The  $\delta^{18}\text{O}$  values are increased by the presence of continental ice sheets, and thus the temperature scale only refers to periods without significant glaciation. The red line a smoothed curve fit and gray background shows the range of measurements. CO<sub>2</sub> concentration through the Cenozoic is difficult to measure, and thus several studies are shown here. The boron-isotope approach is shown as blue circles (Pearson and Palmer 2000). A more recent study (red circles) shows a much stronger correlation of CO<sub>2</sub> with events in the Cenozoic (Tripathi et al. 2009). An alternative approach using alkenones (purple line) shows changes in the Oligocene but not during late-Cenozoic climate change (Pagani et al. 2005). **B.** Changes in global ice volume estimate from ocean sediment cores (Liseicki and Raymo 2005), and deuterium ( $\delta\text{D}$ , a proxy for local temperature), CO<sub>2</sub> and CH<sub>4</sub> concentrations from the EPICA ice core (Petit et al., 1999; Monnin et al. 2001; EPICA community members, 2004; Spahni et al., 2005; Siegenthaler et al., 2005; Jensen et al., 2004). Gray bars denote warm interglacial periods between glacial periods marked by cooling and fluctuating temperatures. Current CO<sub>2</sub> and CH<sub>4</sub> levels, plotted on the same scale as the ice-core data, are shown to the right. **C.** The past 70,000 years of temperatures on the Greenland ice sheet (North Greenland Ice Core Project members. 2004), showing distinct Dansgaard-Oeschger events, the last glacial maximum (LGM), the Younger Dryas (YD) and the Holocene (past 11,600 years). A high-resolution CH<sub>4</sub> record shows that the abrupt temperature fluctuations during the glacial period had global influence (Flückiger et al. 2004; EPICA Community Members 2006). High resolution CO<sub>2</sub> since the LGM is from Monnin et al. (2004).

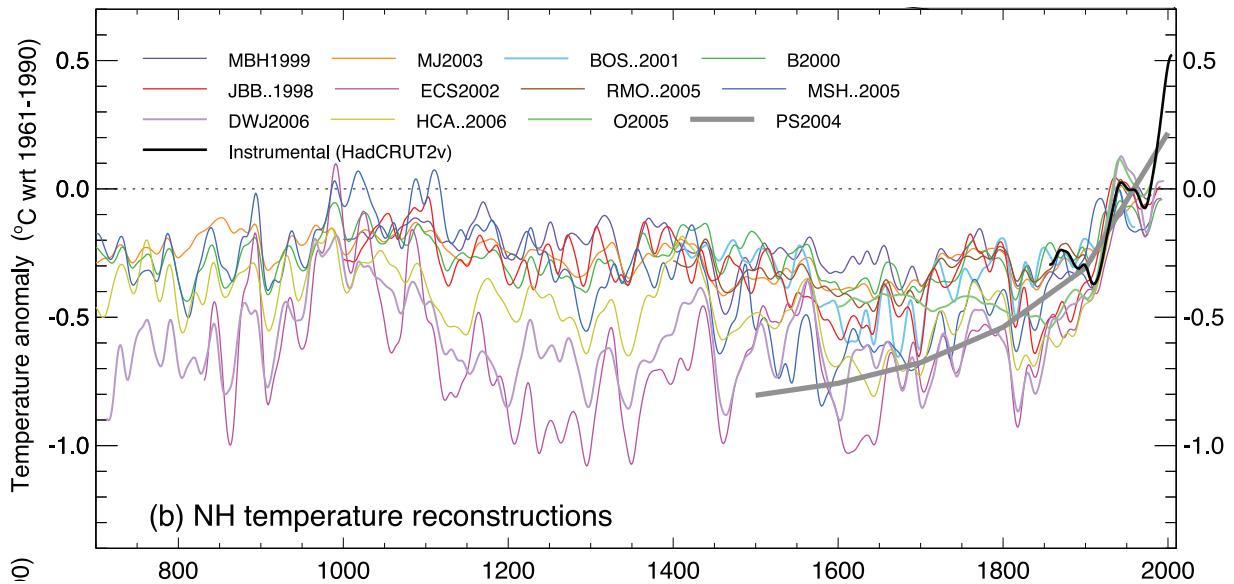
atmospheric CO<sub>2</sub>; thus, increased weathering from the uplift of the Himalaya and Tibet Plateau, which began 55 million years ago, could increase movement of CO<sub>2</sub> from the atmosphere to carbonates in ocean sediments (Garziona, 2008).

#### 1.1.1.2 Glacial and interglacial climate changes

Beginning 2.6 million years ago (the Pleistocene), global climate completed its transition from a “greenhouse” world that lacks ice sheets to an “ice-house” world marked by cyclic glaciations in the northern hemisphere. Causes of the onset of the glacial cycles remains a major area of research, and leading hypotheses involve increased delivery of moisture to North America (to build snowpack) and decreases in summer temperatures (to reduce snowmelt). In contrast, the general pacing of the glacial cycles and the feedbacks in the climate system are better understood. The detailed climate records from ocean sediments and ice sheets reveal dramatic changes in climate and greenhouse gas concentrations that suggest tight linkages among components of the climate system (Figure 1.1B).

During the glacial cycles of the Pleistocene, the three major controls of Earth’s climate were incoming solar radiation (*insolation*), ice extent, and greenhouse gases. Slow, progressive changes over time in three features of Earth’s orbit (orbital shape, axial tilt, and seasonal precession of the perihelion) have combined to affect the latitudinal distribution and seasonal cycle of insolation. The Milankovitch theory of orbital control of onset of glaciations states that times of ice sheet growth occur when northern hemisphere summer insolation is low, a pattern that is broadly consistent with the timing of glacial cycles. During extensive glaciation, ice sheets reflect shortwave solar radiation back to space, affecting both the global balance of incoming and outgoing radiation as well as modifying timing of past glacial cycles

The EPICA ice core from Antarctica reveals a close correspondence of CO<sub>2</sub> concentration and the global ice volume as estimated from ocean sediment cores (blue and purple lines in Figure 1.1B). The proposed causes of the 90 ppm drop in CO<sub>2</sub> during glacial periods include moving atmospheric CO<sub>2</sub> into the ocean, by changes in solubility of CO<sub>2</sub> in the ocean, increased biological productivity in the ocean surface waters, and changes in ocean circulation. In contrast, methane (CH<sub>4</sub>) concentration is closely correlated with the northern hemisphere incoming solar radiation, which affects the strength of monsoons and thus the extent of wetlands (that produce methane) in subtropical climates (Ruddiman, 2006). Both gases have roles in the climate system as forcing ice sheet response and as positive feedbacks to changes in the ice sheet already underway. At cycles of around 23,000 years, the response of ice volume follows changes in CO<sub>2</sub> within a few thousand years, suggesting ice sheets are responding to greenhouse gas forcing (and other factors). However, for cycles of 41,000 years (the orbital tilt cycle) both gases have immediate response to changing ice sheet extent, providing a powerful rapid positive feedback to changes in ice sheets.



**Figure 1.2** Records of NH temperature variation during the last 1,300 years. Reconstructions using multiple climate proxy records and the HadCRUT2v instrumental temperature record in black. All series have been smoothed with a Gaussian-weighted filter to remove fluctuations on timescales less than 30 years; smoothed values are obtained up to both ends of each record by extending the records with the mean of the adjacent existing values. All temperatures represent anomalies ( $^{\circ}\text{C}$ ) from the 1961 to 1990 mean. Figure 6.10 from IPCC (Jansen et al. 2007).

### 1.1.1.3 Deglacial and Holocene climate (the past 20,000 years)

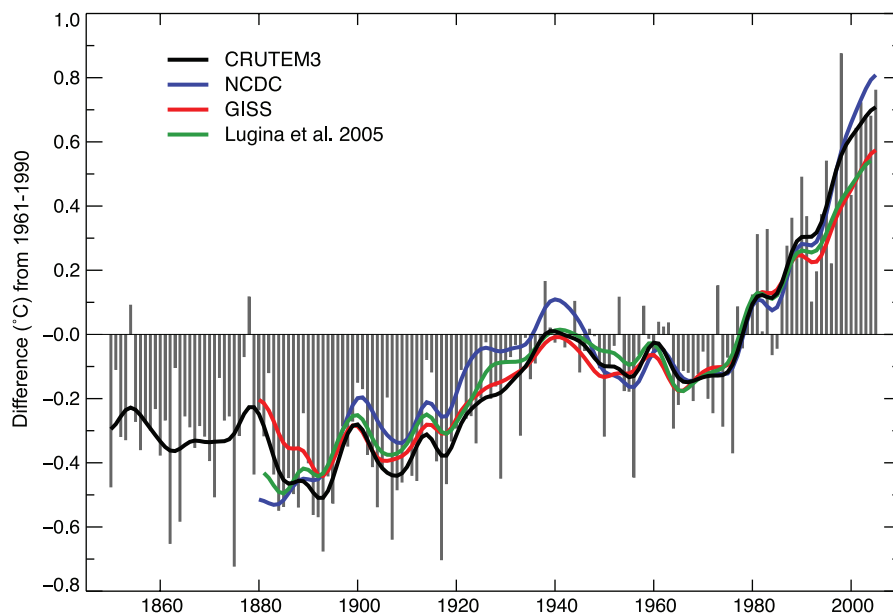
The Last Glacial Maximum (LGM), when the maximum extent of the North American and European ice sheets occurred, occurred near the end of the last glacial period, at 21,000 years ago. Increased summer insolation after that time was sufficient to reduce ice sheet extent. Near the most rapid phase of this deglaciation, at 12,900 years ago, a distinct reversal to a cold climate called the Younger Dryas began and lasted until 11,600 years ago. The causes of this event are unknown, but some data suggest a relationship to a change in ocean circulation patterns in the northern Atlantic initiated by a meltwater pulse, while others have proposed a comet impact as the initiator of the meltwater pulse. The effects of the Younger Dryas period are observed throughout the northern hemisphere, though they are most distinct in the North Atlantic.

The Holocene refers to roughly the last 11,600 years, during which time human civilization developed. Following the Younger Dryas period, the early Holocene was marked by an increase in northern-hemisphere summer insolation and a decrease in northern-hemisphere winter insolation. During these strongly seasonal climates, pollen records show more extensive fire and dry-adapted vegetation in most of North America (except those areas affected by increased monsoonal precipitation). At around 8400 years ago, a major collapse of the Laurentide (North American) ice sheet resulted in a large outburst of fresh water, likely causing a century-scale cold period (at 8200 years ago) by slowing down the conveyor circulation in the North Atlantic. The latter half of the Holocene in North America is marked by a general cooling trend, mirroring the trend in summer insolation.

Tree-ring and other proxy sources of year-to-year variations allow scientists to infer climatic conditions in the last ~2000 years. Using a combination of proxy data and statistical algorithms, a number of researchers have estimated the northern hemisphere average temperatures; errors associated with the sparseness of the proxy records diminish over time. Much of the region around the North Atlantic tended to be warmer than the long-term average in the years 1000 to 1250 (first called the “Medieval Warm Period” and now commonly called the “Medieval Climatic Anomaly”) but colder than average from 1400 to 1830 (the “Little Ice Age”). These anomalies were generally not as strong or synchronous in other parts of the world, and consequently hemispheric reconstructions indicate a difference of at most 1°C (1.8°F) between the warmest decade of the Medieval Climatic Anomaly and the coolest period of the Little Ice Age, and most reconstructions indicate a substantially smaller difference (Figure 1.2). The potential forcings of these climate fluctuations are still being studied, including CO<sub>2</sub> concentration, solar variability, and major volcanic eruptions that increase atmospheric reflectivity and reduce solar radiation reaching the surface. From the coldest period of the 19th century until 1900, hemispheric temperatures rose, by various estimates between 0 and 0.7°C (1.3°F), compared with 0.7°C (1.3°F) warming during the 20th century.

#### 1.1.1.4 The instrumental period<sup>1</sup>

One might surmise that the advent of thermometers would provide a perfect measurement of a location’s temperatures, and that temperatures could simply be averaged to provide the globally averaged temperature. But because these observations originally were intended simply



**Figure 1.3** Annual anomalies of global land-surface air temperature (°C), 1850 to 2005, relative to the 1961 to 1990 mean for CRUTEM3 updated from Brohan et al., (2006). The smooth curves show decadal variations (see Appendix 3.A). The black curve from CRUTEM3 is compared with those from NCDC (Smith and Reynolds, 2005; blue), GISS (Hansen et al., 2001; red) and Lugina et al., (2005; green). From IPCC, (2007) Figure 3.1.

<sup>1</sup> Unless otherwise noted, the material in this section comes from IPCC chapter 3, Trenberth et al., 2007.

to record the day's weather conditions, most records of temperature or precipitation are affected by non-climatic influences: stations moved, instruments changed, the time of observation changed. Consequently it is a substantial scientific effort simply to identify and remove these non-climatic influences from each observational record and to combine point observations into area-averaged data, and to account for data gaps and other uncertainties.

Several research groups have undertaken these calculations and although the details differ slightly, all agree on several main features of global climate. The global land average temperature (Figure 1.3) fluctuated but showed little trend until about the 1920s, rose about 0.3–0.4°C (0.5–0.7°F) between the 1920s and 1940s, declined about 0.1–0.2°C (0.2–0.4°F) between the 1940s and the 1960s, and then rose 0.8–1.0°C (1.4–1.8°F) between the 1960s and 2005. The linear trend in global land average temperature is  $0.8 \pm 0.2^\circ\text{C}$  ( $1.4 \pm 0.4^\circ\text{F}$ ) over the 1901–2005 period according to the various reconstructions.

The climate system has changed in ways consistent with observed warming. The average temperature of the global oceans from the surface to a depth of 3 km (1.9 mi) has increased in the last 40 years, as the oceans have absorbed more than 80% of the additional heat energy added to the climate. Sea level rose 7.5 cm (3.0") between 1961 and 2003; nearly half of that rise was in the last ten years. Ice losses from the ice sheets of Greenland and Antarctica likely contributed to the accelerated rise of the last ten years. Since 1979, when reliable satellite-based global measurements began, the amount of water vapor in the atmosphere has increased in locations and quantities consistent with the extra water vapor that warmer air can hold. Because water vapor is a powerful greenhouse gas, and its abundance is primarily controlled by ocean surface temperatures, water vapor provides a substantial "positive feedback," accentuating other factors that influence surface temperature.

**In summary, past changes in global climate have been substantial, but recent decades have been warmer than at any time in roughly 120,000 years.**

### 1.1.2 Understanding Causes of Climate Change

Scientific assessments continue to underscore that scientific understanding of both the observed changes in global climate and their causes remains strong:

Most of the [global] warming over the last several decades can be attributed to human activities that release carbon dioxide (CO<sub>2</sub>) and other heat-trapping greenhouse gases (GHGs) into the atmosphere. The burning of fossil fuels—coal, oil, and natural gas—for energy is the single largest human driver of climate change (NRC 2010).

#### 1.1.2.1 Drivers of climate change

To a close approximation, net energy input from the Sun - mostly in the form of visible light - is balanced by radiation of infrared (heat) energy back to space, averaged over the globe. "Drivers" or "forcings" of climate refer to natural or artificial processes that change some aspect of the climate by altering this energy balance. These forcings include the amount of solar radiation received at the top of the atmosphere (as affected by direct solar output and the Earth's orbital fluctuations), things that change the reflectivity (albedo) of the planet, such as particles in the atmosphere, and things that affect the efficiency of infrared energy loss to space.

These latter include both clouds and certain trace gases that absorb outgoing infrared energy and are commonly called greenhouse gases. In order of global importance, these greenhouse gases include water vapor, carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), ozone, chlorofluorocarbons (CFCs), of which CFC-12 dominates, nitrous oxide, and dozens of others. Human activities in the Industrial Era have substantially increased the quantity of all of these gases, and some (the CFCs among them) are entirely man-made. Carbon dioxide alone is responsible for about 63% of the total forcing by long-lived greenhouse gases (Forster et al., 2007).

White or grey particles in the atmosphere from smoke, smog, haze and volcanic ash scatter enough incoming sunlight that they offset a substantial fraction of the greenhouse gas warming. Particles also cause additional clouds to form, which adds to the cooling effect, as does the tendency for these clouds to be brighter than natural clouds. Both types of forcing, together, offset up to approximately one-half of the greenhouse gas warming, although confidence in the amount of this offset is low owing to difficulties in measuring the relevant quantities.

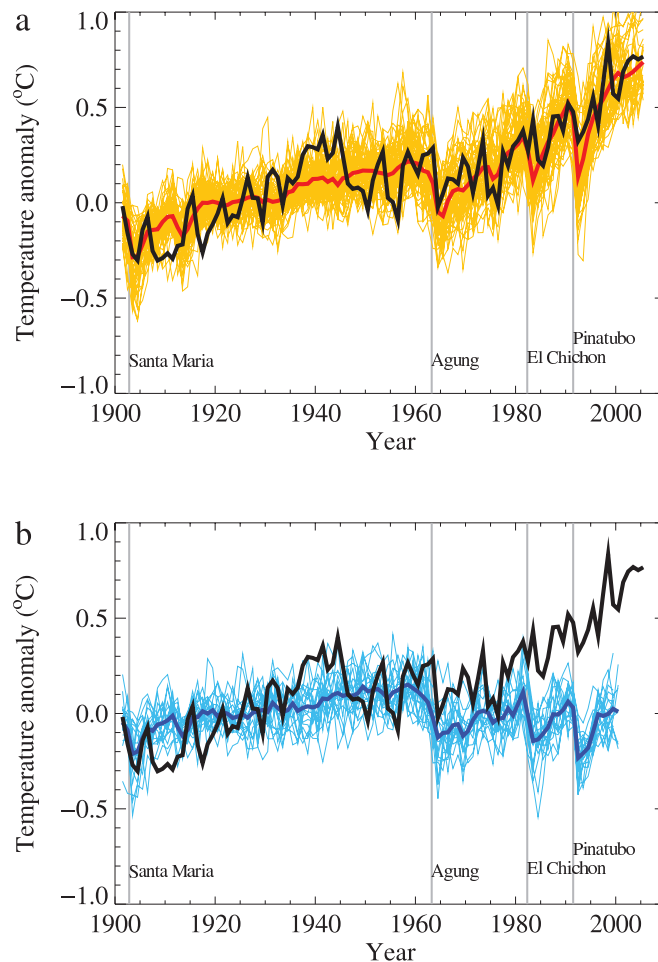
Changes in the sun's energy output and volcanic eruptions are the most important natural external forcings of climate. (Fluctuations in water vapor, surface albedo related to vegetation or snow cover, and other factors are considered internal responses of the climate system.) Solar changes may be partly responsible for the cool period in the 16th to 18th centuries (Figure 1.2) and for the warming early in the 20th century, but observations from satellites of solar output since late 1978 demonstrates that solar changes cannot be responsible for the large increase in global temperatures during the last 32 years: solar output has not increased over that period, but has fluctuated with the roughly 11-year solar cycle whose amplitude is about 0.1%. Since the solar cycle is presently just past a minimum, solar output is actually slightly lower than it was in 1978 (Lean and Rind, 2009).

A rare type of volcanic eruption — a very powerful tropical eruption — can cool the Earth for one to two years. Most volcanic eruptions briefly pollute the troposphere, the layer of the atmosphere with weather, up to about 10km (6 miles) above the surface in midlatitudes and 16 km (10 miles) in the tropics. Besides ash, which quickly falls out, volcanic emissions include sulfur dioxide, which (given enough time) turns into sulfuric acid particles that reflect sunlight. But the particles quickly attract water vapor, form clouds, and precipitate out. Some eruptions reach the stratosphere but in middle and high latitudes stratospheric air is gradually sinking and the volcanic emissions are pushed into the troposphere within a month or two. The most effective volcanic eruptions that cool the Earth are tropical volcanic eruptions of sufficient force to reach the stratosphere, in the latitudes where stratospheric air is rising and hence can suspend the reflective particles.

### *1.2.2 Understanding the factors in climate change*

An easily understood approach to separating natural and human influences on climate change is to perform simulations of past and present climate with human influences included, and then with human influences excluded (Figure 1.4). By comparing observed temperatures and temperatures simulated with only natural influences (lower panel of Figure 1.4), marked differences emerge after about 1960. But simulations with human influences included match quite well the observed record, including drops in temperature associated with the major tropical volcanic eruptions indicated in the figure.





**Figure 1.4** Comparison between global mean surface temperature anomalies ( $^{\circ}\text{C}$ ) from observations (black) and AOGCM simulations forced with (a) both anthropogenic and natural forcings and (b) natural forcings only. All data are shown as global mean temperature anomalies relative to the period 1901 to 1950, as observed and, in (a) as obtained from 58 simulations produced by 14 models with both anthropogenic and natural forcings. The multi-model ensemble mean is shown as a thick red curve and individual simulations are shown as thin yellow curves. Vertical grey lines indicate the timing of major volcanic events. The simulated global mean temperature anomalies in (b) are from 19 simulations produced by five models with natural forcings only. The multi-model ensemble mean is shown as a thick blue curve and individual simulations are shown as thin blue curves. From IPCC (Hegerl et al. 2007), Figure 9.5.

A more sophisticated approach to separating natural and human influences is to compare some aspect of the pattern of change in space and time with the pattern generated by climate model simulations. This pattern-matching or “fingerprinting” approach determines statistically whether the pattern could occur by chance or whether it is consistent with the forcing in question. Using this approach, a human influence on climate has been detected in global mean temperatures, in precipitation averaged in latitude bands, in atmospheric pressure, and in other fields (Hegerl et al., 2007).

Most of the research attributing recent climate change to specific causes has used global climate models (e.g., Figure 1.4). Lean and Rind (2009) instead use empirical data to diagnose four main factors influencing changes in global temperature in the last 30 years. Three are natural: the El Niño/Southern Oscillation, ENSO; cooling by volcanic particles; and energy output of the Sun.

The fourth factor is human influences, a steady and persistent rise. Lean and Rind's (2009) empirical approach explains the recent level period in global temperatures as the result of a competition between the waning phase of the solar cycle and the slow growth of human influences, and suggests that global temperature will resume its increase from 2010 to 2015, followed by another level period. Of course, a large tropical volcanic eruption or ENSO event could change the details.

**In short, several lines of evidence including basic physics point to the rising concentration of greenhouse gases as the cause of substantial global warming since about 1950.**

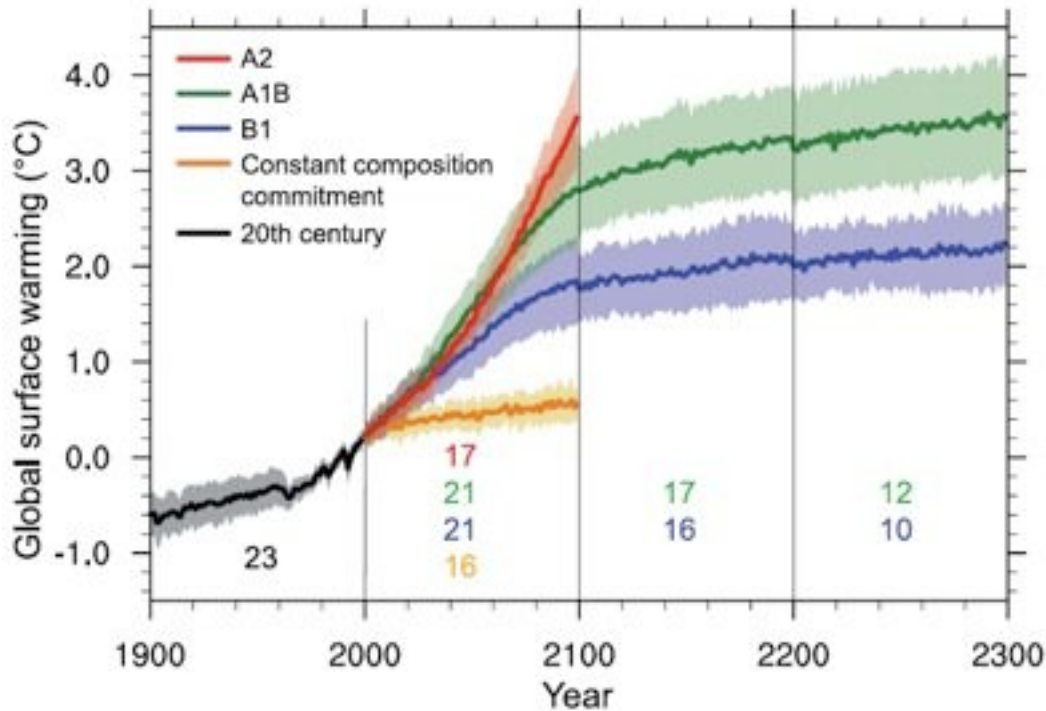
### 1.1.3 Future Global Climate Change

#### 1.1.3.1 Tools and driving scenarios

One approach to understanding future global climate change would be to find a past analog: a period when conditions were similar to what is expected in, say, 2050. However, in the period of most detailed past climate information - the 700,000 years for which data from Antarctic ice cores exist - has no precedent for a climate with greenhouse gas forcing as high as it is today, let alone as high as it will be by 2050. Measurements of CO<sub>2</sub> in Antarctic ice cores never exceeded 300 parts per million, compared with almost 390 in 2010. Indirect measurements suggest that the last time CO<sub>2</sub> exceeded 300 ppm was at least several million years ago (Royer, 2006). Without a clear example from the past, we are left with two approaches to estimating global climate in a future with much higher levels of greenhouse gases:

(1) Using observations, estimate the climate sensitivity: the response of global mean temperature to a doubling of CO<sub>2</sub>. Considering a wide range of studies, the sensitivity lies in the range from 2°C - 4.5°C (3.6°-8.1°F) with a best estimate of 3°C (5.4°F) for a doubling of CO<sub>2</sub>, according to the IPCC (Hegerl et al. 2007). Given that CO<sub>2</sub> has already increased about 40% above pre-industrial concentrations, the likelihood of doubling during this century is fairly high, so the globally averaged increase in temperature during this century will almost certainly exceed 2°C, absent large increases in efforts to reduce global emissions.

(2) Using physically based models of the ocean, atmosphere, land, and ice, calculate the future climate. These global climate models (GCMs) have been developed by modeling groups in many nations. The Intergovernmental Panel on Climate Change (IPCC) coordinated a common set of simulations that used 21 models (Randall et al., 2007). One of many advantages of this approach is that these models estimate changes in climate in far more detail than only global mean temperature.



**Figure 1.5.** Simulated global mean temperature response to both the 20th century radiative forcing (1900-2000), to three scenarios of radiative forcing in the 21st century, and for three assumptions of constant CO<sub>2</sub>: for the 21st century at year 2000 levels (“constant commitment”), and for the 22nd and 23rd centuries at the constant values reached in year 2100 under scenarios A1B and B1. Heavy curves show the multi-model means, shading denotes the  $\pm 1$  standard deviation range of individual model annual means. Numbers in each century denote the number of contributing models. From Meehl et al., (2007).

Simulations of climate over the 21st century (Figure 1.5) require modelers to project the forcing of climate by radiation, especially the warming due to greenhouse gases - CO<sub>2</sub>, methane, and a few others - and the cooling caused by atmospheric particles. In the 1990s, the IPCC produced more than 40 socio-economic scenarios (SRES; Nakićenović and Swart 2000) that generated concentrations of the leading greenhouse gases and reflective atmospheric particles. Of these, six scenarios were extensively discussed, and three of these were chosen by modeling groups for forcing the global climate models: the scenarios B1, A1B, and A2. All scenarios have similar climate forcing factors until about 2020 because CO<sub>2</sub> molecules last so long in the atmosphere (more than 50 years) that the CO<sub>2</sub> concentration in the whole atmosphere changes very slowly after a change in emissions. Of the chosen three, scenario A2 has the highest climate forcing by the year 2100, but before the middle of this century, none of the scenarios is consistently the highest. Another scenario, A1FI (not in the chosen three, and not used by most modeling groups) has even higher climate forcing than any of the chosen three by 2100. Their forecasts of CO<sub>2</sub> concentration for the year 2100 are 549, 717, 856 and over 1100 ppm in scenarios B1, A1B, A2, and A1FI, respectively (from 2 to 3.5 times the pre-Industrial value). Actual fossil fuel emissions of CO<sub>2</sub> since 2001 exceeded all but one of the six SRES scenarios (Myrhe et al., 2009) even though a few countries began to limit their emissions of greenhouse gases.

### *1.1.3.2 Projected global temperature changes*

In the IPCC Fourth Assessment Report (AR4), Meehl et al., (2007) summarize projections of future climate change from the full suite of AR4 GCMs. Figure 1.5 shows the global mean surface temperature simulated by these GCMs. The figure shows global mean temperature rising about 0.7°C in the 20th century, as observed, along with dips in global mean temperature associated with major tropical volcanic eruptions. For the 21st century, note that models estimate an additional 0.2°C of “committed” warming even with constant CO<sub>2</sub>. This underscores the point that the climate system — especially the ocean — is still catching up to the forcing already in place, and that climate change will continue (although at a considerably reduced rate) even after CO<sub>2</sub> is stabilized in the atmosphere.

### *1.1.3.3 Changes in other aspects of global climate*

We summarize here some key aspects of global climate described by Meehl et al., (2007). Globally averaged precipitation increases slightly in 21st century simulations, around 1.4% per degree C (0.8% per degree F), owing to the enhanced water-holding capacity of warmer air. The global hydrologic cycle speeds up, with precipitation generally increasing in areas with above-average precipitation (tropics and mid to high latitudes) and decreasing in the subtropics, around 20-30° latitude in both hemispheres. Models produce some consistent changes in cloud patterns, with most models showing reductions over low to middle latitude land areas.

Changes in atmospheric circulation in the models include a stronger Hadley circulation (rising in the tropics, sinking in the subtropics, and return flow as trade winds), which is linked to the pattern of global precipitation change; and a slight poleward shift and intensification of the storm tracks (e.g., Yin, 2005). The latter change can be linked to global changes in the troposphere including the equator-to-pole temperature gradient in the middle-troposphere.

## **1.2. Climate Change in Oregon and the Northwest**

### **1.2.1 Pacific Northwest Climate in the Past**

Since the last glacial maximum 21,000 years ago, Oregon’s climate has fluctuated greatly over a wide range of timescales. Transitioning from the glacial climate regime to the modern climate regime took thousands of years, and there are fluctuations on timescales of centuries, decades, and year to year, as well as abrupt changes in climate averages and variability.

Paleoclimatologists use a variety of methods to reconstruct these fluctuations and to attribute the fluctuations to factors that are known to affect the climate. In Oregon, there is great potential to study climate history over thousands of years because alpine ice fields (which locally eliminate the geologic sediment records) covered only a small portion of the state during the glacial maximum. In addition, many tree species reach great ages, allowing the study of past climate from annual growth rates.

The three major controls of Earth’s climate - incoming solar radiation (insolation), ice extent, and greenhouse gases - have changed dramatically from the glacial maximum to the present. Slow progressive changes over time in three features of Earth’s orbit (orbital shape, tilt of its axis, and seasonal precession of the perihelion, or closest earth-sun distance), combine to affect

the latitudinal distribution and seasonal cycle of insolation. During the last glacial maximum, extensive ice sheets, which reflect short-wave solar radiation back to space, affected both the global balance of incoming and outgoing radiation as well as modifying the locations of high and low pressure systems, the location of jet streams, and routes of moisture to continental interiors. Greenhouse gases, including carbon dioxide and methane, were lower during the glacial maximum, thus increasing the amount of outgoing longwave radiation escaping from Earth's surface and atmosphere to space.

Insights into the climatic changes of the past come from both climate models and from a myriad of geological records. The discussion below summarizes the millennial-scale patterns for which there is strong agreement between the climate simulations and the data, as well as highlights recent findings of shorter-term and abrupt changes in climate.

#### *1.2.1.1 The Last Glacial Maximum: 21,000 years ago*

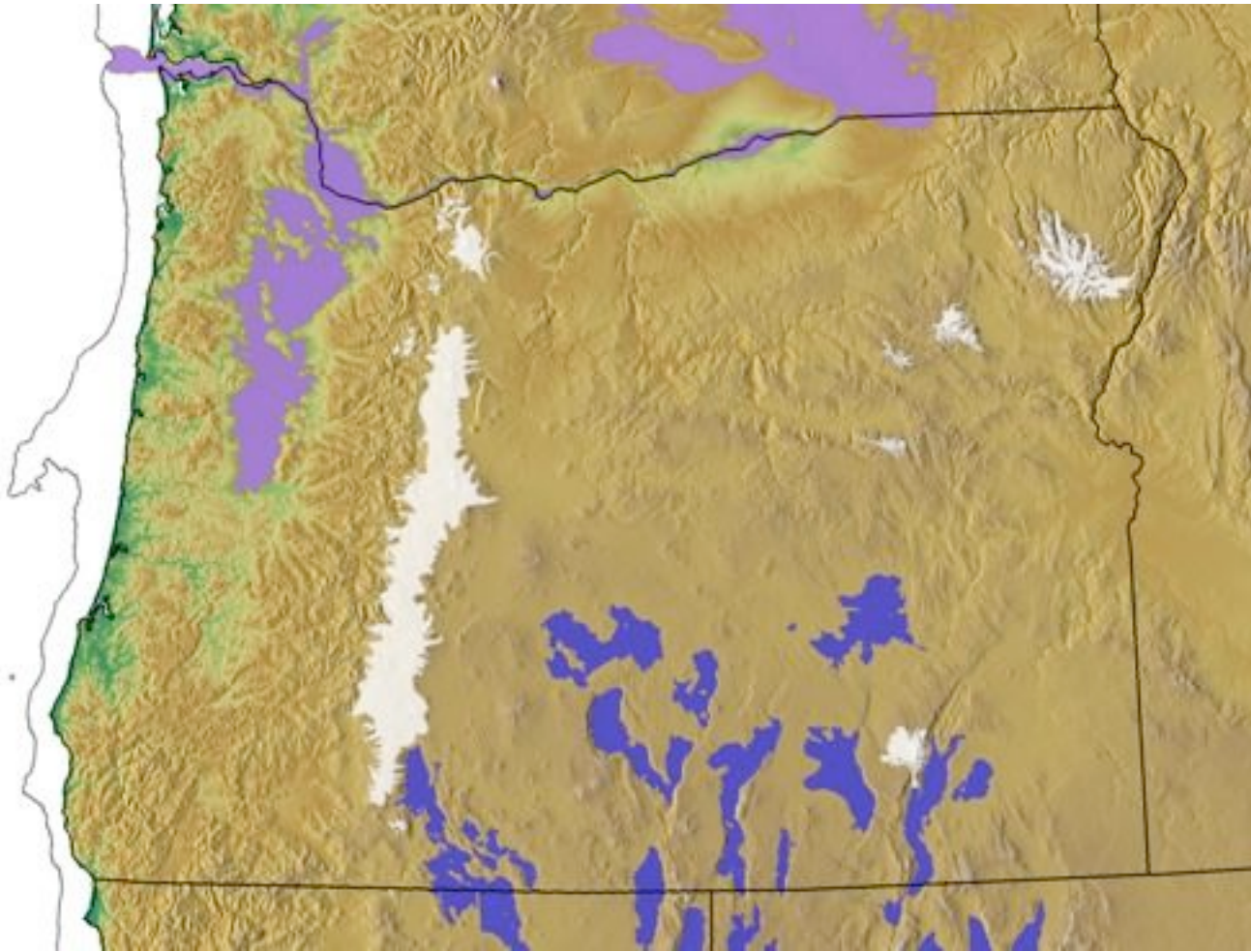
During the height of the last glaciation, the seasonal pattern of insolation was similar to the present day; extensive ice sheets were located to the north and atmospheric CO<sub>2</sub> was as low as 180 ppm (65% of preindustrial levels). The high albedo and high elevation of the ice sheets produced very cold air, resulting in a large high pressure system and associated anticyclonic (clockwise) winds, which were especially intense during winter. The anticyclonic winds spun off the ice sheets producing an east-to-west wind in Oregon, deflecting to the south an onshore flow of moist air. Lower greenhouse gas concentrations also affected the global energy balance.

Oregon's climate was significantly colder and drier than present. The latest paleoclimate reconstructions and models indicate that mean annual temperature was as much as 10°C (18°F) colder in eastern Oregon and about 5°C (9°F) colder in western Oregon. This is consistent with the occurrence of winds from the east during the glacial maximum affecting eastern Oregon more than coastal Oregon. Glaciers along the High Cascades were extensive and merged into continuous ice fields. Cooler temperatures resulted in much less evaporation than today, increasing depths of lakes in the closed basins of central and southeastern Oregon (Figure 1.6). The depths of these basin lakes fluctuated throughout the glacial periods (peaking before the glacial maximum), likely reflecting fluctuations in the strength of the glacial anticyclone and the degree to which the jet stream and moisture were deflected to the south. Similarly, the emplacement of dunes along the Oregon coast (which extended farther west with lower sea levels) occurred during periods before the glacial maximum when the glacial anticyclone was weak, allowing strong winds from the west to move sand inland.

While few glacial maximum pollen records have been collected for Oregon, those available suggest that the Coast Range mountains supported a park-like landscape of trees and meadow, somewhat similar to the colder and drier forests at higher elevation in the eastern Cascades and Rocky Mountains today, while eastern Oregon was marked by many more drought-adapted shrubs near the forest/shrubland border.

#### *1.2.1.2 The Late Glacial: 21,000 to 11,600 years ago.*

A period of deglaciation between 21,000 and 11,600 years ago, driven by changes in insolation, was marked by decreasing ice sheet extent, increasing sea level, and increasing atmospheric CO<sub>2</sub>, resulting in a complex series of climate changes differing greatly across North America. As the ice sheets retreated north into what is now Canada, the glacial anticyclone weakened



**Figure 1.6** The glacial periods left distinctive fingerprints across Oregon. During the Last Glacial Maximum, sea level was approximately 120 m (400 ft) lower than today and the Pacific Coast was 20 - 60 km (13 -38 mi) further to the west (shown as gray line). The “pluvial” lakes of central and southeast Oregon (dark blue) were 70 m (230 ft) deeper than at present for most of the late Pleistocene (and deeper during the early Pleistocene). At roughly 17,000 years ago, glaciers (white) descending from the mountains reached their maximum extent. These glaciers were restricted to the Cascades, Steens, Aldrich, Greenhorn, Strawberry, and Wallowa Mountains. From 20,000 to 15,000 years ago, dozens of Missoula Flood events (purple), originating from glacial lake Missoula where the Clark Fork River was ice-dammed in northern Idaho, swept across eastern Washington and backed into the Willamette Valley, forming glacial Lake Allison to a surface elevation of 120 m (400 feet) above modern sea level. Glacier extent used in this map was compiled from the Atlas of Oregon (Loy et al., 2001) and various other data sources.

resulting in increased onshore wind flow. A large increase in moisture occurred 17,000 years ago causing advances of alpine glaciers throughout the Pacific Northwest, marking the time when alpine glaciers descended to elevations as low as 1000 m (1600 ft) in the western Cascades, 2100 m (3400 ft) in the Wallowas, and 3250 m (5200 ft) on Steens Mountain. At the same time, glacial Lake Missoula breached its ice dam dozens of times resulting in cataclysmic floods down the Columbia River, which backed into the Willamette Valley. These floods recurred as the Cordilleran ice sheet re-advanced to form new ice dams on the Clark Fork River, only to burst and send forth another massive flood. The last Missoula Flood occurred around 15,000 years ago and the alpine glaciers retreated around 14,000 years ago leaving vestiges on a few of the highest peaks. Nearly all lake basins in mid to high elevations of Oregon became ice-free at that time. The few lake-sediment records from unglaciated areas show an abrupt warming 14,000

years ago with the replacement of subalpine habitats by more productive forests of Douglas-fir and alder.

The Younger Dryas period between 12,900 and 11,600 years ago, has been identified to various degrees in the Pacific Northwest. The inconsistency of response likely reflects a lower magnitude of the event than occurred in the Atlantic, and the wide climatic tolerance of the recently-established vegetation at the various study sites. For example, some records show that the Younger Dryas-like climate event in the Northwest slightly lagged events in the North Atlantic (Mathewes et al. 1993). Nevertheless, some well-dated records from speleothems (stalagmites) in Oregon Caves, as well as lake sediments, are broadly synchronous with the Younger Dryas, but the magnitude of the cooling event in the Pacific Northwest is yet unclear (Vacco et al. 2005).

#### *1.2.1.3 The Holocene: 11,600 years ago to present*

Around 11,600 years before present, ice sheets retreated rapidly across North America, insolation was at its peak in seasonality (8% more insolation in the summer and 8% less in the winter compared to today), and CO<sub>2</sub> was at levels typical of the preindustrial period (280 parts per million, vs about 390 ppm in 2010 and 180 ppm during the glacial maxima). Greenland ice cores indicate that the beginning of the Holocene period was marked by an abrupt increase in temperature in a period of less than 5 years.

In the Pacific Northwest, this abrupt warming was observed at several sites in Washington and British Columbia. That the record of this warming is less than clear in many sediment records in Oregon may reflect the facts that (a) warm-adapted vegetation was well established before the Younger Dryas period and (b) many species (e.g., Douglas-fir) tolerate a broad range of climate and their abundances on the landscape hence do not closely follow the climatic changes through the Younger Dryas period.

The early Holocene was marked throughout the Pacific Northwest by hotter summers and increased droughts and forest fires. The increased summer insolation during the Holocene may have led to an intensified Pacific Subtropical High pressure system, which created warm, stable, dry air to its east (i.e., the Pacific Northwest). In western Oregon and Washington, increased summer warmth and wildfires led to widespread Douglas-fir and alder forests, species that are adapted to fire by reproducing rapidly in burned areas (Sea and Whitlock 1995). Prehistoric insect remains recovered from lake sediments in southern British Columbia suggest early Holocene summer temperatures at 3°C (5.4°F) warmer than present, in agreement with temperature reconstructions based on early Holocene pollen data from southeast Oregon (Walker and Pellatt 2003; Minckley et al. 2007). There is mounting evidence, however, that the early Holocene was not uniformly warm and dry, but was marked by distinct century-scale periods of increased moisture (Heine 1998). The remnants of the waning ice sheet to the north may have still been influencing the jet stream across western North America.

An event during the early Holocene deserving special mention is the eruption of Mount Mazama that created Crater Lake 7,600 years ago. Ash deposits from this eruption blanketed the Northwest, especially east of the Cascade crest. This ash layer created seed beds for today's forests, and established the patterns of future forest growth. In some areas, extremely thick ash deposits led to "tephra plains" that remain very dry and sparsely vegetated today. In other

areas, ash deposits thickened soils, weathered into clays, and may have allowed for greater water retention. In still other areas, forests were successfully established on steep rocky slopes only when tephra deposits were laid down (Gavin et al., 2001).

As summer insolation decreased through the middle Holocene, cooler and moister summers resulted in lower fire occurrence and the establishment of the dense, deep-shade tolerant vegetation currently typical in western Oregon and Washington. In Washington, 6000 years before present marks the onset of forests resembling today's old growth Douglas-fir forests (Brubaker 1991). In Oregon, evidence of this transition is less distinct but suggests a progressive increase in moisture until modern forests became established around 4000 to 3000 years ago (Whitlock 1992).

This latter part of the Holocene is termed the "neoglacial" because many alpine glaciers began advancement downslope about 4000 years ago. Between 5000 to 4000 years ago, dunes became more established along the Oregon coast indicative of intensified onshore winds. Later in the neoglacial, many glacial advances were synchronous across the West, including events at 3300 and 2400 years ago. Of all the glacial advances during the Holocene, almost without exception the largest was a series of Little Ice Age glacier advances from 1350 to 1850 AD.

#### *1.2.1.4 The instrumental period: 1850 to the present*

For reasons noted in Section 1.1.4, instrumental records of temperature must be carefully treated to remove non-climatic influences. By about 1920, enough stations in the US Historical Climate Network (Karl et al., 1990) were in place to analyze regionally averaged changes in temperature and precipitation (Mote, 2003) and over the 1920 - 2000 period, they indicated a warming for the Pacific Northwest of 0.8°C (1.5°F)/century, and almost every one of the individual trends is positive (Figure 1.7). Two examples are shown, both with trends around 2.0°F/century and with periods of record 1903 - 2006. However, throughout the instrumental record, regionally averaged precipitation has fluctuated substantially.

Understanding the causes of these trends and fluctuations remains an active area of research. The fluctuations in annual mean temperature and precipitation are partly related to atmospheric variability over the Pacific Ocean (Section 2.2). Mote (2003) estimated that Pacific variability could explain about 10% of the temperature trend over the 1920 - 1995 period. Formal detection and attribution studies like those described in Section 1.2.2 have not been performed for regions as small as the Pacific Northwest, but the analysis of Bonfils et al., (2008) finds a human influence on temperature of the mountainous West.

Other aspects of climate, though perhaps more relevant for society, have received less attention from researchers than warming has. Trends in extreme precipitation are ambiguous. Groisman et al. (2004) examine regionally averaged trends in number of days greater than the 99th and 99.7th percentile of daily precipitation; for the Pacific Northwest, over the 1908 - 2000 period, trends are not statistically significant in any season. Kunkel et al. (2003) examine precipitation extremes averaged over the continental US for a range of definitions (1-, 5-, and 20-year return period; and 1- 5-, 10- and 30-day precipitation totals), and note that all the time series had a similar shape with high values during the late 19th and early 20th centuries, lower values from the 1920s to 1970s, and then increasing; for most definitions of extremes, the recent maximum was larger than the earlier maximum, but combined with the results of Groisman et al. (2004) it



is clear that the recent increase in extremes happened mainly in the eastern third of the country, not in the West. Madsen and Figdor (2007) examine station trends in the Northwest and find a statistically significant *decrease* in extreme precipitation in Oregon over the 1948 - 2006 period. Rosenberg et al., (2010) construct regionally averaged probability distributions from hourly station data, normalized by each station's long-term mean, for 1956-30 and 1981-2005 in Washington State and the Portland, OR, area. For the Portland area stations, the extreme 1-hour precipitation increased across the probability distribution, whereas extreme 24-hour storms decreased slightly for the 99th percentile and increased substantially at all higher percentiles.

### **1.2.2 Patterns of Climate Variability Influencing the Northwest**

Variations of climate include variations across the landscape — spatial patterns — and variations in time — temporal patterns. Spatial patterns of climate in Oregon and the entire Pacific Northwest are strongly influenced by the north-south mountain ranges, chiefly the Cascades but also the coast range and Blue-Wallowa mountains of northeast Oregon. The effects of mountains on precipitation are clear in Figure 1.8, constructed with the PRISM (Parameter-elevation Regressions on Independent Slopes Model) approach to geospatial mapping (Daly et al., 2004) using observations and statistical relationships between terrain and precipitation. The western slopes of the Coast Range and the Cascades are very wet, with many places estimated to receive over 250 cm (100 inches) of precipitation per year. Gradients in precipitation can be quite sharp, with differences of a factor of 10 in less than 32 km (20 miles) near Bend (labeled in Figure 1.8) for example.

Temporal patterns of climate variability in the Northwest are strongly influenced by variations over the Pacific Ocean, chiefly El Niño/Southern Oscillation (ENSO). ENSO involves linked variations in the tropical Pacific Ocean and overlying atmosphere. Most of the time, the warmest water lies north of Australia and the presence of the warm water draws warm moist air, which forms thunderstorms. Hence, the warmest water coincides with heavy precipitation. The air rising in thunderstorms is part of an equator-to-subtropics circulation called the Hadley Circulation, which is part of the global energy cycle and affects atmospheric circulation throughout the globe.

Before an El Niño event, something happens to disrupt the normal distribution of sea surface temperature, winds, and precipitation. Both the warm water and the heavy precipitation move eastward, with warm water anomalies appearing along the equator as far as the South American coast. (In fact, the name El Niño, for “the [Christ] child” was given centuries ago by fishermen who noticed the periodic disruption of the productive fisheries by warm water near Christmas). A typical El Niño event begins during northern hemisphere summer or fall, peaks around late December with warm water anomalies of 1°C or more along the equator, and then fades during northern hemisphere spring, often followed by an accentuated return to normal conditions, called La Niña as an antonym of El Niño. On average, El Niño events occur once per four years, but they have occurred in successive years.

During the El Niño phase of ENSO, the wintertime jet stream tends to split, with warmer air flowing into the Northwest and Alaska, and a southern branch of the jet stream directing unusually frequent and heavy storms toward southern California. During El Niño winter and

spring, Oregon's climate is slightly more likely than usual to be warm and dry. The effect is more pronounced farther north into British Columbia.

One manifestation of ENSO in the North Pacific has been termed the Pacific Decadal Oscillation (PDO), so named because in 20th century records, variations in north Pacific sea surface temperature (SST) patterns appear to have phases lasting 20 - 30 years (Mantua et al., 1997). However, paleo reconstructions of the PDO using tree rings (e.g., Gedalof et al., 2002) indicate a similar behavior of the PDO from the mid-18th to early 19th century, then very different behavior in the succeeding 100 years. Also, after 1998 the PDO index has shown no evidence of decadal persistence. In addition, Newman et al., (2003) show that the best statistical model of the PDO treats it not as a distinct pattern of variation independent of ENSO, but simply a slow North Pacific response to ENSO forcing. Furthermore, linear trends over periods of a few decades can be affected by the phases of ENSO and PDO.

### **1.2.3 Future climate change in the Pacific Northwest**

#### *1.2.3.1 Model evaluations*

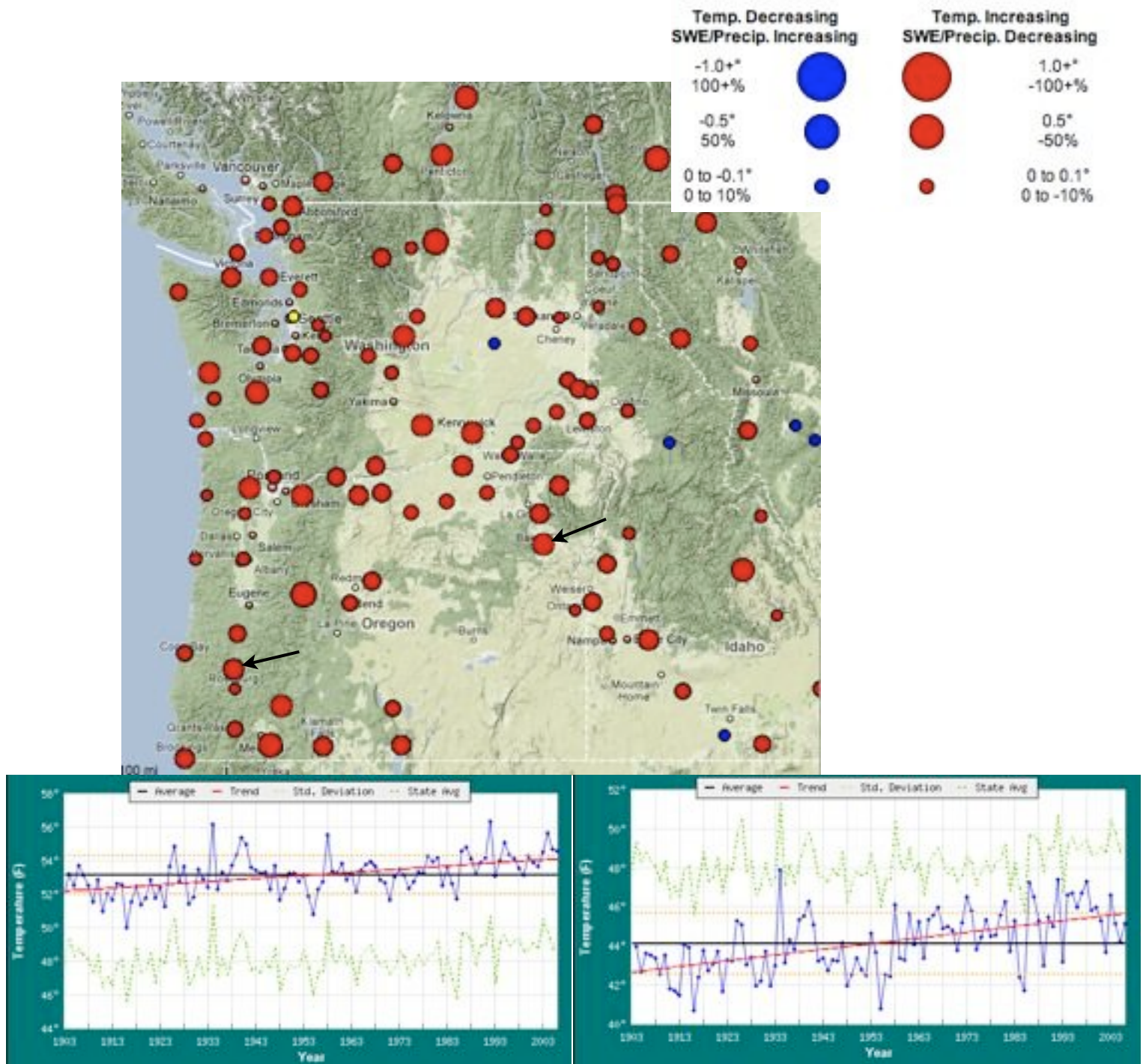
The global climate models used in the IPCC (2007) assessment report were examined for the Pacific Northwest<sup>2</sup> by Mote and Salathé (2010). They compare observed temperature and precipitation with the simulated regional temperature and precipitation in the 20th century, including the annual averages, the seasonal cycle, and the trends. They also compare the temperature, precipitation, and sea level pressure patterns over a much larger region including most of the North Pacific Ocean and North America. See Randall et al. (2007) for a list of the climate model references, attributes, and abbreviations.

The mean temperature produced by the set of all models is about 1.8°C (3.2°F) cooler than observed, while the seasonal cycle of temperature was close to what was observed (within 1°C, 1.8°F in one observational dataset). All models produce the observed contrast between wet winters and dry summers. However a few produce summers only slightly drier than the winters, and for every model, the annual precipitation is considerably higher than observed. Mote and Salathé do not diagnose a reason for this wet bias of the models. Comparing each model's annual cycle with observations and calculating root-mean-square difference to rank the models, the "best" five models for temperature are, with one exception (GISS\_ER), different from the best five models for precipitation.

Mote and Salathé also evaluate the models' linear trend in temperature over the 20th century (see Figure 1.9). On regional scales, temperature trends are influenced more by atmospheric circulation than by greenhouse gas forcing; still, eight of the models simulate a warming in the Northwest for the period 1900–2000 within 0.2°C (0.4°F) of the observed warming of +0.8°C (1.4°F) during that period. In both observations and models, precipitation fluctuates much more than temperature; indeed, there is little evidence that observed precipitation (globally or at these latitudes) responded to greenhouse gas forcing in the 20th century (Zhang et al., 2007).

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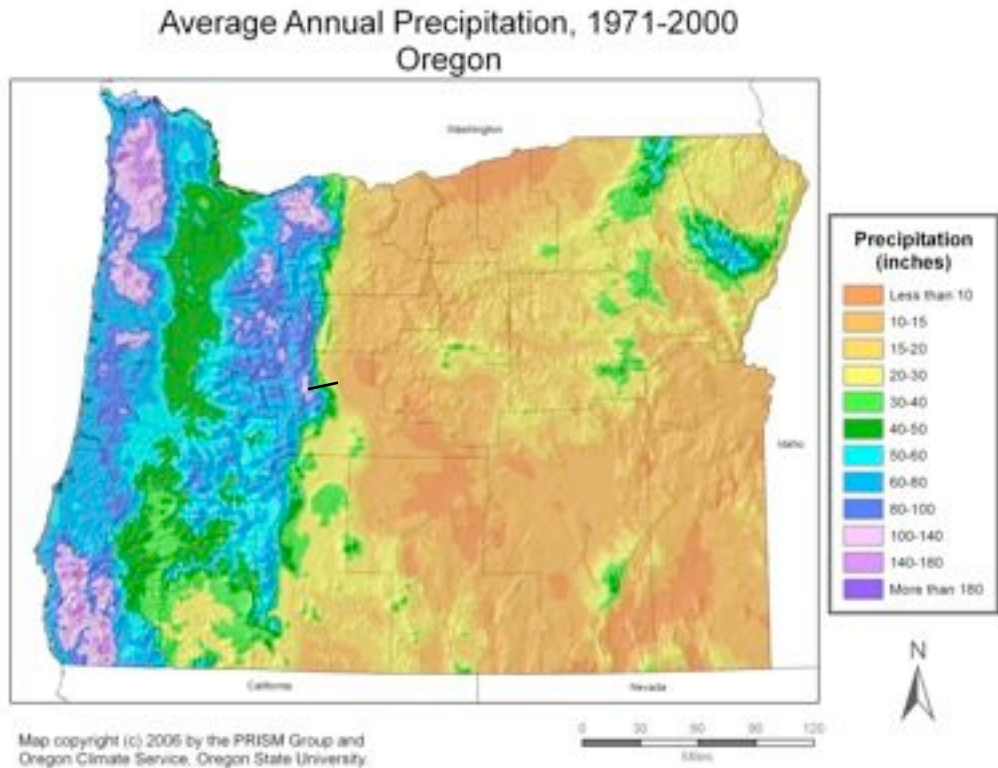
<sup>2</sup> The region of analysis is a rectangle bounded by latitudes from 41.5° to 49.5° North, and longitudes from 124° to 111° West.



**Figure 1.7 (top)** Linear trends in annual mean temperature at US Historical Climate Network stations in the Northwest. Red means warming, blue cooling, yellow no trend; size proportional to warming trend (°F/decade). **(bottom)** Annual mean temperatures at two stations in Oregon indicated by arrows on the map: Drain (left) and Baker City (right) overlaid with the linear trends (red), the mean (solid black) and standard deviation (dotted orange), and statewide mean (dotted green). Figures created using a utility at the Office of Washington State Climatologist, climate.washington.edu.

### 1.2.3.2 Projected changes in annual temperature and precipitation

Mote and Salathé (2010) combine the model results for future periods using “reliability averaging of ensembles,” a technique which gives more weight to models that perform better and that yield results closer to the average of all the models. We refer to these results as



**Figure 1.8** Map of annually averaged precipitation formed using geospatial mapping techniques and monthly mean station observations (Daly et al. 1994, 2007). Black line near Bend highlights one region of very sharp gradient in precipitation.

weighted multi-model means.

Figure 1.10 shows the projected model-average temperature and precipitation for the Pacific Northwest, for all simulations in the B1 and A1B scenarios, from 1900 to 2100. By the 2080s, the models suggest a change in mean temperature of 3.4°C (6.1°F) for the A1B, and 2.5°C (4.5°F) for the B1. Considering the full range produced by all the models across the two scenarios, the range of warming is 1.5–5.8°C (2.7–10.4°F); other IPCC emission scenarios would produce more warming by 2100, but B1 produces the least warming.

The observed trend in regional mean temperature is statistically significant for the 20th century, because the change exceeds what would be expected from a time series with no trend but having the same amount of year-to-year natural variability (Mote, 2003). Likewise, the projected future trends are substantially greater than the trend observed in the 20th century, even for the scenarios having the very lowest temperature changes.

For changes in precipitation, model results do not show very clear trends (bottom panel of Figure 1.10). The vast majority of climate models project increases in average annual precipitation in the northern third of North America, but decreases in the southern third (Christensen et al., 2007); the Pacific Northwest lies in the ambiguous area in between, where some models project increases and others project decreases in precipitation. The simulated multi-model average annual precipitation for the Pacific Northwest is practically unchanged through the 20th and 21st century, although individual models project changes of as much as 10% below or 20% above late 20th century mean precipitation by the 2080s.

### *1.2.3.3 Projected changes in seasonal temperatures and precipitation*

Seasonal changes of climate often have greater impacts than changes in annual average climate. Figure 1.11 depicts the projected change in temperature and precipitation for each season, for three future decades, the 2020s, 2040s, and 2080s in comparison to the 1980s. For both scenarios B1 and A1B, regional warming is projected to be largest in summer. In most seasons B1 has the lowest projected change and A1B the highest, but this will not always be true in the 2020s when the climate forcing of the two scenarios becomes very similar. The most consistent changes in precipitation appear in the summertime, with a large majority of models (68–90% of them) projecting decreases; the multi-model average value reaching –14% by the 2080s. Some models forecast reductions of as much as 20 to 40% in summer precipitation, though these large percentages really only translate to 3 to 6 cm (1.2 - 2.4”) of water depth over the summer season. This is 3 to 6% of the all-model average value for the annual average in the 20th century. While this is a small amount in hydrological terms, summer precipitation and its associated cloudiness nonetheless strongly impacts evaporation, and hence urban water use (Palmer and Hahn, 2002) and forest fires (McKenzie et al., 2004) in the Pacific Northwest.

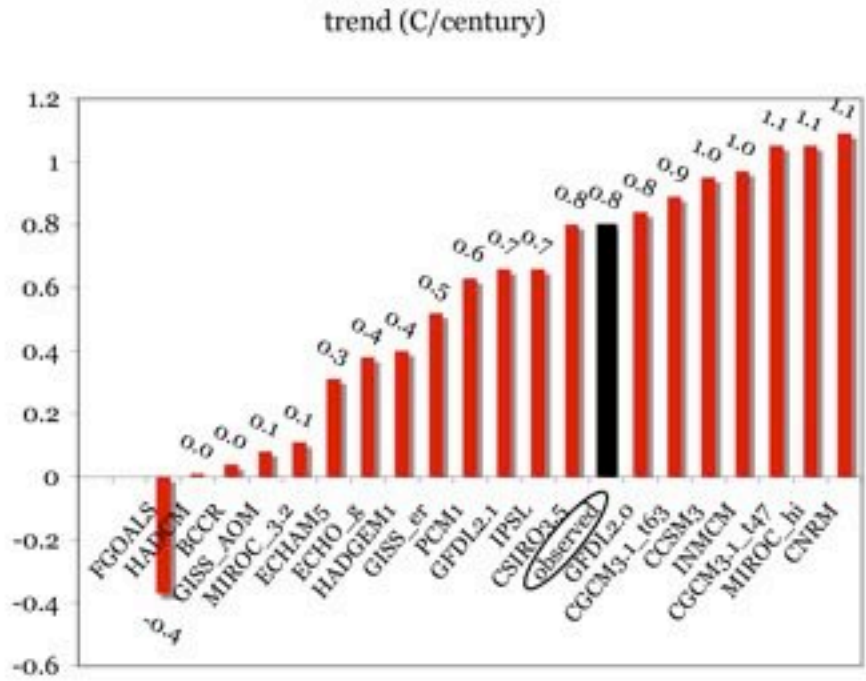
In contrast to summer, a majority of models project increases in precipitation in the winter. The multi-model-mean annual mean precipitation increases +8% (about 3 cm, 1.2” of water) by the 2080s in the A1B scenario, which is still small in comparison to the year-to-year variability. And although some of the models suggest modest reductions in fall or winter precipitation, others suggest very large increases (up to 42%). Changes of this magnitude would substantially alter regional hydrology and ecosystems.

For other important aspects of climate, less research has been done about past and likely future changes. Rosenberg et al. (2010) examine the changes in extreme precipitation in daily outputs of two global models and one regional model; for Portland, small (2 - 10%) and generally not significant increases are found for most definitions of extreme return period and duration.

## **1.3. Past and Future Changes in Properties of the Coastal Ocean**

Oregon’s marine environment (Figure 1.12) is influenced by the open North Pacific Ocean, and by the atmosphere especially over the continental shelf and slope. Oregon’s coastal ocean has strong spatial variations, vertically and in offshore and alongshore directions. Long-term observations of currents and water properties are scarce, but after fifty years of oceanographic research at Oregon State University, it is clear that Oregon’s coastal ocean is highly variable over time, responding to winds and tides, to heating and cooling, and to rainfall and river discharge. The short-term, seasonal and interannual variability all tend to be greatest near shore, over the continental shelf and slope. In spite of this variable background, and the paucity of historical time series, there is growing evidence of substantial changes in Oregon’s marine environment, some of which can be linked to global climate change.

New monitoring programs already in place will provide more abundant time series, but these and other new programs will need to be continued for many years to monitor future change. High-quality long-term observations are required for testing and evaluating models that make predictions; forecasts unconstrained by observations have much less value. Oregon’s



**Figure 1.9** Trend in each model's annual mean temperature for the Pacific NorthWest over the 20th century, and the observed trend (Mote 2003 updated). The observed trend is close to the median trend of the models.

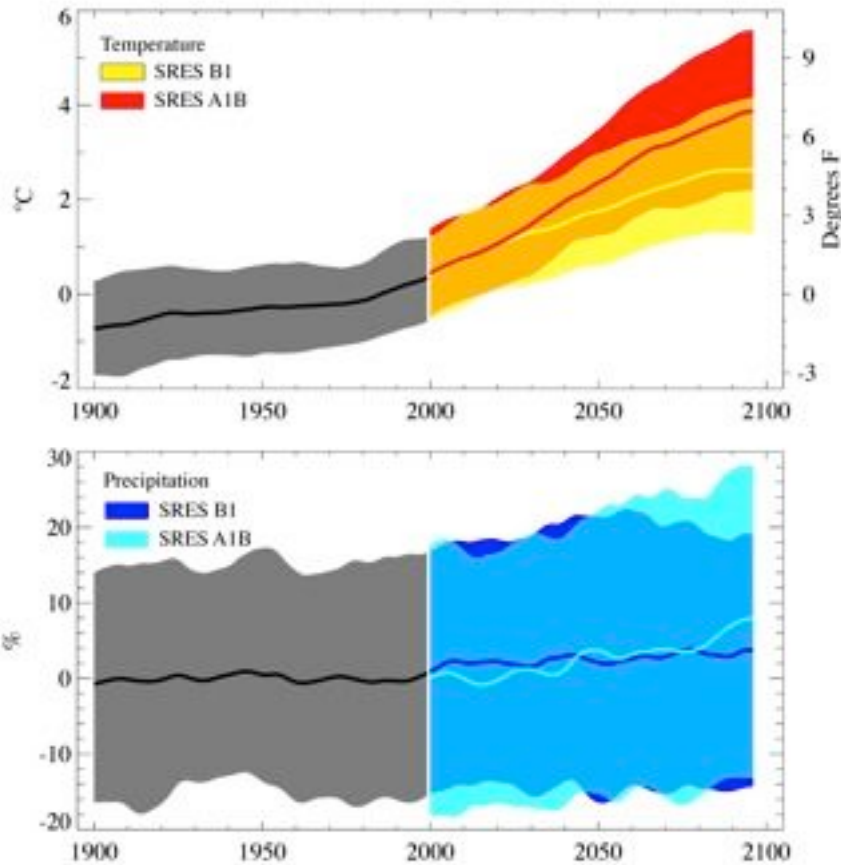
monitoring of coastal waters needs to be continued to provide baseline and to monitor future changes.

### 1.3.1 Observed (past) changes in Oregon's marine environment

In order to provide some context for understanding how the marine environment could change in the future, we describe the types of observations available and the characterization that they give of variability and change in Oregon's coastal waters over the past 10 - 50 years. We also describe the physical processes that contribute to the seasonal and interannual variability.

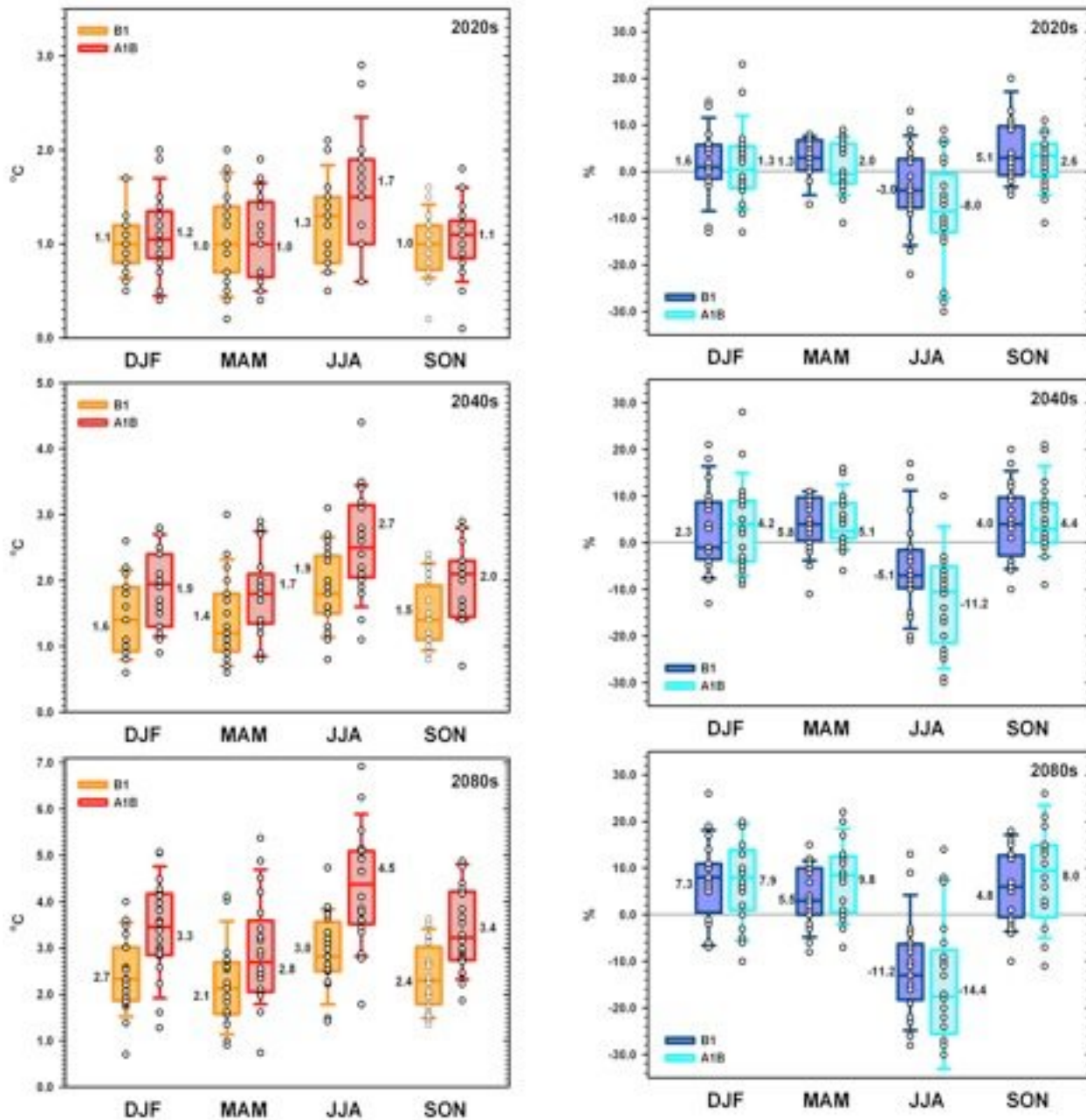
#### 1.3.1.1 Local Wind Forcing

Much of the variability over Oregon's continental shelf is very closely related to local winds, which exert drag on the ocean surface layer. Combined with Earth's rotation, this drag can push the surface layer either toward or away from shore, as well as along the coast in either direction; the amount of water transported (the "Ekman transport") is directly proportional to the wind stress. The sea surface stays nearly horizontal: when surface waters move offshore, they are replaced by water from deeper levels, in a process called upwelling; when surface waters move onshore, they are pushed downward ("downwelling"). The vertical velocity is too weak to be measured directly, but theory shows that the vertical transport of ocean water can be estimated from measurements of wind speed and direction. If the wind is uniform, upwelling or downwelling occurs in a narrow coastal strip whose width is 20 km (12 mi) or less. Deeper waters are colder, saltier and denser than surface waters; they are also richer in nutrients and poorer in dissolved oxygen.



**Figure 1.10** Smoothed traces in temperature (top) and precipitation (bottom) for the 20th and 21st century model simulations for the PNW, relative to the 1970 - 99 mean. The heavy smooth curve for each scenario is the weighted multi-model mean value, calculated for each year and then smoothed. The top and bottom bounds of the shaded area are the 5th and 95th percentiles of annual values (in a running 10-year window) from the ~20 simulations, smoothed in the same manner as the mean value. Mean warming rates for the 21st century differ substantially between the two SRES scenarios after 2020, whereas for precipitation the range is much wider than the trend and there is little difference between scenarios. From Mote and Salathé (2010).

When winds blow southward along the Oregon coast, as they generally do in summer, they cause warm, fresh (low-salinity), nutrient-depleted, but oxygen-rich surface waters to move offshore, and they bring cold, salty, dense, nutrient-rich, oxygen-poor waters up to the surface inshore. The high-gradient region between these very different offshore and inshore waters is called the “upwelling front.” After sustained summer upwelling, waters near the surface over the inner shelf have properties similar to those observed at depths of 200 – 250 m (660 - 820 ft) offshore; the resulting density gradients cause a southward current whose speed is greatest at the surface and decreases with depth. When the local wind blows northward along the coast, as it generally does in winter, surface waters move toward the coast, and warm, fresh, nutrient-poor, offshore waters flood the nearshore region and move downward over the inner shelf. After sustained winter downwelling, the coastal current is northward; its speed tends to decrease with depth. In both seasons, alongshore currents are much stronger than the onshore/ offshore currents of the upwelling/ downwelling circulation.



**Figure 1.11** Range (lowest to highest) of projected changes in temperature (left) and precipitation (right) for each season (DJF=winter, etc.), relative to the 1970 - 99 mean. In each pair of box- and-whiskers, the left one is for SRES scenario B1 and the right is A1B; circles are individual model values. Box-and-whiskers plots indicate 10th and 90th percentiles (whiskers), 25th and 75th percentiles (box ends), and median (solid middle bar) for each season and scenario. Printed values are the weighted multi-model mean of all GCMs for the season and scenario. From Mote and Salathé [2010].

The transition from the downwelling regime to the upwelling regime typically occurs in early spring. Regardless of season, current fluctuations with periods of days-to-weeks are highly correlated with alongshore wind stress, as is the position of the summer upwelling front. Some interannual variability in shelf currents and temperature can also be explained by local

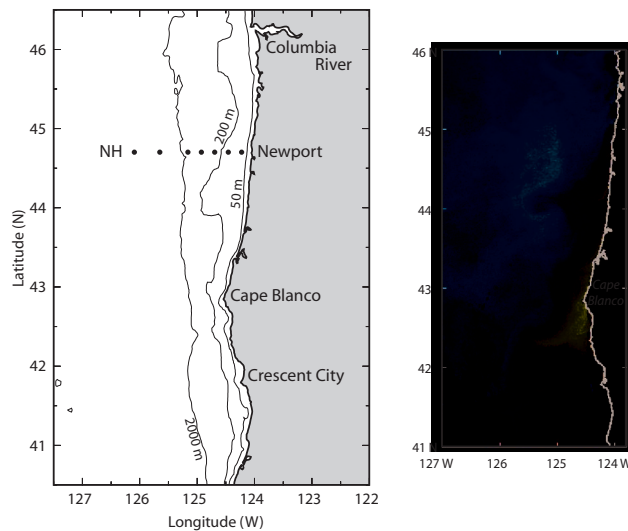


longshore wind stress: for example, unusually strong northward winds in the El Niño winters of 1983 and 1998 enhanced the northward coastal current (Kosro, 2002); unusually late arrival of northerly winds in the spring of 2005 delayed the onset of upwelling by more than a month (Pierce et al., 2006).

Because there are no multi-decade observations of currents or water temperatures from the Oregon shelf, we use three estimates of the alongshore wind stress as valuable indicators of the intensity of upwelling. First, we use winds measured at Buoy 46050, about 37 km (20 nautical miles) west of Newport; these hourly measurements began in 1985, and data are available from the National Oceanic and Atmospheric Administration (NOAA). This time series is not yet long enough to determine a long-term trend, but data indicate that the average intensity of upwelling in each year from 2005 to 2008 was stronger than the 20-year average of 1985 – 2005.

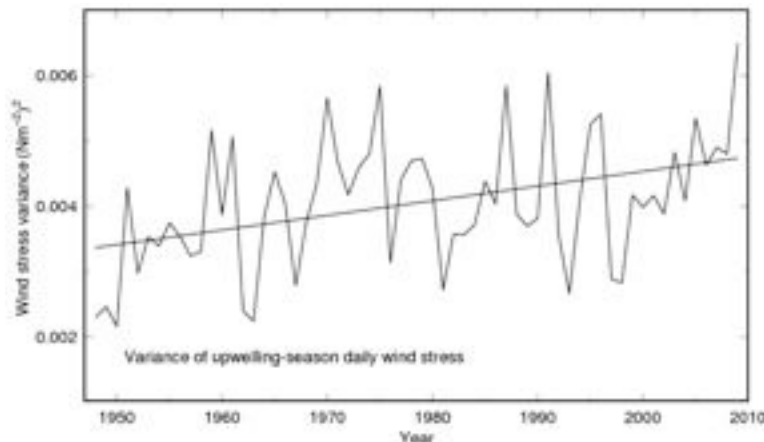
Second, we use wind stress data from the National Center for Environmental Prediction (NCEP, Kalnay et al., 1996), available since 1948 at a spatial resolution of 2 degrees. Though they do not actually resolve spatial scales smaller than 1000 km (625 mi; Milliff et al. 2004), their time series are well correlated with winds measured at buoys in the North East Pacific (Ladd and Bond, 2002). Daily wind stress values were used to determine the dates of onset and cessation of seasonal upwelling, and to calculate the average and variance of the alongshore wind stress during each upwelling season. The seasonal average has no significant trend, but the variance has increased significantly over the last 50 years (Figure 1.13), by about 35% at 45°N and by about 50% at 41°N.

Third, monthly values of the Coastal Upwelling Index at 45°N, 125°W and at 42°N, 125°W provided by the Pacific Fisheries Environmental Laboratory (<http://www.pfeg.noaa.gov>).

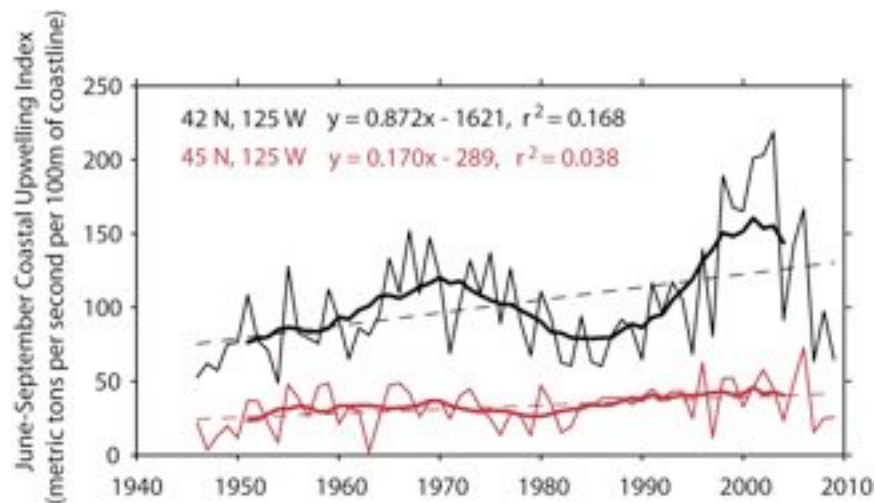


**Figure 1.12.** Maps of the coastal ocean off Oregon: (a) left, stations of the Newport Hydrographic Line (dots), and a few bottom contours: 2000 m (6600) ft at the foot of the continental margin, 200 m (660 ft) at the shelf edge, and 50 m (160 ft) over the inner shelf; (b) right, satellite image of sea surface temperature for 5 July 1999 (from Huyer et al., 2005; white areas represent clouds or fog, red indicates warmer waters and blue cooler).

These values are derived from the Fleet Numerical Meteorology and Oceanography Center monthly average pressure fields using a three-degree mesh. Averaging the June, July, August and September (JJAS) values together yields an annual estimate of the intensity of upwelling. The average JJAS index at this location increased over the past 50 years, particularly off southern Oregon (Figure 1.14), though much of the trend is due to a recent decade of strong winds (1995 - 2005). The slow variations in the 11-year running average do not seem to be correlated with the Pacific Decadal Oscillation (Mantua et al., 1997; but see Section 2.2).



**Figure 1.13.** Annual values of wind-stress variance during the upwelling season (calculated from daily NCEP/NCAR reanalysis wind-stress data see text for details).



**Figure 1.14.** Time series of the June-September average monthly Coastal Upwelling Index at 45°N, 125°W and 42°N, 125°W. Data are provided by Pacific Fisheries Environmental Laboratory. The heavy curves show values of a centered 11-year running average. At these locations, index values of 50, 100 and 200 correspond to wind stress magnitudes of about 0.05, 0.10 and 0.20 N m<sup>-2</sup>, respectively.

### 1.3.1.2 Basin-scale wind forcing

As well as inshore upwelling or downwelling along the coastline, there can also be upwelling or downwelling offshore where the wind field has sufficient “curl” (curvature or shear), as it does off southern Oregon (e.g., Chelton et al., 2007). This curl results both from the topographic interaction of the wind blowing past Cape Blanco (Perlin et al., 2004) and from air-sea interactions around the upwelling front: under the same overlying wind speed and direction, the wind stress at the sea surface is higher over warm water than over cold water. As a result of this positive wind stress curl, the cold summer upwelling domain off southern Oregon extends at least twice as far offshore as it does off Newport (Figure 1.12; Huyer et al., 2005; Springer et al., 2009).

Large-scale atmospheric variations over the North Pacific Ocean also affect Oregon’s coastal ocean by changing the strength of large-scale upstream currents. For example, the North Pacific Current was stronger than normal in 2002 (Strub and James, 2003) and it brought unusually cold, nutrient-rich water to Oregon (Wheeler et al., 2003). The strength of these large-scale currents can be estimated from gradients of sea surface height measured by satellite altimeters (Strub and James, 2003). The altimeter record is not yet long enough to provide reliable estimates of a long-term trend in the large-scale currents. Various indices of the large-scale atmospheric patterns such as the Pacific Decadal Oscillation (Mantua et al., 1997) have proven to be of limited value for monitoring large-scale currents.

Because fluctuations in current and sea level propagate along ocean margins, Oregon’s coastal ocean can be affected by changes in the remote winds over the western equatorial Pacific. For example, during both the 1982 - 83 and the 1997 - 98 El Niño, higher sea-surface temperatures and higher sea levels were observed off Oregon even before local wind patterns became anomalous (Huyer and Smith, 1985; Huyer et al., 2002). These current and temperature anomalies propagate very quickly along the west coast, and can arrive here within a month or so after signals are observed on the equator. Equatorial anomalies in the Pacific are monitored by an array of moorings; data are displayed in real time (<http://www.pmel.noaa.gov/tao/>).

### 1.3.1.3 Freshwater input

Surface salinity in Oregon’s coastal ocean is strongly affected by fresh-water discharge from the land, with two types of seasonal cycles: through rain-dominant coastal rivers and streams in winter (Austin and Barth, 2002), and through the snowmelt-dominant Columbia River in summer (Huyer et al., 2007). In winter, the downwelling circulation pushes the fresh water from coastal rivers toward shore, forming a narrow lens over the inner shelf, and enhancing the onshore pressure gradient and associated northward current; this northward current can reach speeds of  $1 \text{ m s}^{-1}$  (2.2 mph; Austin and Barth, 2002). In summer, the upwelling circulation pushes the diluted freshwater discharge from the Columbia River out to sea where it is carried southward by the coastal currents (Barnes et al., 1972; Rivas and Samelson, 2010). The dilute waters of the Columbia River plume are less dense than surrounding ocean waters, and the inshore boundary of the plume tends to coincide with the upwelling front, enhancing both the density gradient and the intensity of the southward coastal current.

The seasonal cycle of the Columbia River discharge has been modified significantly by major dams and deliberate management: peak discharge historically occurred in late spring, but now occurs in autumn (Sherwood et al., 1990). The annual average discharge of the Columbia River

shows large interannual variability and some interdecadal variability, but no significant long-term trend between 1928 and 2009. In contrast, the average May-through-July discharge has decreased by about 30% between 1928 and 2009 (Figure 1.15); these changes result from a combination of dam construction and reservoir management, and climate variability and change. Future climate-related reductions in summer flow in snowmelt-dominated rivers like the Columbia are likely (see Chapter 3). With less summer discharge, we would expect the Columbia River plume to be less intense and its inshore boundary adjacent to the upwelling front to be more diffuse.

#### *1.3.1.4 Temperature, salinity, and dissolved oxygen*

For more than a decade, 1961 - 1971, water temperature and salinity were measured at intervals of 1 - 3 months at a set of standard stations along a line extending west from Newport to a point 305 km (165 nm) offshore (Figure 1.12). Seasonal sampling of the stations within 190 km (100 nm) of shore resumed for about six years during 1997 - 2003, with limited additional sampling in 2004 and 2005 (Huyer et al., 2007). Both periods also include measurements of dissolved oxygen, though these are less plentiful. Data from the station farthest offshore that was sampled in both periods show temperature decreasing with depth and salinity increasing with depth. The surface layer of the sampled ocean water is thin, warm, quite fresh, and saturated with oxygen. Waters with salinities less than 33.8 represent surface waters of the Subarctic Pacific brought into Oregon's coastal waters by the prevailing California Current; those with salinities less than 32.5 have been locally diluted, usually by discharge from the Columbia River (Barnes et al., 1972). Waters at depths of 300 - 800 m (980 - 2600 ft) with salinities between 33.9 and 34.2 are influenced both by "North Pacific Intermediate Water" which originates in the northwest Pacific (Talley, 1993) and by "equatorial water" which is brought into Oregon's coastal waters by the California Undercurrent which flows northward along the continental slope (Pierce et al., 2000).

Differences between the averages over the two sampling periods (1961 - 1971 and 1997 - 2003, an interval of about 35 years) show some significant long-term changes (Figure 1.16). The surface layer has warmed at a rate of about 0.3°C (0.5°F) per decade; the layer between 200 and 500 m (660 - 1640 ft) has warmed at a rate of about 0.04°C (0.07°F) per decade. Salinity has decreased in the layer between 500 and 800 m (1600 - 2600 ft) at a rate of 0.006±0.004 per decade; this may reflect the large-scale freshening of North Pacific Intermediate Water (Bindoff et al., 2007). Density has decreased in the surface layer and in the layer between 400 and 600 m at -0.007±0.006 kg m<sup>-3</sup> per decade. Integrated over the upper 500 m of the ocean, the observed change in density corresponds to a sea level rise about 3 cm (1.2") in about 35 years.

The concentration of dissolved oxygen has decreased significantly at all depths between 200 and 1000 m (660 - 3300 ft) since 1961-1971.

For stations over the continental shelf and slope, Huyer et al., (2007) calculate long-term temperature and salinity differences separately for winter and summer. They find winter temperatures to be higher during 1998 - 2003 than 1961 - 71 but because of high variability between individual winters, the difference is not statistically significant. Similarly they find no significant difference in the average winter salinities. They did, however, find significant warming and freshening in the summer-season averages (Figure 1.17). The largest temperature change (>2°C, 3.2°F) occurs in the thermocline (the layer of steep temperature gradient) which lies 10 - 20 m (33 - 66 ft) deeper in 1997-2005 than in 1961 - 1971. The layer with salinities

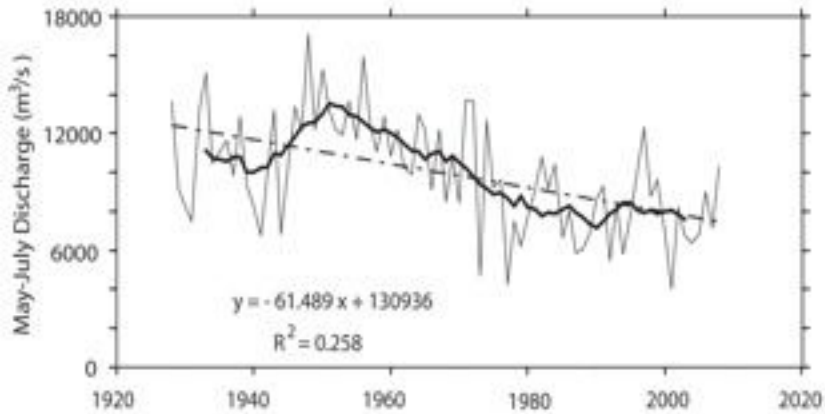
between 32.5 and 33.8 lies about 20 m (66 ft) deeper now than in 1961 - 1971. The large confidence intervals of the salinity difference in the top 20 m (66 ft) reflect very high variability in the position of the Columbia River plume as a result of day-to-day and week-to-week fluctuations in the wind stress. At NH-35, over the continental slope, 65 km (35 nm) west of Newport, the dissolved oxygen concentration at 200 m (660 ft) has been decreasing at a rate of  $0.63 \pm 0.27 \mu\text{mol/kg/yr}$  (Figure 1.18). Inshore, the NH-line shelf has summer oxygen decreases of 1.8-2.0  $\mu\text{mol/kg/yr}$  in near-bottom waters with densities of 1025.8 - 1026.3  $\text{kg/m}^3$ . The decrease in oxygen concentration is larger inshore than at the slope station; this could be related to the increased intensity and variability of wind-driven upwelling (Figure 1.14) which could have caused an increase in primary production and respiration over the shelf.

In recent years, hypoxic waters with very low dissolved oxygen concentrations (less than 1.4 ml/l) have been observed near the bottom on the mid to inner shelf during the upwelling season (Chan et al., 2008; Barth et al., 2010; Adams et al., 2010). Hypoxia seems to be especially prevalent in the region of Stonewall and Heceta Banks. Minimum values are often found over the mid to inner shelf (50 - 100 m water depth), reflecting the effect of local biological production and respiration. The size of the hypoxic zone increases over the upwelling season, reaching its maximum extent in mid to late summer.

The NH-line is now being sampled by means of autonomous vehicles (or “gliders”; Erofeev et al., 2010). Sampling extends 90 km (56 mi) offshore from the point at which the water is 30m (100 ft) deep on the inner shelf to 125.1°W over the continental slope, and vertically from the sea surface to a maximum depth of about 200 m (660 ft). They measure dissolved oxygen as well as temperature and salinity. Routine operations began in 2006, and over 110,000 vertical profiles along 25,000 km of track have now been collected (Erofeev et al., 2010) and the challenge of grafting them to the historical NH-line data sets is being solved (Flink et al., 2010). Glider sampling will continue for the foreseeable future, and we expect that it will show continued warming and further depletion of dissolved oxygen during the summer upwelling season.

#### *1.3.1.5 Nutrients and Acidification*

Nutrient concentrations in the upper ocean off Oregon tend to mirror concentrations of dissolved oxygen: high in deep water and very low in the surface water except at times and locations of active or recent upwelling. Both nutrients and oxygen are strongly affected by local primary production: growing phytoplankton absorb nitrate, silicate and phosphate from ambient waters while releasing dissolved oxygen, which may reach high levels of supersaturation during a plankton bloom. Respiration of organic matter absorbs oxygen from ambient waters, and releases nutrients and carbon dioxide. Surface concentrations of nitrate during the summer upwelling season vary from non-detectable to a maximum of about 35  $\mu\text{M}$ , depending on the fluctuations between upwelling and relaxation events; nitrate is usually depleted before phosphate and silicate (Wheeler et al., 2003). The highest concentrations of inshore surface nitrate during the upwelling season are about the same as those observed at depths of 250 - 300m offshore in winter. The width of the coastal strip with elevated nitrate levels is much greater off southern Oregon than it is off central Oregon because of the stronger upwelling there (Huyer et al., 2005). Nutrient concentrations vary interannually, with lower concentrations during El Niño (Corwith and Wheeler, 2002) and higher concentrations during the Subarctic invasion of 2002 (Wheeler et al., 2003). We do not have historical nutrient data of sufficient quality and quantity to estimate long-term trends in nutrient concentrations.



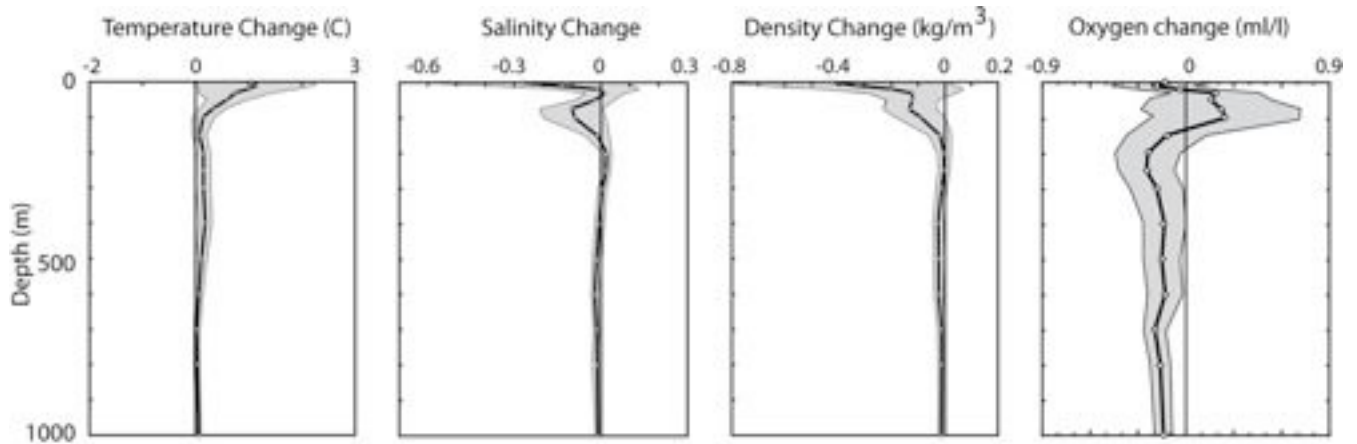
**Figure 1.15.** Time series of fresh-water discharge from the Columbia River for the late spring and summer months of May through July. The time series of monthly values was collated from USGS sources (as described by Smith et al., 2001) and updated with recent values from USGS Station 14246900 (<http://waterdata.usgs.gov/usa/nwis/>). The heavy curve shows a centered 11-year running average.

The acidity of seawater depends on the concentration of dissolved carbon dioxide, and it is therefore especially vulnerable to ocean absorption of elevated carbon dioxide levels in the atmosphere. Dissolved carbon dioxide also arises from respiration: thus ocean acidity tends to be highest when and where oxygen concentrations are lowest. Ocean acidity affects the solubility and availability of carbonate ions necessary for the formation of calcium carbonate shells and skeletons of many marine organisms: organisms are potentially vulnerable wherever (and whenever) the seawater saturation of aragonite or calcite is less than 100% (both consist of calcium carbonate; aragonite is more soluble than calcite). Most of the surface ocean is presently supersaturated for aragonite, while the deep ocean is undersaturated; the boundary between them is called the 'saturation horizon' (Bindoff et al., 2007). The saturation horizon is especially shallow in the Northeast Pacific Ocean, where it lies less than 300 m (980 ft) below the sea surface (Feely et al., 2008); scientists estimate that the saturation horizon has moved 50 to 100 m (160 - 330 ft) toward the surface since 1750 (Bindoff et al., 2007). A very recent (May-June 2007) survey of the western continental margin of North America shows that the aragonite saturation horizon lies at a depth of less than 300 m (980 ft) at offshore locations, but less than 100 m (330 ft) over the continental shelf, and even to the sea surface during strong upwelling (Feely 2008; Juranek et al., 2009). Thus Oregon shelf waters are already potentially corrosive to species that form aragonite shells. As the ocean continues to absorb carbon dioxide from the atmosphere, the saturation horizon is certain to rise, and corrosive effects will increase.

*Units of measure: dissolved substances in ocean water*  
**Salinity** or saltiness: unitless numbers on the "practical salinity scale" which is almost equal to parts per thousand  
**Dissolved gases:** milliliters per liter (ml/l) is equivalent to 1.4 parts per thousand by mass  
**Nitrate** micromolar ( $\mu\text{M}$ )= 14 ppm N

### 1.3.1.6 Summary

Observations of Oregon's coastal waters, mostly by OSU oceanographers, over the past 50 years show an environment that varies tremendously from season to season and from year to year and is influenced by both local and remote processes. Many substantial changes have been observed during this period, including a substantial warming and freshening of the surface



**Figure 1.16.** Differences between average temperature, salinity (parts per thousand), density and dissolved oxygen profiles at NH-85 (85 nm west of Newport) for two periods: 1997-2005 (~38 samples) minus 1961 - 1971 (~75 samples), with 95% confidence limits.

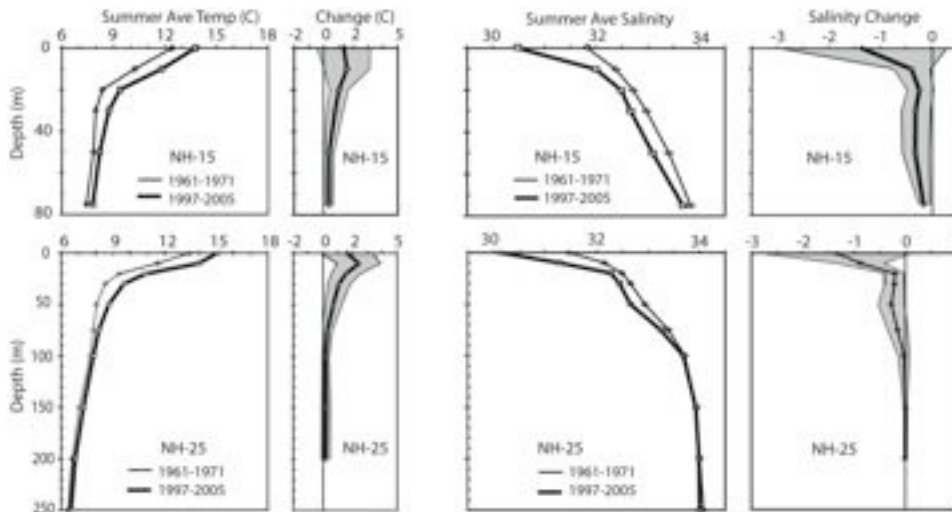
layer year-round and a reduction in dissolved oxygen. Recent hypoxic events represent a scientific surprise and their cause, and possible links to larger climatic changes driven by human activity, still unknown. Interpretation of the causes of these changes, especially vis-à-vis the human contribution, is hampered by the inadequate quantification of year-to-year and especially decade-to-decade variability which could easily be mistaken for a linear trend related to global climate change.

### 1.3.2 Future changes in Oregon’s marine environment

We have made modest progress in estimating recent trends in Oregon’s marine environment, but we have only a very limited ability to predict future changes. Besides assuming persistence of the trends already observed, our principal tool for predicting how future climate will affect the marine environment is the set of global models of the coupled ocean-atmosphere system discussed in Section 1.3 above.

In these models, simulated future changes in the mean surface wind are very small over the Pacific Northwest, especially the alongshore summertime winds that drive coastal upwelling (Mote and Mantua, 2002; Mote and Salathé, 2010). Figure 1.19a shows no significant difference between model estimates of alongshore wind stress for the 1960 - 1999 period and three SRES scenarios for the 2030 - 2059 period. The simulated wind stress is somewhat too weak ( $-0.03 \text{ N m}^{-2}$  vs  $-0.05 \text{ N m}^{-2}$  at  $45^\circ\text{N}$  and  $-0.1 \text{ N m}^{-2}$  at  $42^\circ\text{N}$ ; Risien and Chelton, 2008), but the global models provide the only quantitative prediction available.

Each of the 20 coupled global models discussed above has an ocean model with data points spaced more closely than the atmospheric model, and each model simulates sea surface temperature (SST). However, the modeled SST of Oregon’s coastal waters is quite different from the observed SST, especially in the seasonal cycle, because the ocean model is still too coarse to represent the complex oceanic processes over the continental margin. Figure 1.19b shows the simulated mean annual cycle for the 1970 - 1999 and 2030 - 2059 periods for coastal grid points between  $46^\circ\text{N}$  and  $49^\circ\text{N}$  latitude. The modeled increase in SST is about  $+1.2^\circ\text{C}$  ( $2.2^\circ\text{F}$ ), somewhat less than for the land areas ( $+2.0^\circ\text{C}$ ,  $3.6^\circ\text{F}$ ), but a significant change compared to the typical interannual variability of the coastal ocean. Note that the simulated seasonal cycle



**Figure 1.17** Summer-average temperature and salinity profiles at two stations on the NH-line calculated separately for two periods: 1961 - 1971 and 1997 - 2005, and the difference between them (with 95% confidence limits). NH-15 and NH-25 are 15 and 25 nautical miles west of Newport.

for 1970-1999 does not adequately represent the observed temperature of waters over the inner continental shelf, which are likely to be as cool as 8 - 12°C (46 - 54°F) in summer (see Figure 1.12); it more adequately represents surface waters about 100 km offshore. The forecast increase of about 1.2°C is also likely to apply to offshore waters. Note that this modeled increase is less than the summertime increase observed in recent decades (Figure 1.17).

### 1.3.3 Mean Sea Level

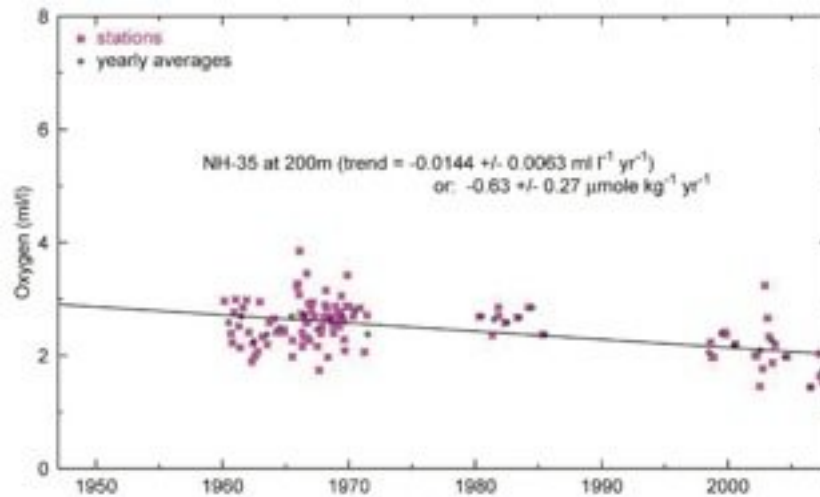
Globally, sea surface elevation rises when land ice melts, increasing the amount of water in the sea, and also when the ocean temperatures rise (due to thermal expansion). Gradients in sea surface elevation are associated with ocean currents – this is why satellite altimeters can be used to study the ocean circulation. Along the west coast of each continent, including North America, summertime winds blowing from higher latitudes pull water offshore and water must rise up from the depths to replace it. This coastal upwelling not only affects the properties of the surface water as explained in section 1.3.2, it also affects the height of the coastal ocean waters. There is approximately 0.5m (19”) difference in mean sea level between winter (higher) and summer (lower), owing to the wind-driven ocean circulation.

These variations are smaller than the tides and are usually noticeable only at times of high or low tide, and they have little effect on the marine environment except in the intertidal zone. The surface elevation measured by coastal tide gages is relative to the land, which itself may be moving slowly upward (e.g., from glacial rebound) or downward (from tectonic subduction). Global sea level rise, and impacts to the Oregon Coast, are explained in Chapter 6.

## 1.4. Outlook and knowledge gaps

The climatic and marine trends described above are based on available observations. In many cases, the observing networks or sampling frequency have suffered declines in recent decades,





**Figure 1.18** Dissolved oxygen concentration in ml/l at 200 m depth at NH-35 (35 nm west of Newport, Oregon) plotted as a function of time.

and scientists' ability to monitor our changing environment and place those changes in a longer-term context is constrained by these declines. While clever statistical analysis and data rescue are expanding both the availability and applicability of past observations (e.g., by digitizing daily records at weather stations previously available only in monthly means), observations and monitoring for the future will require vigorous and sustained effort. The Climate Reference Network is a good start: a nationwide network of 120 high-quality climate stations with multiply redundant instruments and a large buffer of land cover unlikely to change in future decades. Preserving legacy stations and marine sampling capabilities will be important for placing new observations in context with historical observations.

Labor-intensive oceanic observations initiated in the 1960s have recently been augmented by unmanned gliders, long-term moorings, and coastal radar arrays to provide more frequent and continuous sampling of critical properties of Oregon's coastal ocean. These observations will help understand both the natural and man-made variations of the temperature, salinity, dissolved oxygen, nutrients and currents, all of which contribute to the ecological and economic productivity of Oregon's coastal waters.

As this Assessment is being written in 2010, results from a new generation of climate models will become available from modeling groups around the world to support the assessment activities of the IPCC Fifth Assessment report, which scheduled for release in 2013. Enhanced regional modeling capability through a citizen science effort called regional climateprediction.net, hosted by OCCRI, will also be available in 2011. These thousands of simulations of regional climate at 25 km (16 mi) spatial resolution will provide an unprecedented combination of statistical and spatial detail for the western US.

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## 2. Climate change in Oregon: defining the problem and its causes

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### Summary and Knowledge Gaps

Human activities can affect Earth's climate and particularly its temperature by two fundamental processes: first by changing atmospheric composition which causes a greater trapping of the Earth's heat, and second by changing the amount of sunlight reflected or scattered by the atmosphere or the Earth's surface. The first increases the natural greenhouse effect, caused mostly by water vapor and carbon dioxide along with a few non-CO<sub>2</sub> greenhouse gases, and leads to global warming. The second causes the albedo to change which can either increase or decrease Earth's temperature. Most of what is driving global warming comes from the direct emissions of carbon dioxide, methane, nitrous oxide and other source gases released by human activities related to the production of energy and food. The climatic effect of such emissions is increased by water vapor feedback, which means as global warming occurs due to the increase of the greenhouse gases mentioned above, the amount of water that is held in the atmosphere increases, causing a further increase of temperature. There are many other feedbacks that are less well understood. Additionally, various gases emitted by human activities produce ozone in the lower atmosphere, which also adds to global warming.

Changes of albedo due to human activities can either exacerbate or ameliorate net global warming depending on a complex set of conditions that drives such changes. The albedo effect is thought to be small at present, but its future trend is not well understood. Earth's albedo is determined by a large number of disparate elements in the environment - dominated by clouds but also including aerosols and surface elements such as forests, ice caps, and oceans. Human activities that release gases such as sulfur dioxide can increase the albedo through the formation of sulfate aerosols in the atmosphere producing a cooling effect, while the direct release of black carbon aerosol (soot) can increase global warming under the right circumstances, or melt glacial and polar ice further decreasing the albedo.

The sources of Oregon's greenhouse gas emissions can be broadly listed as energy, agriculture, industrial processes, and waste management (Figure 2.1). Energy, particularly electricity consumption and transportation, is the largest source of greenhouse gas emissions in the state. Emissions associated with the consumption of electricity have been between 20 - 24 MMTCO<sub>2</sub>e (million metric tons of CO<sub>2</sub> equivalent) per year in the last decade, representing about 33% of

Oregon's total emissions. The transportation sector represents about 37% of greenhouse gas

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emissions in Oregon, ranging from about 21 to 25 MMTCO<sub>2e</sub> over the last twenty years.

In light of Oregon's small population, metrics other than total emissions should be used to assess Oregon's contribution to climate change. The simplest of these is per capita emissions, which provides a method to compare the carbon footprint of Oregonians to national and international norms. Oregon's per capita emissions of 18 MTCO<sub>2e</sub> in 2005 was the eleventh lowest of all U.S. states, or about twenty percent lower than the national average (24 MTCO<sub>2e</sub>). However, compared to developed countries, Oregon's per capita emissions rank quite high. Compared to the 39 industrialized countries with reported inventories in 2005, Oregon emissions are fifth highest, and are nearly double the European Community average. Relative to the global average, Oregon's per capita emissions are almost three times higher. One contributing factor to Europe's low emissions seems to be high population densities; a correlation also observed in U.S. states.

Ultimately, global scale reduction of the climate warming will require a global scale agreement and implementation. A single state such as Oregon, by itself, will not be able to alter the course of global warming. However, once there is a concerted effort to implement a global policy, each state or similar municipality, will need to tailor their contribution to what causes emissions and global warming from their region.

## 2.1 The Causes of Climate Change

Human activities can affect Earth's climate, and particularly its temperature, by two fundamental processes: first by changing atmospheric composition, which causes an increased trapping of the Earth's heat, and second by changing how much sunlight is reflected or scattered by the atmosphere or the Earth's surface. The first increases the natural greenhouse effect, caused mostly by water vapor and carbon dioxide along with a few key non-CO<sub>2</sub> greenhouse gases, and leads to global warming. The second causes the albedo or the reflectivity of the earth to change, which depending on how it is affected, can either increase or decrease the surface temperature. Most of what is driving global warming and the resulting climatic changes comes from the direct emissions of carbon dioxide, methane, nitrous oxide and other source gases released by human activities mostly related to the production of energy and food. The climatic effect of such emissions is increased by water vapor feedback, which means that as the earth warms due to the increased levels of the greenhouse gases the amount of water vapor held in the atmosphere increases causing a further increase of temperature. There are many other atmospheric feedbacks that are less well understood. Additionally, various gases emitted by human activities produce ozone in the lower atmosphere, also adding to global warming.

Changes of albedo due to human activities can either exacerbate or ameliorate net global warming depending on a complex set of conditions that drive such changes. The albedo effect is thought to be small at present but its future trend is not known. The Earth's albedo is determined by a large number of disparate elements in the environment; dominated by clouds but also including aerosols and surface features such as forests, ice caps, and oceans. Human activities that release gases such as sulfur dioxide can add sulfate aerosol in the atmosphere that in turn increases the albedo causing a cooling effect, or the release of soot aerosol (black carbon) that can, under the right circumstances, increase global warming, or melt glacial and polar ice and further decrease the albedo. Land use changes such as re-forestation can reduce the albedo and may offset some of the gains of carbon sequestration.

In terms of environmental policy to reduce climatic change, the first target is reductions in the source gases. When concerns about global warming first developed, it seemed that controlling carbon dioxide might solve the problem. In time however, it became clear that such a policy, as difficult as it is was to implement, may not be enough. It was shown that although the non-CO<sub>2</sub> greenhouse gases are individually not as abundant as carbon dioxide, there are several of them and they are twenty to several thousand times more effective at causing global warming for each kilogram added to the atmosphere when compared with each added kilogram of carbon dioxide (the global warming potential is used as such an index). Therefore, reductions of these gases were included under a more comprehensive plan to control global warming in the Kyoto Protocol. Now, we know that there are yet other drivers of climate change that may require scrutiny such as aerosols and albedo altering mechanisms affected by human activities. How all these elements can be integrated into a policy that is both effective and economical is a difficult challenge for legislators, policy makers and scientists.

Ultimately, global scale reduction of warming trends will require a global scale agreement and implementation. A single state such as Oregon, by itself, will not be able to alter the course of

global warming. However, once there is a concerted effort to implement a global warming policy, each state or similar municipality will need to tailor their strategies to what causes emissions of greenhouse gases from their region.

In view of the preceding discussion, we classify the drivers of climate change into three categories. First, we consider greenhouse gases and black carbon emissions as the main global warming elements that can be managed directly. On the second level are the global warming effects of ozone changes and the potential cooling effects of sulfur emissions arising from precursors rather than direct emissions. And finally, there are potential changes of albedo due to land use change and other indirect effects. As we implement direct policies to mitigate climate change it is important to remain cognizant of these other complex interactions that may undo our efforts, or though less likely, may allow us to relax our targets and meet the same goals.

In this chapter we focus on the emissions of greenhouse gases, since the first policies to reduce global warming will most likely be based to a large extent on controlling these emissions. To understand the drivers of future climate change for Oregon we write the annual anthropogenic emissions of a greenhouse gas in terms of basic factors that drive emissions. As an example, consider Oregon's annual emissions (E) in tons of carbon dioxide emitted per year from energy use. These can be written as a product of three more or less independently changeable variables. These are the emission factor (K = tons CO<sub>2</sub> emitted / BTU of energy used, in this example), the per capita consumption rate (C = BTU used per person per year) and the population (P = number of people). This formula  $E = K \times C \times P$  can be written for any greenhouse gas and any activity recognizing that it is the product of the emission factor (K), the per capita activity rate (C), and the total activity (P). We will use this general framework later to discuss emissions from various sources in Oregon and each of these variables will take on specific meanings related to the source and activity under consideration. To continue our example, the total emissions of carbon dioxide from Oregon then would be the sum of these estimates from all activities that result in emissions of carbon dioxide. To get an estimate of the total effect of Oregon's emissions on the climate, we have to make similar estimates for the other greenhouse gases such as methane and nitrous oxide. Often the other greenhouse gas emissions are multiplied by a factor such as the global warming potential, which is usually quite large, to arrive at the number of tons of carbon dioxide that if emitted, would have a similar climatic impact as the emissions of the non-CO<sub>2</sub> greenhouse gas. This way, we can come up with a single number (tons) of equivalent carbon dioxide emissions from Oregon for a given year. Clearly this number will change from year to year since any or all of the components change in time (K, C, and P). Most of our control strategies focus on reducing the emission factor, and to some extent on reducing per capita consumption, which could reduce affluence.

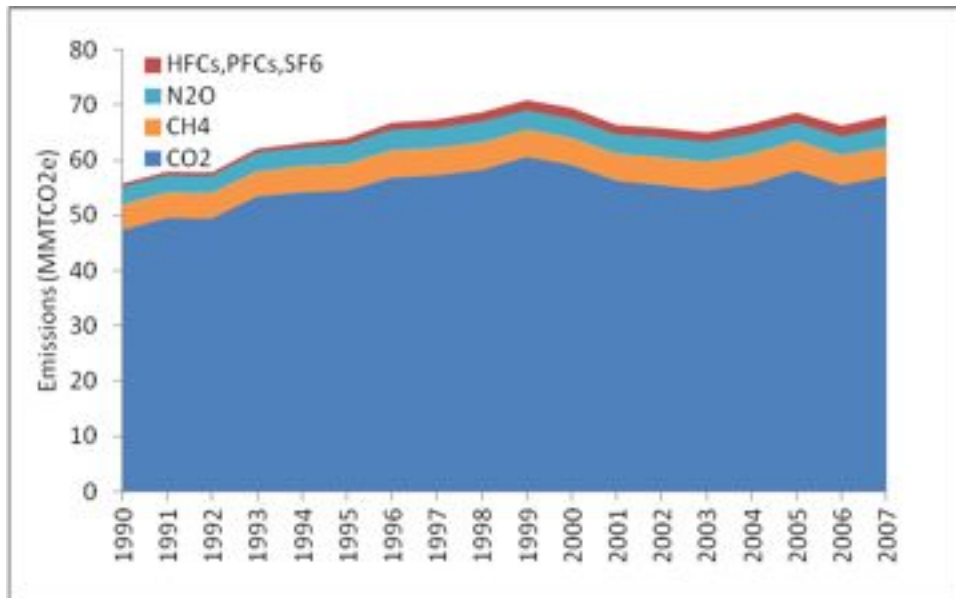
While this is a universal formula that can be used to estimate emissions from states, or countries, or even the whole world, the components that are likely to change are quite different on these various geographical scales. On a global scale, for example, the emissions calculated from such a formula have been, and still are driven most by changes in per capita consumption rates (C) and much less by population increases contrary to what most people think. China in recent times is a good example of emissions rising sharply as the per capita consumption has risen so that now China's carbon dioxide emissions exceed those of the United States. For many of our states, including Oregon, the population is already very affluent compared to world



standards. There is a saturation effect whereby people are not likely to consume more per capita than they already are. Therefore for Oregon the major driver of future climate change may well be the expected changes in population about which very little can be done. Thus our projections of future greenhouse gas emissions from Oregon depend heavily on expected population increases that are driven not by the natural increases but rather by people moving in or out of the state. The effect of population changes can be normalized by targeting a reduction in per capita emission rates rather than in the absolute tons of greenhouse gases emitted from Oregon over the coming decades.

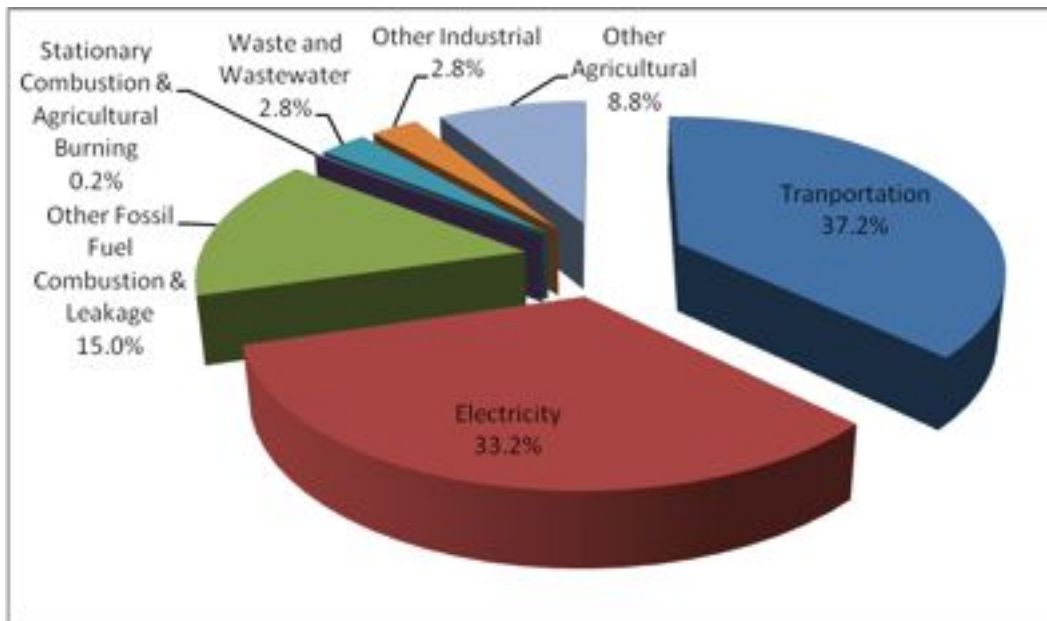
In this chapter we examine Oregon’s place in the climate change issue and how the state may approach its role in national and global policies to limit greenhouse gases and other causes of global climate change with a mixture of mitigation and adaptation. To this end, we describe first the emissions of greenhouse gases from various sectors representing different relationships with per capita consumption and population. The present estimates are based on inventory methods that are subject to considerable uncertainty which can impede the success of policies aimed at reducing emissions. To guard against such an occurrence, a validation component is necessary as has been advocated by a recent report from the National Academy of Sciences (2010). We will examine validation case studies and methods that exist and hold promise for future policy. We tie together these findings in the final section where we deal with what emissions we expect from Oregon and how these are justified by the discussion of the factors specific to Oregon. In addition, we discuss some issues and novel strategies that are of particular importance for policies to limit emissions from small regions such as Oregon.

### 2.1.1. Emissions and Trends of Greenhouse Gases by Sector



**Figure 2.1** Oregon’s greenhouse gas emissions by gas. Emissions are reported as million metric tons of equivalent carbon dioxide (MMTCO<sub>2e</sub>). Emissions of non-CO<sub>2</sub> greenhouse gases are scaled by their respective global warming potentials.

Greenhouse gas emissions can be categorized either by gas species (for example carbon dioxide, methane, and nitrous oxide) or by economic sector and human activity (energy use, electricity generation, agriculture, etc.). There are advantages to each classification depending on the planned use of the inventory. For scientific assessment of a greenhouse gas, the former is required to delineate the sources and sinks of the gas. For policy guidance, the latter approach is typically used in recognition that economic controls are typically applied to specific sectors of activity and not to any one particular gas. In this approach, emissions of non-CO<sub>2</sub> greenhouse gases are scaled by their global warming potentials to produce equivalent carbon dioxide emissions (CO<sub>2</sub>e). Here we report emissions by sector but include a figure of Oregon's greenhouse gas emissions by gas species for reference (Figure 2.1). In 2005 carbon dioxide contributed 86% of total emission, while methane, nitrous oxide, and the high GWP gases respectively contributed 7%, 4%, 3% of the total (GWP is the Global Warming Potential as defined in Forster et al. (2007)).



**Figure 2.2** Sources of greenhouse gases in Oregon. Data is averaged over 2003 - 2007, Oregon Greenhouse Gas Inventory, 2010.

The sources of Oregon's greenhouse gas emissions can be broadly listed as energy, agriculture, industrial processes, and waste management (Figure 2.2). The energy sector consists of a number of important sub-sectors including electricity use and transportation. Unlike some greenhouse gas inventories, emissions from electricity use are kept separate here and are not distributed according to residential, commercial, or industrial use. Rather, greenhouse gas emissions listed for these sectors are only from the direct combustion of fossil fuels. We feel this method is more relevant for policymakers as it clearly identifies the impact of changes to Oregon's mix of electricity suppliers.

## 2.1.2 Energy Use

### 2.1.2.1 Electricity

Greenhouse gas emissions from electricity can be estimated based on either production or consumption. The U.S. EPA (2009) reports production-based emissions since their chief concern is to develop a national inventory, and tracking emissions where they are produced rather than where the electricity is consumed is simpler. To evaluate the role of states in the national emissions, it makes more sense to track electricity consumption rather than production. This method reduces emissions for energy exporting states and increases emissions for importers.

Oregon's mix of electricity sources is nearly evenly divided between coal and hydropower. Emissions associated with the consumption of electricity have historically been one of the largest sources of greenhouse gases in Oregon, between 20 to 25 MMTCO<sub>2</sub>e (million metric tons of CO<sub>2</sub> equivalent) per year in the last decade, representing about 33% of Oregon's total greenhouse gas emissions. Oregon tracks these emissions by tracing back the power used by Oregonians to its sources. In most years Oregon has imported anywhere between one and twenty percent of its electricity. In good water years when hydropower is abundant, Oregon exports electricity. As most of Oregon's imported electricity is generated by coal-fired plants, the switch from a production-based to a consumption-based inventory increases Oregon's emissions. About two-thirds of Oregon's emissions from electricity use come from out-of-state energy supply. Emissions from electricity use was one of the fastest growing sources of greenhouse gas emissions from 1990 to 2007, though much of this increase was due to the shutdown of the Trojan nuclear plant in the early 1990s and the subsequent replacement of its lost production with coal-generated electricity (Oregon, State Reports 2008, 2009, 2010).

Emissions from electricity consumption are highest for residential use, followed by the commercial and industrial sectors (9, 7, and 6 MMTCO<sub>2</sub>e respectively for 2003-2007 average use in round numbers). Though industrial emissions have remained the same or decreased from 1990 to 2007, residential and commercial emissions increased by 45% and 55%. These large increases are likely driven primarily by population growth.

### 2.1.2.2 Transportation

The transportation sector has been one of the single largest sources of greenhouse gas emission in Oregon and throughout the Pacific Northwest, over the last twenty years. Emission estimates are derived from fuel use for Oregon provided by the U.S. Department of Energy for the state, and not aggregated from vehicle use statistics. Because transportation fuels are taxed, these data are expected to be accurate (Oregon Department of Transportation, 2009).

Burning fossil fuels in automobiles and other vehicles used to transport goods and people leads to emissions of several greenhouse gases. Carbon dioxide is the main emission and methane and nitrous oxide are emitted in lesser quantities. Accounting for emissions from the transportation sector should also include full life cycle costs, specifically emissions from extracting, producing and distributing transportation fuels and in manufacturing, distributing and disposing of vehicles themselves. The Transportation Research Board Special Report (TRBS, 2008) provides a comprehensive review of emissions from the transportation sector.

Worldwide estimates show that transportation related greenhouse gas emissions account for about 20% of total global greenhouse gas emissions. All combustion engine transportation modes emit greenhouse gases including rail, buses, airplanes, trucks, ships, passenger vehicles, light duty trucks and motorcycles. Light-duty vehicles such as passenger cars, pickup trucks, mini-vans and sport utility vehicles account for 60 percent of all emissions (TRBS, 2008). However, emissions from the air transport (12.4%) and truck freight (18.4%) are significant and are projected to grow faster than emissions from light duty vehicles.

Emissions of carbon dioxide and other greenhouse gases from the transportation sector follow the same formula as discussed earlier:  $E_i = K_i \times C_i \times P_i$ . Here "i" represents the vehicle type (cars, trucks, rail etc);  $K_i$  is the emission factor for type "i" vehicle (Tons GHG emitted / BTU consumed);  $C_i$  is the energy consumed by or the efficiency of this type of vehicle (BTU consumed / mile traveled) and  $P_i$  is the number of miles travelled/year by type "i" vehicles. The total emissions is the sum over all the types of vehicles represented by the index "i." The primary driver of transportation sector emissions historically has been the level of transportation activity measured by vehicle miles traveled by people and transportation of goods. Improvements in vehicle fuel efficiency that reduce emissions have been overwhelmed by increased activity and by switches to more energy intensive modes, such as from freight rail to trucks.

Gross total emissions from all sectors of the Oregon economy amount to about 67 million metric tons of carbon dioxide (CO<sub>2</sub>) equivalent for the year 2005. This tabulation is based on the consumption by Oregonians, regardless of where the energy comes from. The transportation sector accounts for about 37% of the greenhouse gas emissions in Oregon. This is a larger percentage than the national average because Oregon's total energy use sector includes hydropower resources, which do not result in greenhouse gas emissions and thus reduce emissions from sectors other than transportation.

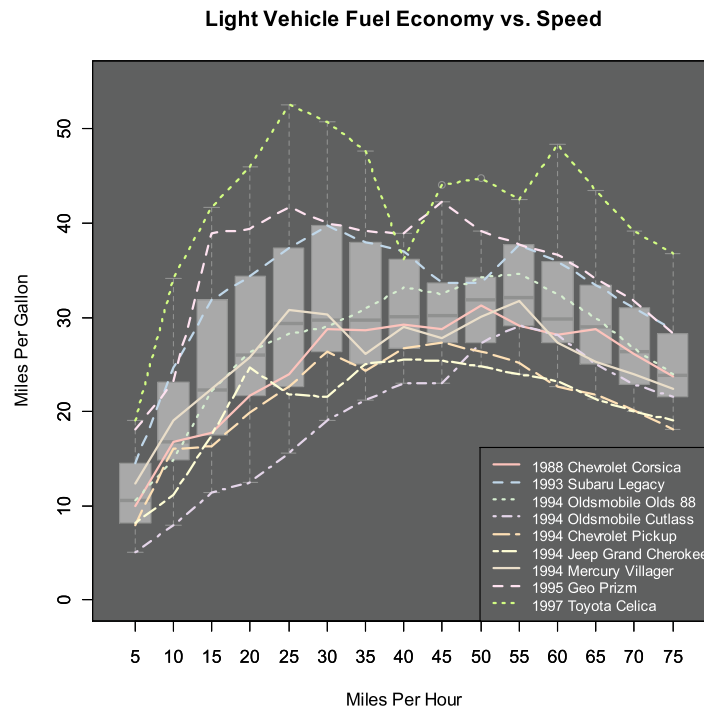
Next, we examine each of the factors affecting emissions from transportation: the energy efficiency of vehicles, carbon content of fuels or emission factor, and the miles driven.

*Vehicle Efficiency* : Vehicle efficiency has a major effect on greenhouse gas emissions. There is both political and technical uncertainty in our ability to predict future vehicle efficiency, however, the technologies for reducing fuel consumption are well known. They include engine efficiency technology, transmission technologies, reductions in vehicle weight and improved aerodynamics. Even when vehicle efficiency is improved, greenhouse gas reductions may not be realized because of driver behavior, the adoption rate for the technology as fleets turnover, or decisions to use such technologies.

*Carbon Content of Fuel*: Motor vehicle fuels vary in the amount of greenhouse gases they produce for the energy they contain, especially when emissions for producing and transporting the fuels to the end users are included in the calculation. The greenhouse gas production of different fuels is known as the carbon intensity of the fuel. It is measured as the grams of greenhouse gas, expressed as CO<sub>2</sub> equivalents, per mega joule of energy contained in the fuel (or another energy unit). For example, the California Air Resources Board has calculated that

gasoline emits about 96 grams of greenhouse gas per mega joule. In comparison, the emissions from biodiesel produced from waste cooking oil are about 14 grams of greenhouse gas per mega joule. Therefore, greenhouse gases emissions can be reduced by lowering the carbon intensity of transport fuels.

*Efficiency of the Transportation Network:* The operational efficiency of the transportation network affects the efficiency of vehicles. Vehicle travel speeds affect light vehicle fuel efficiency. Figure 2.3 shows that vehicle fuel efficiency and the speed at which maximum efficiency is achieved varies among different models of vehicles. In general, fuel efficiency declines at speeds below 25 mph and over 60 mph.



**Figure 2.3** Light vehicle fuel economy vs. steady state speed (Davis et al., Transportation Energy Data Book, ORNL, 2009, Table 4.28)

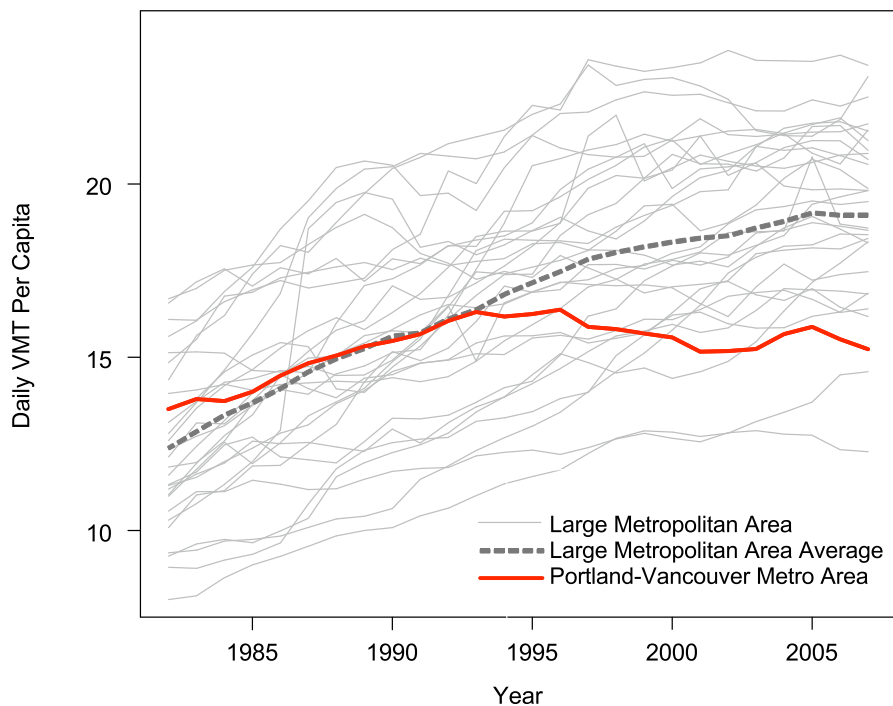
Fuel economy is also adversely affected by vehicle deceleration and acceleration. Deceleration wastes energy as the vehicle slows down; acceleration uses more energy than constant speed travel of the same distance; stopping wastes fuel in idling as well. The design and operation of roads affects vehicle speeds and the amount of acceleration, deceleration and stopping of cars. Optimization of traffic signal spacing and coordination of traffic signals allows for optimization of traffic progression and minimizes stopping at traffic signals. Freeway management strategies, such as incident management and ramp metering, also smooth out traffic flow and improve vehicle fuel efficiency thus reducing greenhouse gas emissions.

While increasing speeds can improve vehicle fuel efficiency, it may also increase the amount of vehicle travel. The distances that people travel are affected by travel speeds and times. In the absence of other influences, travel distances increase as travel speeds increase and travel times decrease. The net effect on greenhouse gas emissions will be the result of complex interactions

and cannot be determined without modeling the specific situation.

Improving transportation system efficiency can also be important for reducing greenhouse gas emissions from public transportation. Urban transit buses running with low occupancies produce more greenhouse gas emissions per passenger mile of travel than a high efficiency single-occupant automobile (M.J. Bradley & Assoc., 2007; Univ. of MN, 2008).

Amount of Driving (VMT): It is estimated that Vehicle Miles Traveled (VMT) in the United States will increase by about 60% between 2005 and 2030 (Ewing et al., 2007). The miles traveled have been growing at a relatively slow rate in Oregon, and the Oregon Transportation Plan forecasts an increase of 40 percent over that time. The growth of miles traveled in Oregon began to level off and per capita miles travelled began declining even before fuel prices started their rapid rise in recent years, Figure 2.4. The miles traveled per capita in the Portland metropolitan area started declining in the mid-1990s (Lomax and Schrank, 2009). Meanwhile the per capita miles travelled for other large metropolitan areas have continued to grow.



**Figure 2.4:** Daily Vehicle Miles Traveled (VMT) per capita on major roads in large metropolitan areas, 1982 - 2007 (Texas Transportation Institute Urban Mobility Report database.) Large Metropolitan areas have populations from 1 - 3 million in 2005 or later. Major road daily VMT per capita is calculated by adding annual average daily VMT for freeways and arterial roads, then dividing by the metropolitan area population.

Total motor fuel consumption in Oregon has increased by only 0.25 percent from 1999 to 2007, while the population of the state increased by 10.4 percent. The net effect has been a 9.2 percent decrease in consumption per capita (see Oregon Dept. of Transportation Data website). Some of

the leveling off in state highway miles driven may be due to the shifting of a portion of traffic away from state highways to local roads as a result of rising congestion. These trends, if they can be maintained will make it easier for Oregon's overall strategy to limit greenhouse gas emissions to agreed upon targets.

#### *2.1.2.3 Other combustion: residential, commercial, and industrial*

Most of the energy use in this category comes from the burning of natural gas and other fossil fuels to heat homes and businesses. Collectively, emissions from this energy use are about 17% of the state total in Oregon. Emissions from the residential and industrial sectors rose rapidly from 1990 to 2005 (29% and 26% increase respectively) and are among the fastest growing sectors. Although the flows of natural gas are well understood, the data on the use of other heating fuels, especially fuel oil and propane, are highly uncertain. In addition, the blurring of residential and commercial uses in many areas makes it difficult to differentiate uses between these two sectors. Data aggregated between the two sources is more reliable.

#### *2.1.2.4 Waste management*

Waste streams are managed with a variety of methods including incineration, wastewater treatment plants, and landfills. The incineration of waste is a source of carbon dioxide, some of it may be of fossil origin, while wastewater treatment and landfills are sources of both methane and nitrous oxide. Municipal and industrial landfills are the second largest source of methane after enteric fermentation (digestion of carbon food sources in ruminant animals). In many anaerobic systems, that is, where methane producing bacteria grow in the absence of oxygen, a significant fraction of the methane that is produced is oxidized by other bacteria before it can be released to the atmosphere. Overall, emissions from waste contribute only about 3% to Oregon's total greenhouse gases, but they have increased by 24% since 1990.

#### *2.2.1.5 Agriculture*

Emissions of the greenhouse gases methane and nitrous oxide from agriculture in Oregon were estimated to be about 7% of the state's annual greenhouse emissions (Oregon Dept. of Energy, 2004). Carbon dioxide emitted from harvest, field burning, or pruning is not counted as an addition to the atmosphere, as it is considered part of the annual cycle of CO<sub>2</sub> when crops re-grow in spring.

For methane, the agricultural emissions come from ruminant livestock, particularly cattle. Ruminants ferment cellulose in their stomachs, producing methane as a by-product of digestion. Emissions vary depending on the age of the animal and the digestibility of the feed (Johnson et al., 2000). State agricultural data, submitted to the federal government, are used to estimate these agricultural greenhouse gas emissions. There are many known sources of uncertainty in these estimates making the estimates potentially inaccurate.

The application of fertilizers for agriculture, and to a lesser degree, for residences and commercial buildings, is a source of nitrous oxide to the atmosphere. By analyzing the data on the fertilizer use in Oregon it is possible to estimate emissions. Additional sources of nitrous oxide and methane come from animal manure, agricultural biomass burning and wildfires. Estimates from these sources at this time small, less than 1% of the agricultural source for biomass burning, while manure management is about 9% of the total agricultural source.

### 2.1.2.6 Industrial sources

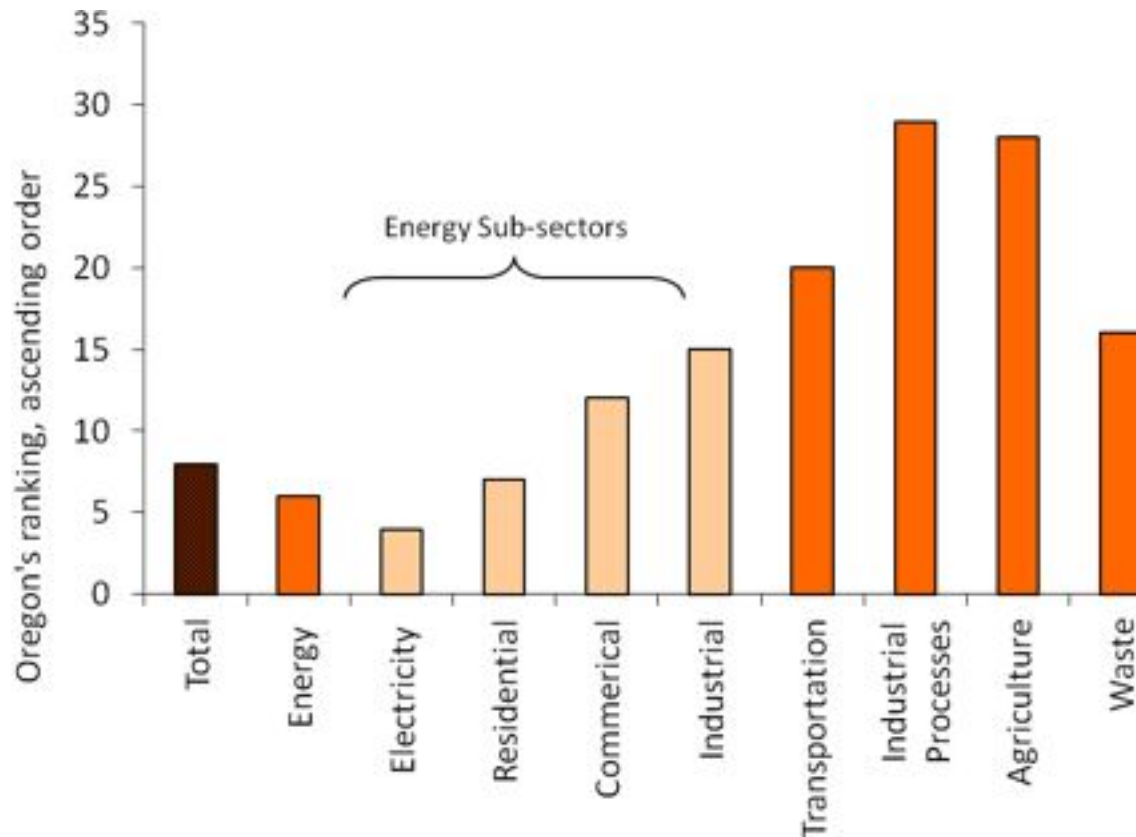
Manufacturing and industrial facilities emit greenhouse gases through a number of chemical processes used to create products. These sources include cement and lime manufacturing which generates carbon dioxide; aluminum, and semiconductor production which release small amounts of high global warming potential gases such as the perfluorocarbons and sulfur hexafluoride. Because in the past there has been no requirement to report greenhouse gas emissions from these types of facilities, estimates of industrial emissions are extremely uncertain, mostly derived from taking population-based proportionate shares of national emission estimates and applying them to Oregon. The trend from industrial emissions is thought to be high, with emissions increasing by over 50% since 1990. Still they contribute less than 5% of Oregon's emissions. Starting in 2009 Oregon began requiring reporting of emissions from many industrial sources, which will lead to improved emissions data for many sources.

## 2.2. Oregon Emissions in Perspective

In the previous section we delineated Oregon's greenhouse gas emissions according to economic sectors. This provides an important perspective on what the sources of Oregon's emissions are and what activities may be targeted for mitigation. Next we will place Oregon's emissions into perspective with regard to both national and global emissions. It comes as no surprise that Oregon contributes only a small fraction to national and global emissions. In 2005 Oregon's emissions were 1% of U.S. national emissions and 0.2% of global emissions. Even if policies in Oregon were to generate dramatic reductions in emissions, these would have imperceptible impacts on global climate change. Global emissions will determine the climatic impacts that Oregon will experience and to which the state will need to adapt.

In light of Oregon's small population, metrics other than total emissions should be used to assess Oregon's contribution to climate change. The simplest of these is per capita emissions, which provides a method to compare the carbon footprint of Oregonians to national and international norms (Figure 2.5). Oregon's per capita emissions of 18 MTCO<sub>2</sub>e in 2005 were the eleventh lowest of all U.S. states or about 25% lower than the national average (24 MTCO<sub>2</sub>e). However, compared to developed countries, Oregon's per capita emissions rank quite high. Of the 39 (industrialized) countries with reported inventories in 2005, Oregon's emissions are fifth highest, and are nearly double the European Community average. Relative to the global average, Oregon's per capita emissions are almost three times higher. One contributing factor to Europe's low emissions seems to be high population densities; a correlation also observed in U.S. states as we discuss below.





**Figure 2.6** Oregon's ranking of per capita emissions by sector relative to other U.S. states, data year 2005. Ranking is based on data in ascending order. (That is lowest emission is 1; highest emissions per capita is 50.) Emissions by sector data from World Resources Institute Climate Analysis Indicators Tool (CAIT US Version 4.0, 2010), except for the electricity sector data which was derived from the U.S. EPA (2010).

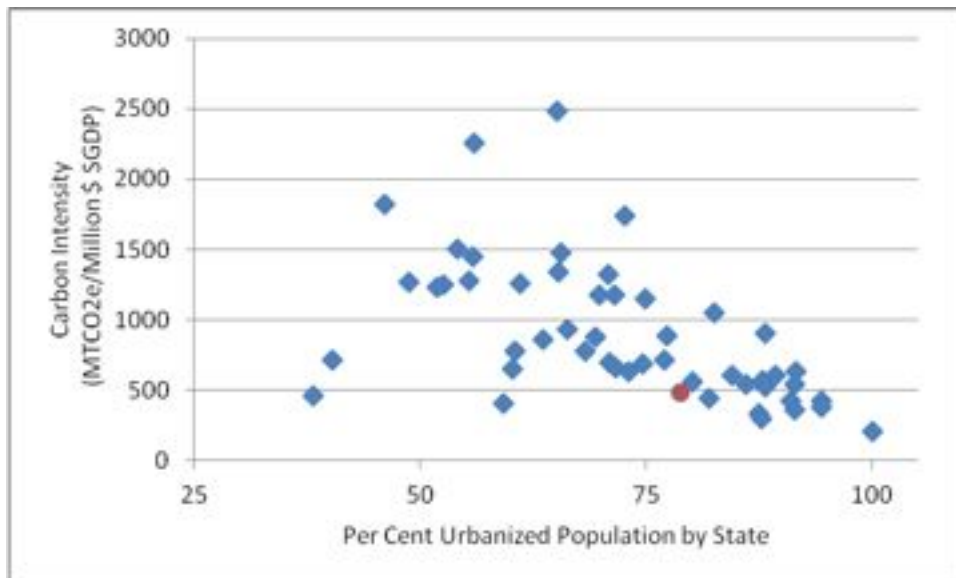
Why are Oregon's emissions low compared to other U.S. states? Answers here will help policymakers identify and target sectors that may be amenable to future emission reductions. Figure 2.6 shows Oregon's ranking relative to all states in sector-based per capita emissions. A low ranking means that Oregon has low per capita emissions in that sector relative to other states. Of the four major economic sectors, Oregon's total per capita emissions are driven primarily by energy. In energy use Oregon ranks eleventh lowest over all states, and this ranking in turn is driven primarily by electricity generation where Oregon ranks thirteenth lowest in the country. Within the framework of our equation  $E / P$  (per capita emissions) =  $K \times C$  this ranking is based on a combination of per capita electricity consumption ( $C$ ) and the emission factor ( $K$ ) for Oregon's electricity consumption, or a combination of both. In 2008 Oregon had the fourteenth highest per capita consumption rate of electricity (U.S. Energy Information Administration, 2010) and the eleventh lowest emission factor (tons CO<sub>2</sub>e per MWh) among states (US EPA, 2010), which in large part is due to the abundance of hydroelectric power sources in the region that provide Oregon's electricity.

In other sectors, Oregon's ranking is closer to the national average. Per capita emissions from industrial processes and agriculture rank 21st and 28th respectively, while Oregon's per capita transportation emissions are ranked 21st nationally. Oregon's residential emissions also rank

low relative to national norms (eighth). Residential energy usage is dominated by fossil fuel combustion used for heating. The low emissions are in part due to Oregon's mild natural climate with below average number of degree heating days, ranking twenty-ninth in the country.

Finally, one of the most useful ways to assess Oregon's greenhouse gas emissions is by the carbon intensity of its economy. The carbon intensity reflects the amount of greenhouse gases emitted per one dollar of gross state product (GSP) produced. It is calculated simply by dividing the state's Oregon's greenhouse gas emissions by its GSP. A state planning to lower its emissions, while keeping economic output high, would aim to reduce this number.

Oregon emits 460 metric tons of CO<sub>2</sub>e per million dollars of GSP (2000 data) ranking favorably among other states. Oregon is the eleventh least carbon intensive economy in the country, but is the most carbon intensive of the contiguous Pacific coast states. The other states with low carbon economies are primarily small New England states plus the District of Columbia. The economies of the Pacific coast states benefit from low carbon electricity sources, but the eastern seaboard states rely primarily on carbon-intensive coal for electricity, which means their low carbon emissions must be due to other factors. These states are highly urbanized and have among the highest population densities in the country. In Figure 2.7 we plot carbon intensities as a function of state urbanization. Here urbanization is defined according to the US Census Bureau (U.S. Census Bureau, 2010).



**Figure 2.7** The economic carbon intensity is plotted for all states relative to their urbanization. Oregon is highlighted in red. Urbanization is defined by US Census Bureau 2000 Census of Population and Housing, <http://www.census.gov>; state emissions data for 2000 from the US EPA, <http://www.epa.gov>; SGDP (State Gross Domestic Product) data for year 2000 from the US Dept. of Commerce Bureau of Economic Analysis. <http://www.bea.gov>.

A negative correlation exists between carbon intensity and urbanization; generally as urbanization increases, carbon intensity decreases. This correlation likely reflects underlying causal relations between the two variables. For example, as population urbanizes, per capita

miles driven likely decrease due to shorter commutes and proximity to public transportation. Agricultural activities, which are carbon intensive on account of fuels, fertilizers, and transportation, also likely decrease with urbanization. Oregon's population is 79% urbanized. Of states with similar urbanization (e.g., Delaware, Ohio, Pennsylvania), Oregon carbon intensity is lowest.

In summary, Oregon has low per capita emissions compared to other states while maintaining a relatively high gross state product, producing an economy that is the eleventh lowest in carbon intensity. Oregon benefits from being close to hydropower generation and a mild climate keeps heating emissions low. In addition Oregon has an above average rate of urbanization, reducing per capita miles driven and other factors that generate greenhouse gases. Partially offsetting these factors is Oregon's large agricultural sector, which tends to be carbon intensive.

## **2.3. Uncertainty and Validation of Emissions**

### **2.3.1 Uncertainty and Validation**

Greenhouse gas emissions can be estimated by several independent means. An emissions inventory is a common method by which estimates are made for each process that releases a greenhouse gas to the atmosphere. These estimates are based on an emission factor and an extrapolation factor. For example, we may have estimates based on measurements of the average number of grams of CO<sub>2</sub> emitted per mile of driving. We can multiply this by an estimate of the number of miles per year that people drive in Oregon (or the per capita miles driven times the population, to put it in the same form as  $E = K \times C \times P$  discussed earlier, where the combination  $C \times P$  is the number of miles driven per year). The accuracy of both these factors is questionable and may lead to systematic under or over estimates of emissions. In addition to the problem of accuracy just described, there may be substantial year-to-year variations in these factors depending on environmental or economic conditions, hence an estimate for one year may not be reliable for another.

Most regulations for air and other forms of pollution require measurements and testing to determine whether compliance with regulations has been achieved. For mitigating climate change also, methods to validate emissions inventories must be made an integral part of the policy. Without validation we will neither know whether our estimates are reliable and accurate, nor will we know whether our policies to reduce emissions are working.

The space and timescales over which greenhouse gas inventories are taken also have a major effect on the accuracy of the estimates. Generally, the smaller the space and timescales are, the less reliable the numbers are likely to be. This is partly due to the fact that the actual emissions tend to vary more from one small space to another. Since we cannot measure the emission factors from each small region, applying averaged emission factors based on data from distant locations is likely to produce large uncertainties in the estimates. Over large areas the average emission factors are more reliable as deviations tend to cancel out. For very large scales such as

over a hemisphere or the global scale, there are potential constraints that can be used to check the accuracy of emission inventories. For instance, observations of excess concentration seen in the northern hemisphere compared with the southern hemisphere limits on how much emissions may be emitted from the north (Khalil and Rasmussen, 1981). In some cases, such as for methane or nitrous oxide, the total global annual emissions can be constrained by estimating how many tons of these gases are destroyed annually by known atmospheric or terrestrial processes. This has to match the amount we emit and the change of concentration that is observed on the global scale. Such constraints are not directly applicable to smaller spatial scales such as a state like Oregon, but they suggest ways to achieve the same end. In recent times, satellite observations of greenhouse gases show promise for future validation studies for small sized regions.

Although there is no substitute for an emission inventory, there are methods by which we can verify both whether our estimate is accurate and whether our regulations are causing the desired reduction in greenhouse gas emissions. Increasingly this validation is done by direct measurements of greenhouse gases in or near large sources such as urban areas. Existing or new techniques will have to be included in policies to control greenhouse gas emissions from Oregon to validate whether the policies are working (National Academy of Sciences, 2010).

### **2.3.2 Case Studies**

In Oregon two studies dealing with greenhouse gases have shown promise for validation of changes. The first was by Khalil and Rasmussen (2004) who reported evidence of substantial decreases in emissions of ozone depleting compounds from the Portland area and nearby regions, while greenhouse gases did not show a similar trend. In the second and ongoing study Rice and others are looking at CO<sub>2</sub> concentrations and the <sup>13</sup>C isotopic composition of CO<sub>2</sub> from three regional monitoring stations in Multnomah County (Rice and Bostrum, 2010). The study takes advantage of seasonal prevailing winds from the Columbia Gorge to track the relative concentrations of CO<sub>2</sub> between a rural site at the edge of Portland, a downtown site, and an urban residential site. Early results from summer and fall measurements indicate enhanced CO<sub>2</sub> at the urban sites is almost entirely from automotive sources. Data collection continues and will provide evaluation of variations in urban CO<sub>2</sub> throughout a full calendar year. Sources should vary with season, e.g., increased use of natural gas and oil for heating in winter months. Second, more extensive data collection and analysis of the carbon isotopic composition of CO<sub>2</sub> in Portland should help differentiate between important CO<sub>2</sub> sources and their temporal trends. Isotopes are a new and state of the science method for looking at the origins of greenhouse gases in various environments.

### **2.3.3 The Role of Aerosols**

Atmospheric particles, either liquid or solid (aerosols), can play a significant role in climate change, particularly at regional scales of the size of Oregon. Atmospheric aerosols affect the Earth's surface temperature by scattering and absorbing radiation and altering cloud properties, such as how long clouds persist. The direct effect of aerosols is scattering and absorption of radiation. The indirect effects are typically separated into modification of cloud albedo

(reflectivity) through a change in the number of cloud droplets per cubic meter of air, and droplet size for a fixed cloud liquid water content (Twomey, 1977), and the second indirect effect is modification of cloud liquid water content, cloud height, and cloud lifetime (Albrecht 1989). Further effects of aerosols have been proposed (Hansen, 1997; Koren, 2008; Isaksen et al., 2009)

Generally aerosols with significant fractions of dust or black carbon absorb the Sun's radiation resulting in positive radiative forcing that causes warming of the atmosphere and the surface, while aerosols with significant fractions of other constituents (sea salt, sulfates, nitrates, organics) are non-absorbing and cause a cooling of the surface. Non- or weakly absorbing aerosols dominate most latitudes (Ramanathan et al., 2001), and thus produce the overall net-cooling effect; however, absorbing aerosols may play an important role at high altitudes and at local scales (Charlson et al., 1992).

At present it is not known how aerosols are affecting Oregon's climate and to what extent their emissions in the future can mitigate the climatic change that may occur here. The prevailing conditions with substantial annual rainfall and many sources of organic aerosols suggest that the aerosol effects may be important for Oregon climate in the future.

## 2.4. The Challenge of Meeting Climate Targets

### 2.4.1 Future Emissions

#### 2.4.1.1 *Social drivers of future greenhouse gas emission levels*

The impacts of climate change in Oregon will depend on the extent of global climate change. The extent of global climate change in turn will be determined by emissions of greenhouse gases and the interaction of those emissions with the natural climate system. What factors, then, will determine the amount of future greenhouse gas emissions emitted in Oregon? As discussed earlier, there are three elements that determine emissions (E), these are the emission factor (K), per capita consumption rate (C), and population (P). When emissions are considered for the entire state across economic sectors and activities we can use carbon intensity (MTCO<sub>2</sub>e per million dollars) as the emission factor K, and GSP per capita as the consumption rate C. We can then examine the patterns of these three drivers for Oregon in the past, present, and future. We consider three time periods for which we have economic and emission data, 1990-1999, 2000 - 2005, and 2010 - 2020. For the latter period we use forecasts of economic activity and population.

We look at how much of the percent change in emissions  $\% \Delta E$  over each of these periods is driven by the percent changes in the three factors ( $\% \Delta K$ ,  $\% \Delta C$  and  $\% \Delta P$ ) For example, we define the percent change for the first period as  $E(\text{in } 1999) - E(\text{in } 1990)$  divided by  $E(\text{in } 1990)$  and multiplied by 100% to convert to percent. The same is done for the other variables K, C and P and for the other time periods. Table 2.1 lists these changes for the three time periods.

<i>%Changes of Variable</i>	<b>1990-1999</b>	<b>2000-2005</b>	<b>2010-2020</b>
Population ( $\Delta P$ )	16 %	6 %	13 %
GSP per capita ( $\Delta C$ )	30 %	6 %	8 %
Carbon intensity ( $\Delta K$ )	-17 %	-10 %	??
Emissions ( $\Delta E$ )	25 %	1 %	??

**Table 2.1** Changes in emissions and drivers. Values are percentage changes over the time period indicated.

Delineating the drivers of emissions in this fashion reveals why Oregon's emissions are changing and what to expect in the future. During the 1990s Oregon reduced the carbon intensity of its economy by 17%. In spite of this decrease, Oregon's emissions still grew by 25%. The reasons are clearly seen; population grew by 16% and consumption or gross state product per capita increased by 30% thus overwhelming the gains in carbon intensity. Thus despite a double digit decrease in the gross emission factor, emissions still rose by double digits.

During the early part of the last decade Oregon reduced its carbon intensity by 10%, but this reduction was again offset by increasing population and consumption. By the year 2020 Oregon's population is expected to increase by 13%. If we assume Oregon's economy will grow at ~2.5% per year, a rate that seems likely to continue once the current recession ends (<http://www.census.gov/compendia/statab/2010/tables/10s0655.xls>), then per capita GSP will increase ~8% by 2020. If the carbon intensity of the economy remains constant over the next period, then we should expect Oregon's emissions to increase by about 20%. This highlights the challenge Oregon faces to reduce its future emissions. Since most governments appear disinclined toward policies that curb population growth or economic growth, emissions will grow at a rate that is the product of population growth and growth in per capita income: the rate will continue to increase barring changes in available technologies or consumer and producer choices among those technologies. Past growth trends suggest this upward pressure on emissions will be about 20% per decade in Oregon. Given this, state policy-makers face the daunting task of developing policies that reduce carbon intensity (i.e., emissions per dollar of GSP) by about 2 to 3% per year just to avert increases in CO<sub>2</sub>e emission levels. Generating decreases in emissions will require policies that reduce carbon intensity at rates greater than those 2% to 3% per year levels.

This analysis raises an important question about what metric Oregon should use to assess its future greenhouse gas emissions. Policies regulating emissions will likely try to reduce emission factors (K). For example, higher efficiency vehicles and increased production of renewable energy would lower the emission factor for the transportation and energy sectors respectively. Even if Oregon successfully reduces emission factors across sectors through mitigation policies, these reductions will be offset by population and economic growth. Of the population growth from 2000 to 2020, it is estimated that 63% will be due to net migration into the state. This added growth will put greater pressure on actions designed to reduce emission factors and may derail efforts to reduce total overall statewide emissions by target dates.

Oregon's per capita emissions have been constant or declining over the past decades. This suggests that Oregon may wish to explore the use of a modified per capita emissions metric to

assess its emissions goal instead of total emissions. The basic idea is that the targets for the state should be set by managing the per capita emission rate rather than the total emissions. This way Oregon will not be punished for net migration into the state as other states are rewarded for net migration out. This new metric would use a modified form of population that would be updated annually only by net migration and not natural growth. Oregon's per capita emissions would be calculated using this modified population to normalize for net migration into or out of the state. For example 68% of Oregon's population growth by 2020 is expected to be from net migration into the state. Thus natural population growth by 2020 is only about 4%. Using the modified metric would require Oregon to reduce its carbon intensity by a more manageable 12% rather than 21% to keep emissions constant. If this metric were adopted by all states, then national inventory targets could still be met and states would have a fairer allocation of responsibility towards the success of their mitigation policies.

### **2.4.3 Policy Considerations**

There are two ideas that we want to bring up in closing. The first is that policies to reduce greenhouse gas emissions at the state level and perhaps even on the national scale can be set as an average over several years to a decade with flexibility in year to year emissions. Or what amounts to the same thing, a target can be set for aggregate emissions over a 10 year period, with flexibility on how much is emitted in each of the years of the target period. As long as emissions can be maintained on average at target levels within the specified time period, which may be 5 year or 10 years, it would be acceptable to allow increases in emissions over some years to accommodate unexpected opportunities for economic or industrial growth. Climate change responds very slowly to changes of emissions and thus maintaining an average emission rate on target over a decade or perhaps an even longer period can produce nearly the same results as trying to maintain the same emissions every year. This is unlike the case for urban air pollution where violations of a standard on even one day can lead to harmful effects.

The second matter relates to the actions that Oregon can take given the complex and uneven responses from the rest of the states and other countries of the world. Even if policies in Oregon were to generate dramatic emissions reductions, these would not insure that Oregonians will get manageable or modest climate change in the future unless similar policies were adopted by people in other states and countries. Because both the emissions that cause climate change and their undesirable impacts are global in scale, the costs of action to reduce emissions will be borne by those taking such actions but the benefits of those actions will accrue to everyone. Similar situations have been called the "Tragedy of the Commons" (Hardin, 1968) and are known to create strong incentives for people to take less action than is necessary to remedy the problem. Indeed, arguments are likely to be made that Oregonians should not adopt policies that may inhibit local economic growth unless we can be assured that those policies will be matched by other governments around the world, thereby actually reducing overall global emissions and stemming the effects of climate change. The flexibility of being able to relax emissions for a few years at a time while maintaining emissions at the target on average can reduce the burden of taking action to reduce global warming. Whatever actions are taken in Oregon we should be clear that Oregon's efforts to reduce emissions of greenhouse gases will not directly and immediately reduce the impacts of global climate change that we will

experience in Oregon or affect the costs of adapting to climatic change.

## 2.5 Key points

The main points we have discussed are the following:

- Higher population density can in some circumstances lower per capita greenhouse gas emissions. We have discussed this effect and related indices of how to put Oregon in context of global change.
- We argue that state goals should be set as limits on per capita emissions rather than total state-wide emissions. This would reward states that make reductions in emissions and attract economic growth rather than states where emissions may be reduced by migration or economic downturns.
- We have put Oregon greenhouse gas emissions in the context of other states and the world and argued that emissions from energy use should be evaluated by per capita consumption rather than the more readily available data on per capita production by state.
- State and country policies can set targets as emissions over a decade, or possibly longer, rather than for each year. This would allow flexibility in controlling emissions within the decadal period which could be relaxed over a few years because the state is seeing a growth of an important industry or has economic opportunities as long as the 10 year aggregate emissions goal is met. Since climate does not respond rapidly to year by year changes of emissions, there is no need for policy to limit emissions on an annual basis. This is unlike the case for air pollution where the impact is immediate and hence increases of emissions even above daily targets are not permitted.
- Direct validation of emissions reductions is necessary to know whether our policies are working or not. Hence validation has to be made an integral part of policies to control greenhouse gas emissions.



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### 3. Climate Change and Freshwater Resources in Oregon

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#### Summary and Knowledge Gaps

Climate change will affect various sectors of water resources in Oregon in the 21<sup>st</sup> century. The observed trends in streamflow show significant declines in September flow and, although not significant, increases in March flow in many transient rain-snow basins. These streamflow trends are associated with rising temperature and coincident declines in snowpack in spring in the latter half of the 20<sup>th</sup> century. While there are no distinct trends in high precipitation events, such events are associated with climate variability such as El Niño/Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO). Effects of ENSO and PDO are more pronounced at the beginning and end of the wet season in the Willamette River basin.

The amount and seasonality of water supply is projected to shift as the distribution of precipitation changes and temperatures rise. Higher summer air temperatures accompanied by reduced precipitation are projected to increase evapotranspiration and decrease stream flow in summer. Although there are no distinct spatial patterns of changes in precipitation and temperature across the State in the 21<sup>st</sup> century (uniform increase in temperature across the region), significant regional variations do exist. The magnitude of change depends on the importance of snow in the current water budget, so projected changes are greater for mountainous regions than for low-elevation areas. Transient rain-snow basins, such as those in the Western Cascade basins, are projected to be more sensitive to these changes in precipitation and temperature. The high Cascade basins that are primarily fed by deep groundwater systems could sustain low flow during summer months. Basins in the east of the Cascades are projected to have low summer flow in a distant future as groundwater recharge declines over time. April 1 snow water equivalent (SWE) will decline and the center timing of runoff will become earlier in transient rain-snow basins as snowpack is projected to decline consistently in the 21<sup>st</sup> century.

These model projections should be viewed with caution for several reasons when considering climate change impacts on water supply in Oregon. First, this chapter shows that few consistent trends in runoff are apparent in streamflow records from Oregon; instead, the direction and magnitude of change in streamflow varies by season, by basin size, and among ecoregions in Oregon. Second, observed streamflow trends (e.g., declining flows in summer, or

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in September) may be explained by factors that may not be directly related to global climate change. For example, recent low-flow years are attributable to low precipitation years (especially 2001 and 2005) and perhaps to interannual variations in snowpack associated with cyclical variation in ocean temperatures, while long-term decreases in summer flows are attributable to the combination of summer precipitation decline and increasing water withdrawals for consumptive use. Third, model projections do not account for possible resilience and adaptations in natural ecosystems that may alter water use and lead to smaller than expected changes in streamflow. More work is needed on vegetation responses to climate variability, the interactions between soil water and vegetation, and the relationship between streamflow and precipitation (runoff ratios) in large basins.

Water quality is also projected to change with rising air temperature and seasonal shifts in flow availability. Water temperature is projected to rise as air temperature increases in the 21<sup>st</sup> century, particularly in urban streams where natural riparian vegetation is typically lacking. A decline in summer stream flow will exacerbate water temperature increases, because the low volume of water will be heated up more quickly than during times with larger instream flows. Changes in water temperature can have significant implications for stream ecology and salmon habitat in many Oregon streams. Lower order streams in transient rain-snow basins and in semi-arid eastern Oregon will be the most vulnerable to rising summer air temperature and diminished low flow. Sediment and phosphorus loads are expected to increase in winter as winter flow is projected to rise. Conservation-oriented urban development could potentially reduce storm runoff amount and subsequent sediment and pollutant loads, providing potential opportunity for local adaptation to climate change. At the basin scale, new dam or reservoir operation rules might be required to maintain environmental flows in summer. The complex interactions among changing hydrology, watershed biogeochemistry, and land management need further investigation.

As shown in the Portland water consumption case study (Section 3.6), when other demand factors are held constant, increases in temperature alone result in higher demands for peak season water. While demand during winter months is expected to remain constant, research on urban water demand suggests temperature-induced water consumption, particularly among single family residential (SFR) households. These impacts are also evident at multiple scales, including the household, neighborhood, and region. At the regional scale, urban land uses have different water demands, and will have varying impacts on water demand. Overall, single-family residential land use is the largest consumer of water. At the neighborhood scale, the density of urban development helps predict future water use, where higher density residential developments have lower per capita water demand. Finally, at the household scale, a coupling of structural attributes (e.g., building and lot area) and temperatures affect water demand. High-density housing developments with smaller homes could limit the growth of residential water demand relative to other water uses in the region.

Uncertainty is still high in projecting future changes in runoff, water quality, and urban water demand in Oregon. While the main source of uncertainty stems from the choice of global circulation models, additional sources of uncertainty include GHG emission scenarios, downscaling methods, hydrologic model structure and parameterization, and impact assessment methods. Multi-ensemble models that take into account all sources of uncertainty

with different weights might provide a means of quantifying different sources of uncertainties. Communicating uncertainty to water resource decision makers is another challenge for adaptive water resource management in a changing climate. While a more sophisticated hydrologic impact assessment model is yet to be developed, climate adaptation strategies can be implemented at multiple spatial scales.

Land use planning may be helpful in meeting the future water needs of the State. Currently, land use and water resource management agencies have limited coordination in their responsibilities. Zoning and public involvement can be instrumental to improving the coordination between land and water management agencies. Zoning can be used to link types of future development that include a combination of infill, expansion, connecting existing developments, with explicit identification of water demands on different land uses in the region. To date, few plans have explicitly included dimensions of integrated land and water management. Outreach and education campaigns can help inform the public about the relationship between water demand and supply, but can also assist in adapting to a future with increasingly limited resources. The details of those plans and the precise nature of the outreach and education campaigns will require further investigation, and will likely be part of the second assessment of Oregon's water resources.

### 3.1 Introduction

The hydrology and water resources of Oregon are sensitive to changes in precipitation and temperature, but the rate of change varies across basins with different topographical, geological, and ecological characteristics. According to the Fourth Assessment Report (AR4), many Oregon streams will experience higher winter flow and reduced summer flows as temperature rises and the variability of precipitation increases. In addition, various human activities, especially land cover modification and dam or reservoir operations, have modified the hydrologic regime of many Oregon streams since the late 1800s. Understanding the complex interactions among climate systems, terrestrial systems, and human systems is essential to predicting future changes in water resources and implementing sustainable water resource management in Oregon.

For this first statewide climate impact assessment, we have both initiated some new research studies using downscaled climate change simulations, and compiled existing relevant studies, putting them into the context of climate change impact assessment. While most studies rely on empirical statistical data analysis using observed data, some case studies use downscaled global circulation model results combined with hydrologic simulation models for climate change impact assessment (e.g., Graves and Chang, 2007; Franczyk and Chang, 2009a; Chang et al., 2010a; Praskiewicz and Chang, 2011; Chang and Jung, 2010; Jung et al., in review). Others use synthetic climate change scenarios (e.g., Tague et al., 2008 and Tague and Grant, 2009). Based on these case studies and the best available information, we attempt to assess the current status of Oregon water resources and identify emerging water issues under the stress of climate change.

This chapter is composed of six main sections. Section 3.2 assesses observed variability and trends in various components of hydrology (e.g., snow water equivalent, glacier mass balance, extreme hydrologic events) in selected Oregon river basins. Section 3.2 assesses future changes in surface water hydrology including spatial and temporal variations of runoff, snow water equivalent and uncertainty in projecting future runoff. Section 3.3 describes future projections of surface water, methods of downscaling for hydrologic impact assessment, trends in future precipitation and temperature in the 21<sup>st</sup> century, and uncertainty associated with climate impact assessments. Section 3.4 examines potential changes in groundwater systems and their contribution to streamflow under future climate change scenarios. Section 3.5 investigates possible changes in water quality with a focus on water temperature and nutrients. Section 3.6 describes case studies of Portland and Hillsboro municipal water demand associated with climate variability. Section 3.7 discusses water infrastructure management, including urban water demand management and dam operation. The concluding section offers a concise summary of the main findings of this water resources impact assessment and discusses possible future research directions.

## 3.2. Observed Variability and Trends (Historic Perspective)

Streamflow in Oregon is highly variable in space, and over multiple time scales. It varies in space according to elevation, topography, geology, and basin area, and varies seasonally according to the amount of precipitation, relative proportions of rain and snow, topography, geology and vegetation. Streamflow also fluctuates on interannual time scales. Changes in snowpack accumulation and melt from climate warming are expected to influence streamflow, but these effects will be more pronounced where streamflow patterns are controlled by snowmelt. Glacial melt and retreat also may affect streamflow, but only in very small, high-elevation basins, and this effect will diminish as basin size increases. Streamflow also depends on the human-controlled factors of vegetation cover, urbanization, and river regulation (e.g. by dams); changes in these factors have significantly altered streamflow in the past century. Therefore, it is extremely challenging to disentangle long-term trends in streamflow from temporal variability. It is also easy to mistakenly attribute observed trends to climate, when they may be due to flow regulation (dams) or land use changes.

### 3.2.1 Annual and Seasonal Surface Flow and Variability

#### 3.2.1.1 *Water budget*

The water budget indicates the potential mechanisms and magnitude of various hypothesized streamflow changes in response to climate variability. The conceptual water budget for Oregon watersheds involves multiple components, including precipitation, cloudwater interception, canopy evaporation, transpiration, snow storage, and snowmelt. Climate change and variability potentially affect all these components.

#### 3.2.1.2 *Spatial patterns of annual runoff*

The spatial patterns of runoff in Oregon pose significant challenges for detecting climate change effects on historical streamflow. Most of Oregon is forested, strongly influencing runoff patterns through evapotranspiration, which may exceed 50% of precipitation. Precipitation is orographic, and highest in mountains and in western Oregon (see Chapter 1). Because precipitation is concentrated in mountainous areas and in western Oregon, large drainage basins in the eastern two-thirds of Oregon produce much less streamflow than the Willamette and coastal basins (see Figure 3.1 for major river basins in Oregon). Additionally, the lower Columbia, Willamette, and Oregon Coastal watersheds produce higher peak flows and water yields than the eastern Oregon watersheds, although they are partially covered by forests. The highest peakflows occur in southern and northern coastal Oregon, reflecting the high precipitation and steep drainages (see Figure 3.2).



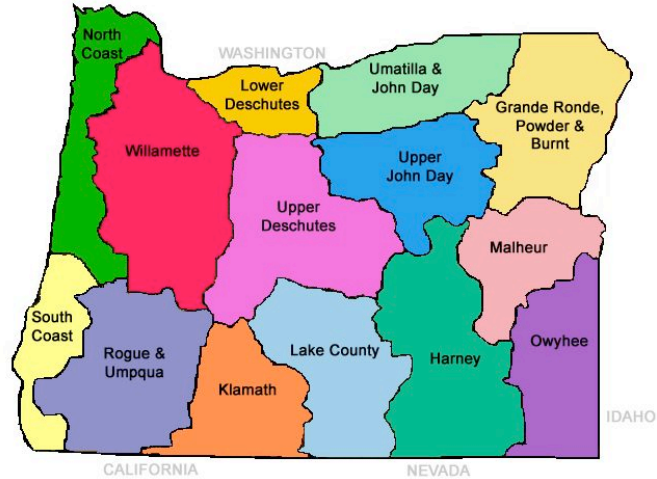


Figure 3.1 Major river basins in Oregon

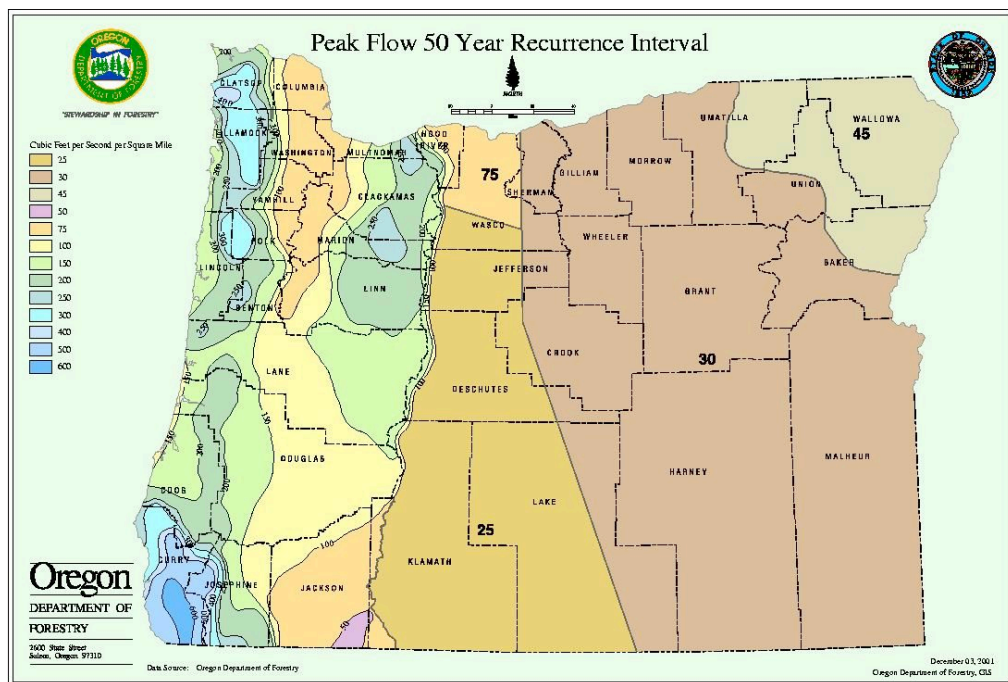
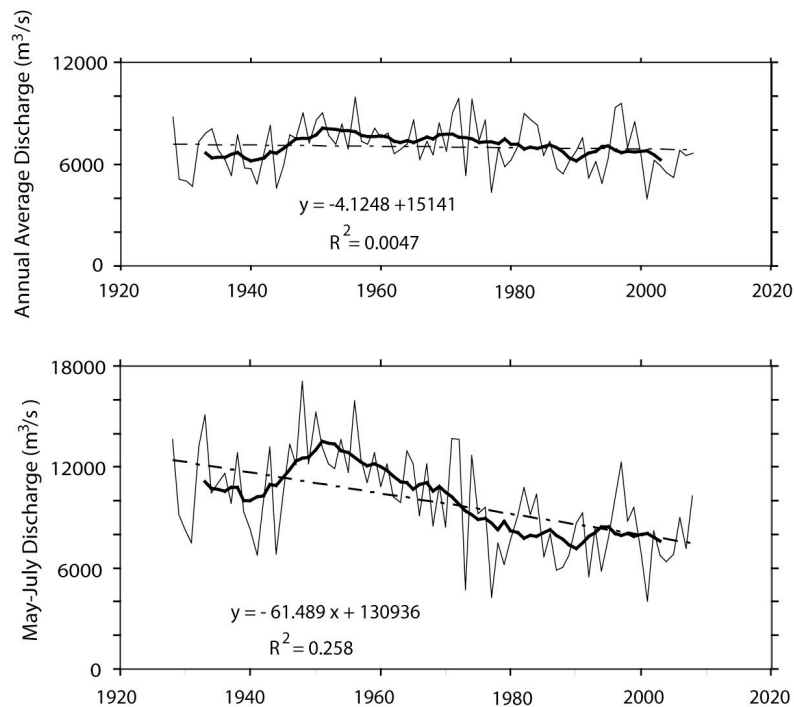


Figure 3.2 Peak flow 50 year recurrence interval (source: <http://www.odf.state.or.us/atlas/maps/peakfl75.jpg>).

The seasonal cycle of the Columbia River discharge has already been modified significantly by major dams and deliberate management: peak discharge formerly occurred in late spring, but now occurs in autumn (Sherwood et al., 1990). The annual average discharge shows large interannual variability and some interdecadal variability, but no significant long-term trend

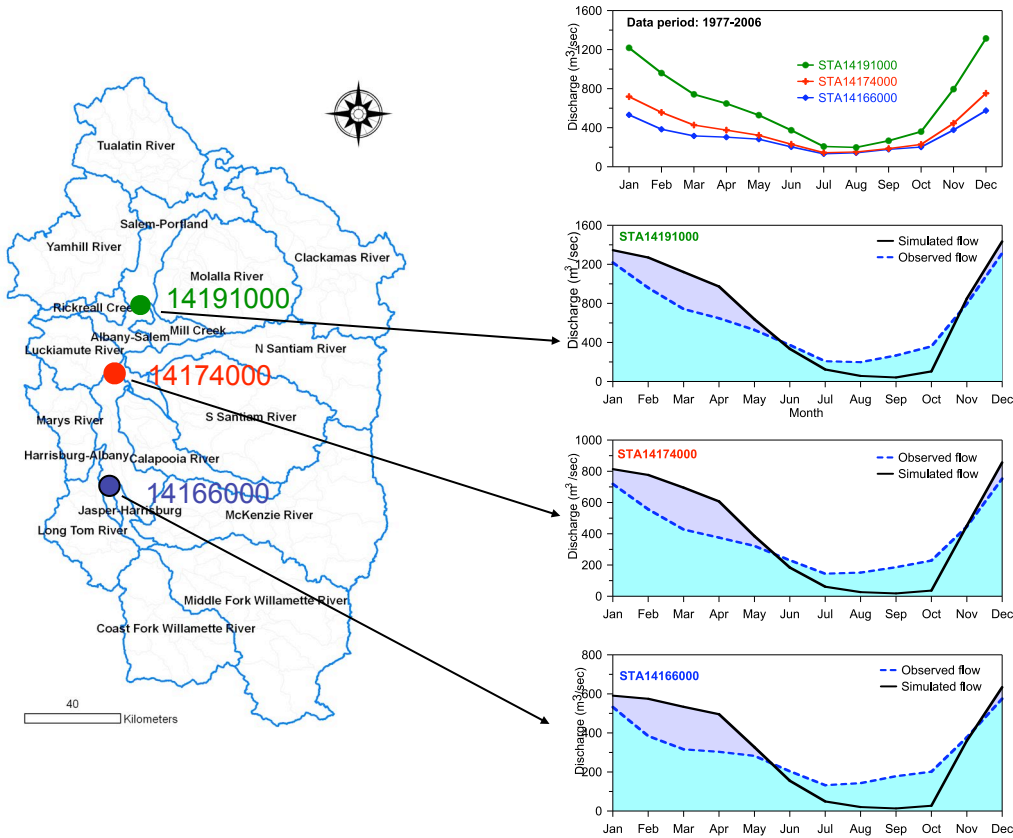
between 1928 and 2009 (Figure 3.3). In contrast, the average May-through-July discharge has decreased by about 30%; most of this decrease occurred between 1950 and 1990, as a result of management for flood control, irrigation and hydroelectric power. In recent years, concern for salmon smolt survival has led to increased spillage over the dams in spring and early summer; if this concern continues to prevail, the summer discharge might recover or at least stabilize.

Most populated areas occur in the lower reaches of large basins, but upstream dams and land use regulate streamflow at downstream gages. Basins above dams provide records that are unaffected by dams, but these watersheds are mostly in areas of low population density, and streamflow in these basins has been affected by forest harvest and other land use changes over the past century. The construction of dams for flood control and irrigation in the middle part of the 20<sup>th</sup> century throughout much of western Oregon greatly diminished peak discharges and altered the seasonal pattern of discharge in large basins, such as the Willamette River. A hydrologic simulation model of the natural flow regime (Figure 3.4) illustrates the impact of dams between 1977 and 2008 for three stations in the Willamette River: late summer flow is augmented by water released from dams.



**Figure 3.3** Annual average and May – July discharge in the lower Columbia River, 1928-2009

Forest harvest significantly and persistently increased winter and spring water yields in small watersheds of western Oregon (Jones and Post, 2004), and also altered peak discharges of at least small peaks, and (arguably) large peaks in small and intermediate basins (Jones and Grant, 1996, Thomas and Megahan, 1998, Beschta et al., 2000, Jones, 2000, Grant et al., 2008).



**Figure 3.4** Comparison of the observed flow and the PRMS simulated flow for the three monitoring stations in the Willamette River (Chang et al., 2009)

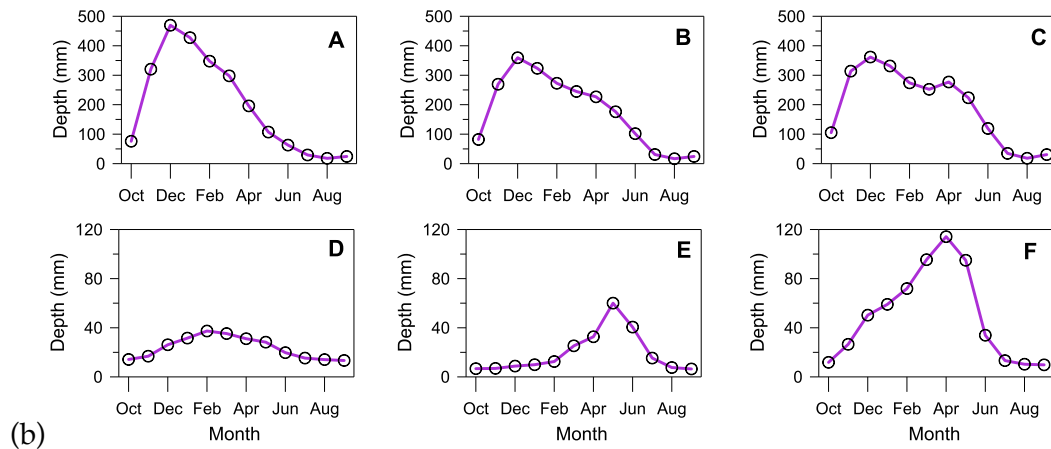
### 3.2.1.3 Temporal patterns of streamflow

Seasonal patterns of runoff vary across Oregon depending on precipitation type (rain vs. snow), basin size, topography, and geology. Runoff in Oregon is strongly seasonal: over 75% of streamflow occurs in the six months of October to April (Willamette River, John Day River, mean monthly discharge, Oct to Sep). In small basins on highly weathered old volcanic rocks in western Oregon streamflow varies even more by season. In contrast, streamflow from basins on recent, porous lavas of the High Cascades (e.g., Clear Creek) have low seasonal variability because deep groundwater augments summer low flows (Tague et al., 2008; Chang and Jung, 2010). In contrast, flow in the western Cascades (e.g., Lookout Creek), primarily fed by shallow subsurface flow, diminishes rapidly during dry summer season.



**Figure 3.5** Comparison of late summer streamflow in Clear Creek (groundwater fed) and Lookout Creek (shallow subsurface-fed). Photo credit: Chang.

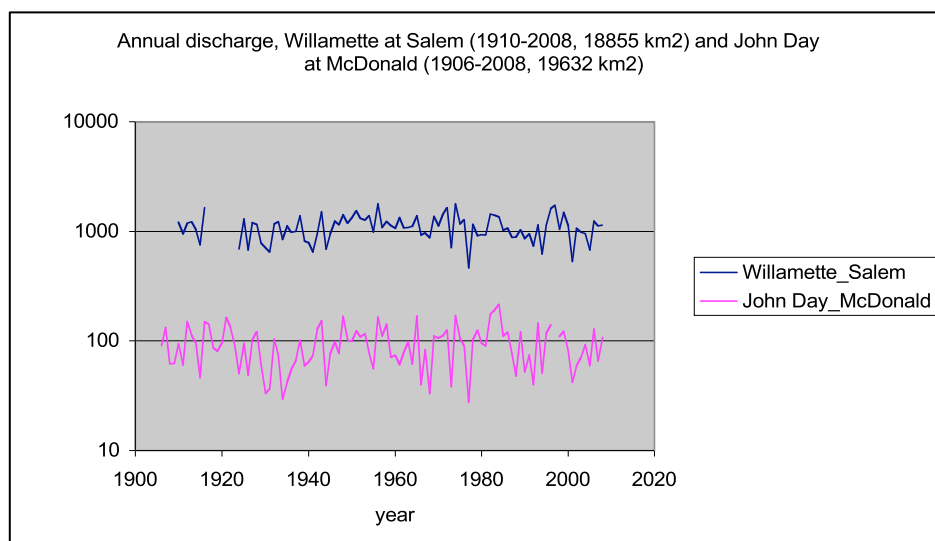
Figure 3.6 illustrates monthly hydrographs for six representative basins in Oregon. They are located in different hydrologic and ecoregions, which reflect different climate and vegetation regimes. Basins A (coastal basin) and B (Willamette Valley) are primarily fed by rainfall, while flow in basin C (Hood River) is contributed by a mix of rain and snowfall, and basins east of the Cascade Range (D, E, and F) are fed by snowmelt (Fig. 7a). Basins A and B have a rainfall-dominated peak in December, basin C has a rainfall-dominated peak in December and a snowmelt-dominated peak in April, and basins D, E, and F have a single snowmelt-dominated peak in late winter and spring (Figure 3.7b). Total annual runoff amounts in basins in eastern Oregon, which received much less precipitation, are much smaller than those in the Valley or coastal areas. Geology also controls the timing and amount of runoff in the Deschutes basin (Figure 3.7b-d).



**Figure 3.6** Monthly mean runoff for annual total runoff and the ratio of summer flow to annual flow (Source: Chang et al. in preparation). A = Wilson River near Tillamook; B = Little North Santiam River near Mehama; C = Blazed Alder Creek near Rhododendron; D = Warm Springs River near Kahneeta Hot Springs; E = Donner und Blitzen River near French Glen; F = Umatilla River above Meacham Creek near Gibbon.

### 3.2.2 Trends in annual and seasonal flow

Observed interannual trends in annual discharge in very large basins can be seen from 100-year records at the Willamette River (Salem) vs. John Day (McDonald). The lowest streamflow in 100 years of record was 1977 on both the west and east sides of the Oregon Cascades (Figure 3.7). The wettest years were in the early 1970s on the west side, and early 1980s (ENSO) on the east side. On the west side, 2001 and 2005 were among the six lowest-ranked streamflow years, but these were not unusually lowflow years on the east side.



**Figure 3.7** Annual discharge 1906 - 2008 on the west side (Willamette) and east side (John Day) of the Cascade Range in Oregon

Lins and Slack (1999) found decreases in streamflow in the Pacific Northwest streams, particularly in low flow regimes during the 20<sup>th</sup> century. Subsequent studies in the PNW also show declining streamflow trends (Hamlet et al., 2007; Stewart et al., 2004, 2005; Barnett et al., 2008). Similarly, Luce and Holden (2009) found significant decreases in the magnitudes of the lowest 25% of streamflow years over the period 1948-2005 in Idaho, Washington, and Oregon, and speculate that on the east side of the Cascades these declines may be due to declining precipitation. However, precipitation is not declining in the central western Cascades of Oregon (Jones, unpublished data from the Andrews Forest, and PRISM maps/ data from C. Daly). More work is needed to relate streamflow trends to precipitation in large basins.

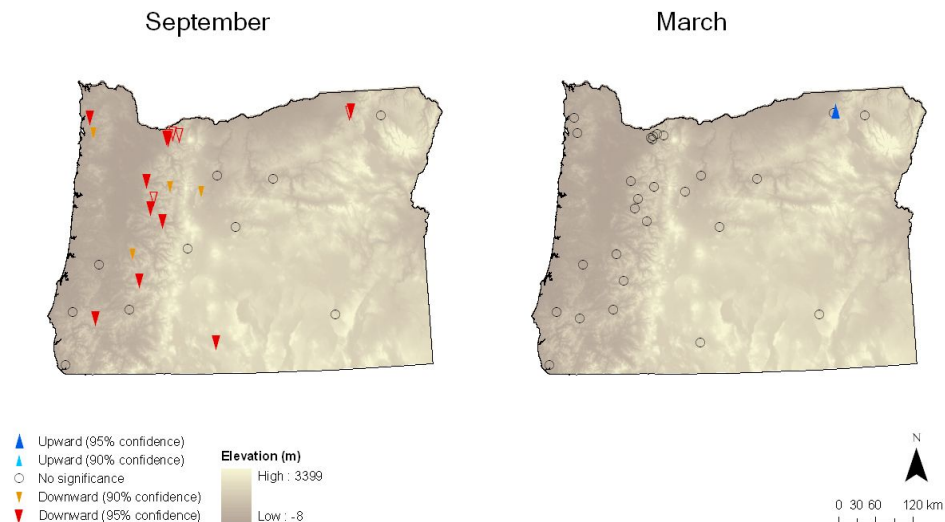
Warming air temperatures are expected to shorten snowpack duration and speed snowmelt timing, resulting in earlier peak annual streamflow. Based on a study of the western United States, Stewart et al., (2004, 2005) found that peak streamflow timing now comes one to four weeks earlier than it did in the the middle of the 20<sup>th</sup> century, and attribute this change to earlier spring snowmelt. However, the temporal center of mass of snowmelt-dominated streams in Oregon historically occurs in March, whereas the western basins most affected by warming are

those with peak streamflow in April to June. Oregon streams in this study mostly experienced shifts of <10 days, and most of these streams were in eastern and southeastern Oregon (Stewart et al., 2004, 2005).

To assess climate variability influences on streamflow in Oregon, we selected USGS and Oregon Department of Water Resources stream gauging stations that have more than 30 years of record and have not been affected by upstream dams or significant diversions. Thirty stations in Oregon meet such criteria and are analyzed for trends; 21 were analyzed for years 1958 - 2008, and 9 with shorter records were analyzed for years 1975 - 2008. The Mann-Kendall's test was used to detect the direction and significance of trend in each station. While summer flow declined in over two thirds of the stations during the study period, spring flow increased in one third of the study stations. Twenty-five stations exhibit declining trends in mean annual flow, while only 4 of the 25 stations show significant trends (Table 3.1) (Chang et al. in preparation). September flow declined significantly at most of the studied stations, while March flow increased significantly for only two stations (see Figure 3.8). Decreasing September precipitation appears to be responsible for the declines in September flow.

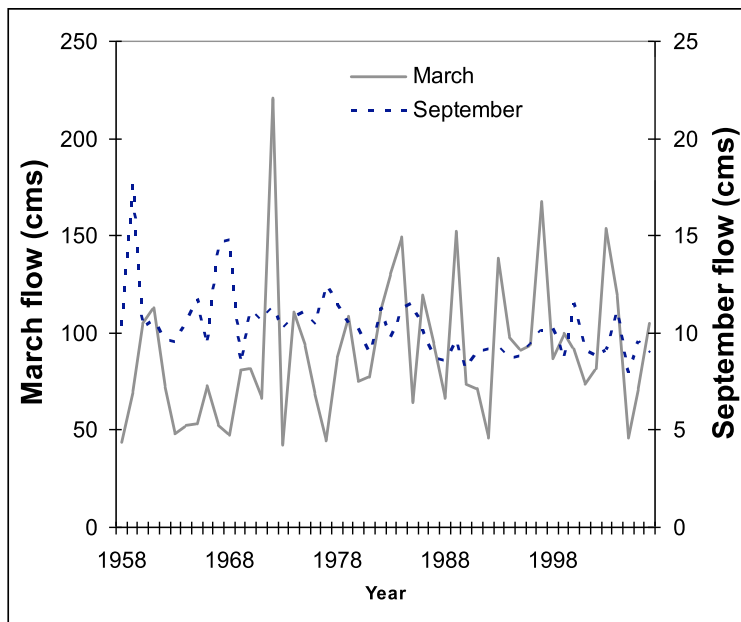
**Table 3.1.** The number of positive and negative trend stations for 30 stream gauging stations (21 with period 1958-2008, 9 with period 1975-2008). Numbers in parenthesis show statistically significant trend stations ( $P < 0.05$ ).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
+	9 (0)	1 (0)	14 (1)	17 (0)	7 (0)	11 (0)	6 (0)	4 (0)	3 (0)	4 (0)	7 (0)	13 (0)	5 (0)
-	21 (1)	29 (2)	16 (2)	13 (3)	23 (5)	19 (1)	24 (2)	26 (9)	27 (16)	26 (3)	23 (2)	17 (2)	25 (4)



**Figure 3.8** Trends in average runoff for March and September for 30 stream gauging stations. Numbers in parenthesis show statistically significant trend stations ( $P < 0.05$ ).

The Umatilla River above Meacham Creek (USGS station number 14020000) illustrates a case of increasing flows in early spring, and declining flows in September over the period 1958 and 2007 (see Figure 3.9). The increase in March streamflow may be due to earlier spring snowmelt. The interannual variability of September flow also declined during the study period.



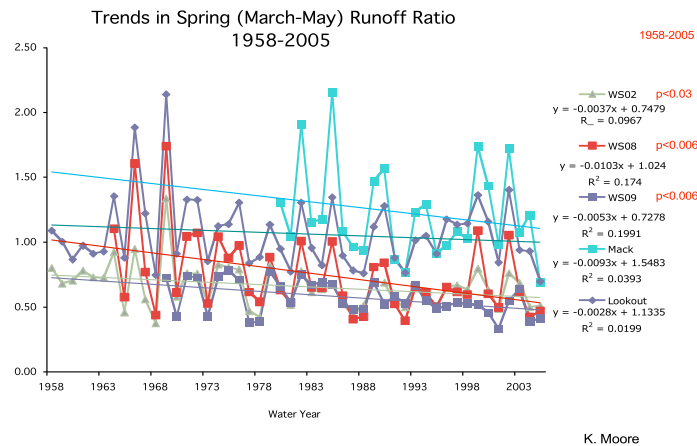
**Figure 3.9** Trends in March and September flow for Umatilla River above Meacham Creek, near Gibbon

In the Upper Klamath River basin, dry season (April to September) and summer streamflow (July to September) declined 16%, and 38%, respectively during the period between 1961-2009 (Mayer and Naman 2010). This decline is closely associated with decline in April 1<sup>st</sup> snowpack, which decreased approximately 40% during the same study period for snowcourse sites located below 1820 m elevation.

Streamflow trends vary according to the underlying geology and the importance of snow in the annual hydrograph. In the Cascade Range of western Oregon, Jefferson et al., (2006) found that relative streamflow in August (i.e., August streamflow as a proportion of annual flow) decreased significantly over the past century in two snow-dominated basins, but not in two rain-dominated basins. Basins draining the High Cascades (Clear Lake and McKenzie River) experienced significant declines in August streamflow from the early 1920s (McKenzie River) or early 1950s (Clear Lake). However, basins draining the highly-weathered western Cascades (South Santiam, Smith River) did not experience declines in relative streamflow in August over similar periods of record.

In small, undisturbed forested basins, runoff ratios and baseflow have declined significantly during spring, but they have not changed during summer or winter in the Andrews Experimental Forest in the Willamette basin, over the period 1952 - 2006 (Moore, 2010: Figure

3.10). These patterns suggest that declining spring streamflow is explained by increasing air temperatures and corresponding declines in snowpack accumulation and spring melt, as well as increased evapotranspiration from increased spring air temperatures. Corresponding increases in winter rain have not produced detectable increases in winter runoff in these small basins, either because the increase in rain is relatively small compared to interannual variability, or because warming temperatures have increased photosynthesis and transpiration in winter, mitigating any effect of increased ratio of winter rain to snow. Declining spring discharges also were not associated with declining summer discharges, either because the decline in spring runoff is not sufficiently large to influence summer soil moisture storage and runoff, or because dominant conifer trees are adapted to intra- and interannual variations in moisture availability and adjust transpiration accordingly (Moore, 2010).



**Figure 3.10** Declining spring runoff ratios from small, forested reference basins in the Andrews Forest, western Oregon.

In the Portland metropolitan area, there are no significant trends in annual mean flow between 1950 and 2000 regardless of urban development during the study period, suggesting that shift in climate regime may have masked the urban influence on hydrology, although urban streams show the flashiness and dryness (Chang 2007).

Overall, despite apparent increases in spring air temperatures and corresponding decreases in snowpacks, few consistent trends are apparent in long-term streamflow records.

### 3.2.3 Trend in Snow Water Equivalences

The timing of streamflow depends on snowpack size and the timing of melt in much of the western US, including many parts of Oregon. Annual precipitation in western Oregon is high (above 2500 mm in mountainous areas), but 70 - 80% of this precipitation occurs in winter (November to April). Hence, summer streamflows are dependent upon snowmelt. Therefore, climate warming effects on snowpacks may reduce streamflow during spring and summer periods, when water yield is limited.



Analysis of historic data show that warmer temperatures at higher elevations result in a shift in the form of precipitation toward more rain and less snow. Significant declines in snow water equivalent (SWE) in the Pacific Northwest and a shift from snow to rain coinciding with increases in temperature since the 1950s are well documented (Mote, 2003; Mote et al., 2005; Knowles et al., 2006), and this change has been related to trends in hydrologic response (Mayer and Naman, 2009).

Throughout the intermountain West, current analyses of projected climate change impacts predict that rising temperatures will diminish snowpacks, and these studies predict future summer water shortages (Folland et al., 2001; Service, 2004). Knowles and Cayan (2002) predict that the April to July fraction of total annual flow will be reduced by 30% in the Sierras by 2060 as a result of reduced snow accumulation and earlier melt. More recent climate simulations taking different greenhouse gas emission pathways into account predict future snowpack reductions of 30 – 90% (Hayhoe et al., 2004).

Snowpacks in the Pacific Northwest are expected to be particularly sensitive to warming. Climate models predict continued winter warming of 0.2 to 0.6°C per decade in the Pacific Northwest (Mote and Salathé 2010), and Cascade snowpacks are projected to be less than half of what they are today by 2050 (Leung et al., 2004). Lower elevations of the Cascade Ranges, for example, are predicted to exhibit the greatest differences in the timing and magnitude of snowmelt (Hayhoe et al., 2004; Payne et al., 2004). Because snow in much of the Cascades accumulates close to the melting point, future warming would mean that large areas could shift from a snow-dominated to a rain-dominated winter precipitation regime (Nolin and Daly, 2006), potentially increasing winter peak flows and reducing summer low flows as discussed above in Section 3.2.2.

In response to temperature increases in the Pacific Northwest (Cayan et al., 2001; Regonda et al., 2005), snowpacks in western North America have declined over the past 50 years (Mote et al., 2005). Using measurements of April 1 snow water equivalent (SWE) dating back to 1950, Mote et al. (2005) noted that the Pacific Northwest has experienced the largest declines in snowpacks in the western United States. A similar decline in April 1 snow water equivalent has been identified in the Clackamas River basin of Oregon between 1948 and 2000 (Graves and Chang, 2007). This change can be primarily attributed to an increase in winter temperatures (Mote, 2003; Mote et al. 2005; Barnett et al. 2008).

Some large portions of the mountains of Oregon may lose their snowpack, converting the hydrograph from a snowmelt to a rain-dominated pattern. Knowles et al. (2006) documented a significant trend towards increased rainfall and decreased snowfall (corrected for changes in precipitation) over the western United States from 1949-2004. The Pacific Northwest demonstrated a strong connection between Pacific Decadal Oscillation and temperature for days on which precipitation occurred. However, longer-term temperature trends also appear to be responsible for the shift from snowfall to rainfall. Most watersheds on the western slope of the Oregon Cascades encompass elevations that receive winter precipitation as a mixture of rain and snow. These watersheds have complex winter hydrographs that are dependent on the distribution of rain and snow during individual events, which in turn is controlled by storm temperatures and catchment hypsometry. Snow cover typically accumulates at temperatures

close to the melting point, and thus is at risk from climate warming because temperature affects both the rate of snowmelt and the phase of precipitation. With a projected 2°C winter warming by mid-century, 9200 km<sup>2</sup> of currently snow-covered area in the Pacific Northwest would receive winter rainfall instead (Nolin and Daly, 2006).

Regional climate models predict that Pacific Northwest summers will become hotter and drier over the next century (Christensen et al., 2007), exacerbating existing stresses. Tague et al. (2008) used a hydro-ecological model named RHESS to examine the influence of geology on Cascadian streamflow response to warming scenarios. Their model showed that warmer temperatures resulted in greater reductions in August discharge and annual minimum flows for the High Cascades than the Western Cascade watershed, both in terms of absolute volumes and normalized by drainage area. The Western Cascade streams, however, showed greater relative reductions in these summer streamflow metrics. Model results illustrate that differences between the responses of the two sites were primarily due to differences in groundwater flow, as manifested in drainage efficiency of the watersheds. Spatial differences in recharge characteristics and the timing of snow accumulation and melt were shown to be important, but secondary, in terms of explaining responses at the two sites.

#### **3.2.4 Trend in Glacier Mass Balance**

Glacier runoff contributions to streamflow provide critical water supply in many mountainous regions (e.g. Singh and Singh, 2001; Barnett et al., 2005). Historical records and future climate projections point to the loss of midlatitude glaciers throughout the world (Oerlemans, 2005; Lemke, 2007), resulting in significant changes to both total annual and summer streamflow downstream (Chen and Ohmura, 1990; Barnett et al., 2005; Hock et al., 2005; Juen et al., 2007). Glacier runoff supplies fresh water to numerous communities in throughout the world and is highly sensitive to changes in temperature (Chen and Ohmura, 1990). Warmer temperatures cause increased glacial melt but as glaciers recede, their potential contributions to water supplies are diminished (Barnett et al., 2005; Hock et al., 2005). Glaciers also moderate intra- and inter-annual flow variability by storing water in the form of ice during years of high precipitation and releasing melt water during seasons and years of high temperature (Fountain and Tangborn, 1985). The hydrologic properties of glaciated watersheds differ from glacier-free watersheds in several ways. Glaciers release an estimated two to ten times more water than neighboring catchments of equal area and altitudes in the United States (Mayo, 1984). Runoff variability in glaciated watersheds is controlled primarily by surface energy fluxes whereas runoff variability in glacier-free watersheds is dominated by precipitation patterns (Jansson et al., 2003). There is a lag effect caused by glacial storage and the delayed networking of englacial and subglacial conduits (Jansson et al., 2003) such that runoff from glacier melt is delayed until later in the summer, when other contributions to streamflow are much reduced. Glacier melt decreases streamflow variation, bolsters late season runoff, and is especially important in drought years (Fountain and Tangborn, 1985). Under negative mass balance conditions, glaciers discharge a greater volume of water than is input in the form of precipitation and this “excess discharge” can be substantial, even for watersheds having less than 15% glacier coverage (Lambrecht and Mayer, 2009).

In the northwestern United States, glaciers diminished throughout the 20<sup>th</sup> century and model simulations suggest this trend will continue through the next 100 years (Dyurgerov and Meier, 2000; Hall and Fagre, 2003). Recent studies document that Mount Hood's glaciers have decreased in length as much as 61% over the past century (Lillquist and Walker, 2006). Coe Glacier has diminished at a rate 27% slower than that of the Eliot in the last century (Jackson, 2007), and we estimate that by about 2057 its area will be about 61% of its present day area. On a regional basis, temperatures are expected to increase by a range of 1.1 – 6.4°C in the next 100 years (Lemke et al., 2007). Nolin et al. (in review) showed that for the Upper Middle Fork Hood River, 74% of late summer streamflow is derived directly from glacier melt, most of which goes to irrigation of high value crops in the Hood River Valley. Their model simulations indicate that, while increased temperature leads to more rapid glacier melt and therefore increased streamflow, glacier recession ultimately overcomes this effect, leading to substantial declines in streamflow. These results show that the disappearance of Mount Hood's glaciers will likely result in the loss of about 27% of total late summer discharge in the Upper Middle Fork Hood River.

Glaciers in Oregon, like much of the west (e.g., Nylén, 2004; Hoffman et al., 2007) have been receding since the start of the last century when observations first began (Lillquist and Walker, 2006; Jackson and Fountain, 2007). The glaciers rapidly retreated since about 1910, slowed and advanced during the 1960s to middle 1970s before retreating again in the early 1980s. Since the late 1990s glacier retreat has accelerated. Between 1900 and 2004, the glaciers in Oregon have lost about 40% of their area. Some glaciers have lost as much as 60%. No glaciers are advancing in Oregon. (details about glacier change in Oregon: <http://glaciers.research.pdx.edu/states/oregon.php>)

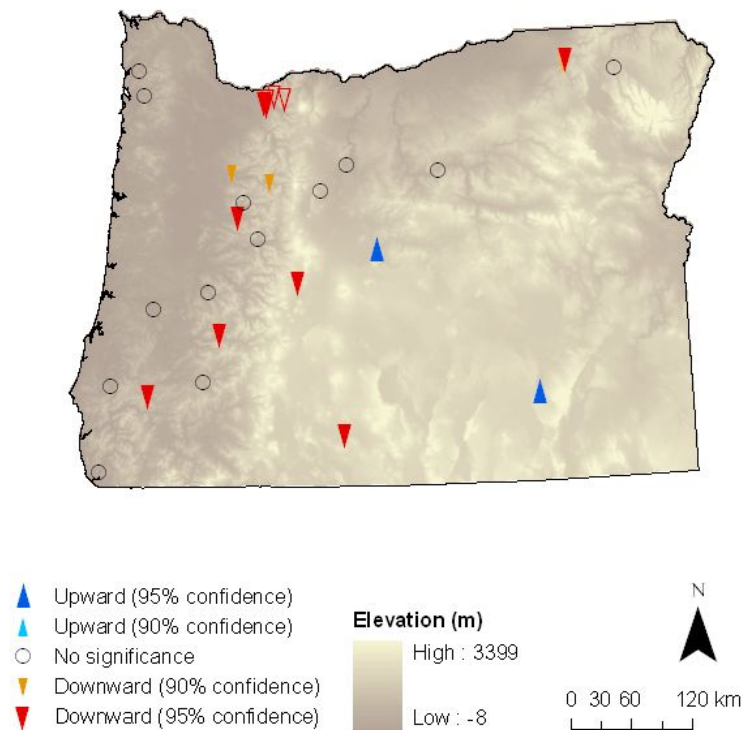
Generally speaking, glaciers respond to variations in snow accumulation which nourish the glacier and to variations in summer air temperatures which cause melt. No long term trends in precipitation exist but summer air temperatures have been warming. Consequently, the shrinkage of glaciers in Oregon is due to warming air temperatures (Jackson and Fountain, 2007). This supports other work regarding the thinning of seasonal snowpack in Oregon (Mote, et al., 2005; Nolin and Daly, 2006). We expect that as the climate continues to warm, the glaciers will continue to recede.

Glaciers are locally important contributors to water supplies, and their contributions are important for augmenting summer lowflows. However, the area of glacial cover is very small, and the proportion of total water yield in Oregon that originates from glaciers is extremely small.

### **3.2.5 Trend in Extreme Hydrologic Events**

In an analysis of climate change impacts for the State of Washington, Rosenberg et al. (2009a) found that peak flows and total annual precipitation have decreased over time while the magnitude of large, low frequency events of all durations has increased in some areas. In this study, trends in high flow (top 5% daily flow) and low flows (low 5% daily flow) were examined for the same 30 gaging stations in Oregon that were used in section 3.2.1. There are no significant trends in high flow for most of the stations examined (not shown). The average of the

driest 5% of years, however, decreased at 25 sites, and 12 of these trends were significant (see Figure 3.11). Seventeen out of the 21 sites with longer records showed decreases in the average of the driest 5% of years, and the M-K test showed that 9 of these negative trends were significant. Most of the stations that exhibit significant negative trends are located in high elevations, suggesting that diminishing spring snow covers and consequent low summer flows may explain the declines in low flows in those stations. However, increased water use by young forest plantations, which were established during the period of streamflow record in these basins, also may be a factor (e.g., Perry, 2007). Only two stations show a significant increase in low flow.



**Figure 3.11** Trends in the average flow for the driest 5% of years, with significance determined by the M-K test (Source: Chang et al., in preparation).

The largest peak flow events in Oregon are produced by rain-on-snow events, when warm rain and winds contribute to rapid snowmelt (Harr, 1981, 1986). The Cascade Range of Oregon produces the highest 1% of floods on record in >500 km<sup>2</sup> basins in the United States, because large storms produce sustained rainfall and sometimes snowmelt for multiple days over broad areas of mountain ranges (O'Connor and Costa, 2004). Changes in forest cover significantly and persistently increase peak discharges in forested basins upstream of dams in western Oregon, especially for small events (<1-yr return intervals), but also, arguably, of large events (>1-yr return periods) (Jones and Grant, 1996; Thomas and Megahan 1998; Jones, 2000; Beschta et al., 2000, Grant et al., 2008).

If extreme rain-on-snow events are sensitive to the area of simultaneous snowmelt, climate warming could have a range of effects on extreme floods. Hamlet and Lettenmaier (2007) speculated that a climate warming-induced reduction in snow-covered area could reduce flood risk, but an increase in the effective basin area contributing to runoff from rainfall could increase flood risk. Climate-warming effects on extreme rain-on-snow floods are likely to depend on changes in atmospheric circulation and air mass behavior. Extreme rain-on-snow events occur when a rare sequence of marine polar air masses is followed by marine tropical air masses, creating simultaneous melt in large snow-covered areas and producing large effective contributing areas and extreme floods.

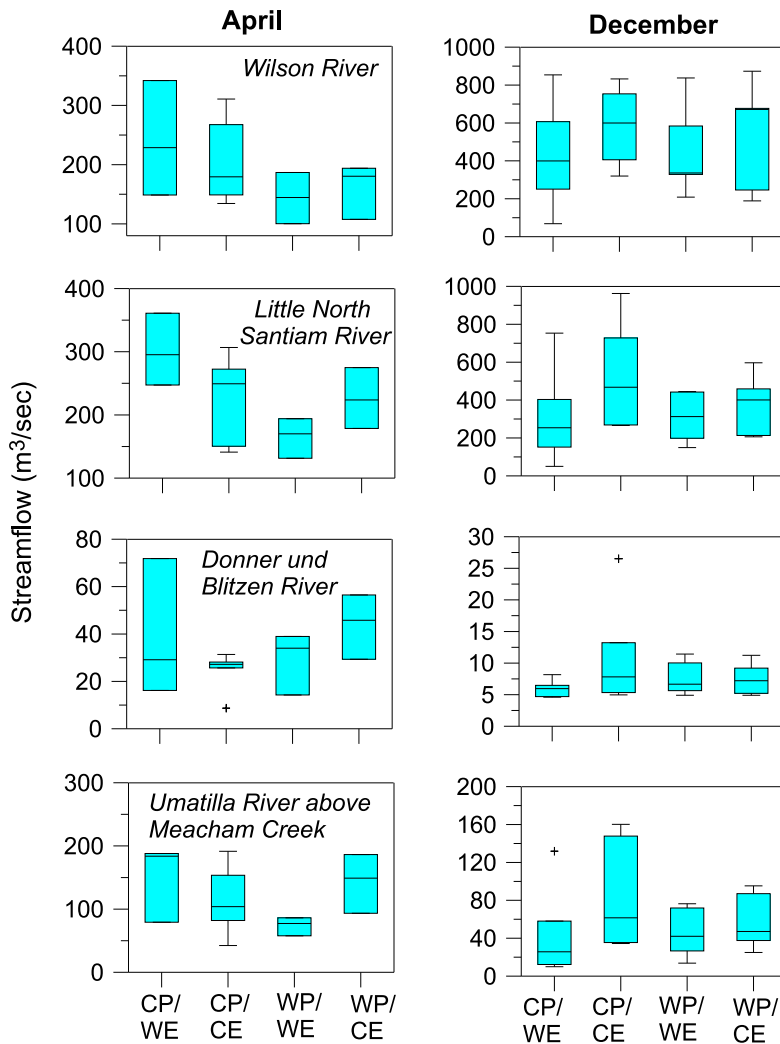
The probability of the sequence of events leading to an extreme rain-on-snow flood is already very low, and will only be affected by climate change if climate change alters (1) the occurrence of widespread snowpacks or (2) the energy of warm, wet tropical air masses.

### **3.2.6 Relation Between Climate Variability (ENSO & PDO) and Hydrology**

This seasonal variability of heavy rainfall has implications for the quantity and quality of water resources in the Willamette River Valley.

In the western Cascades of Oregon, winter air temperatures, April snowpack, and winter streamflow are strongly related to the Pacific Decadal Oscillation. Over the period 1958 - 2007, in years with positive PDO (warm ocean temperatures near the coast of Oregon), air temperatures were significantly higher than average, snowpacks were significantly lower than average, and winter streamflow was significantly lower than average (Jones, in preparation).

These relationships—lower than average December and April streamflow in years with warm ocean conditions (WP/EP) - also are apparent in streamflow from basins in the Willamette Valley (Figure 13). The relation between wintertime precipitation intensity, as measured by both simple intensity and number of heavy precipitation days per year, and climate variability as measured by different phases of ENSO and PDO, shows some mixed results for the eight stations in the Willamette basin between 1972 and 2006. While the relation between ENSO phase and precipitation intensity is generally negative in November and positive in April, the relation between PDO and intensity is generally negative and strongest in January and March. These varying seasonal associations with ENSO/PDO phase may be associated with the Willamette Valley's location in the transitional zone between positive and negative El Niño response and to the moderating effects of out-of-phase ENSO/PDO (Praskievicz and Chang, 2009a). Figure 3.12, illustrates the relation between different phases of ENSO/PDO and streamflow variability in April and December for four stations (A, B, D, F) shown in previous Figure 3.6. As shown in this Figure, December streamflow is high during the cool phase of PDO and La Niña years. In April, three sites show lowest median flow during the warm phase of PDO and El Niño years.



**Figure 3.12** Differences in April and December streamflow among four combinations of warm and cold PDO/ENSO phases for 4 USGS stations. Box and whiskers represent all years in category. CP/WE = cold PDO and warm ENSO; CP/CE = cold PDO and cold ENSO; WP/WE = warm PDO and warm ENSO; WP/CE = warm PDO and cold ENSO.

### 3.2.6 Climate Variability and Water Resources

The overall effect of climate variability on water resources in Oregon depends on hydrologic mechanisms operating at multiple spatial and temporal scales (snow water storage and melt, evapotranspiration). Three aspects of Oregon geography and hydrology will critically determine whether climate change effects exceed interannual variability of climate: (1) the extent of basin area affected by changes in snow water storage and snowmelt, which is associated with basin size, topography, and geology, (2) ecosystem adaptation and resilience to climate variability and trends, and (3) the relative magnitude and rate of climate-induced changes compared to historical effects of anthropogenic activities, such as dams and land use change on the magnitude and timing of streamflow.

In general, we expect the following.

- Climate change effects on streamflow will be largest close to melting glaciers or in seasonal snow zones, and decline in increasingly large basins as the snow-affected zone decreases as a proportion of contributing area.
- Climate change effects may be mitigated by ecosystem adaptations to climate variability, such as increased water uptake by vegetation during winter, which could offset predicted increases in rain:snow and winter discharge, and decreased water uptake by vegetation during summer, which could offset predicted declines in summer discharge.
- Historical effects of land use change (forest harvest, forest expansion after fire suppression) and dam management (winter water storage and summer releases) may be larger than as-yet-observed streamflow responses to climate change.

These issues will be discussed in more detail in section 3.3.

### **3.3. Projected Future Changes in Surface Water Hydrology**

Future changes in surface water hydrology will depend on a range of factors. Hydrologic and climate models have been used to explore a range of possible outcomes from expected climate changes. Most of the model efforts have focused on the first three of these four hypothesized mechanisms for streamflow response to climate change.

- Increased air temperatures lead to decreases in the ratio of snow to rain, which decreases snow water equivalent (water stored in snowpacks), which decreases the snowmelt contribution to runoff in the spring;
- Decreased spring runoff carries over into summer, leading to decreased summer streamflows;
- Increased air temperatures decrease the ratio of snow to rain, which increases winter streamflow; and
- Increased air temperatures increase evapotranspiration and decrease spring and summer streamflow.

The overall effect of these mechanisms on water resources depends on (1) the extent of basin area affected by changes in snow water storage and snowmelt, (2) ecosystem adaptation and resilience to climate variability and trends, and (3) the relative magnitude of climate-induced changes compared to historical effects of dams and land use change on streamflow.

Future changes in climate factors that will affect streamflow include changes in peak flows, summer low flows, and seasonal water yield. These future changes will depend on future precipitation (not predicted to change much) and future temperature and its effects on snow storage and ET. Future temperatures are expected to reduce snow-covered area in much of Oregon, especially in the forested mountains. Reductions in snowpack are expected to increase winter flows (higher rain:snow) and reduce water delivery in spring and summer. However, these streamflow changes will also depend on forest vegetation response to future warming. For example, if future warming increases photosynthesis and respiration in the winter, that may offset some of the expected future increases in winter water yield and peak flows. Also, if future warming and reduced summer streamflows enhance hydrologic drought, drought-adapted conifers may be able to compensate by reducing ET, which in turn may offset some of the expected future declines in summer lowflows. Such changes in flow regime will have significant economic impacts for basin-wide water uses (Franczyk and Chang, 2007). Future changes in runoff will also be affected by land use changes, which should be factored into future climate change impact studies (Praskievicz and Chang, 2009b). The spatial variability of the current water use patterns could then be factored into adaptive water resource management in a changing climate (Franczyk and Chang, 2009).

A variety of studies have developed quantitative estimates of the expected future impacts on surface water hydrology associated with climate change for hydrologic systems in the Western US. The hydrological response to projected future shifts in climate conditions has been described in parts of northwestern Oregon by Graves and Chang (2007) and Franczyk and Chang (2009a). Context: “by Graves and Chang (2007) and Franczyk and Chang (2009) in the Oregon Cascades by Tague et al. (2008) and Tague and Grant (2009), and in California by Dettinger et al. (2004), Hanson and Dettinger (2005), and Dettinger and Earman (2007a). All of these studies show that the general hydrologic response to warming and the resulting reduction in the ratio of snow to rain will be increased winter runoff, earlier snow melt, and diminished spring and summer runoff. An analysis of the hydrologic response to climate change in the upper Deschutes Basin based on ensemble GCM predictions coupled to hydrologic models shows similar changes in runoff (Waibel et al., 2009)

This chapter summarizes key findings of the available literature and suggests research directions that may serve to increase the capacity to adapt to changing future conditions in Oregon.

### **3.3.1 Changes in snow water equivalent**

Hydrologic systems in Oregon are relatively sensitive to changing climate, in large part because of the presence of seasonal snowpack. The snowpack develops in the mountains each winter, storing water through the period, and releasing it during spring, as air temperatures increase. This spring melt is channeled through a system of storage reservoirs, which are operated to both reduce downstream flooding and to provide water supply across much of the state over the relatively dry summer months. The amount of water stored as snow and the timing of melt depend very directly on spring air temperatures. As outlined earlier in this report, a wide variety of research has evaluated trends in historic snowpack data, with an emerging consensus



that the snowpack throughout the West has experienced measureable declines over the period for which measurements are available.

The trajectory with which these observed changes will continue into the future is of particular interest to managers and stakeholders, particularly in light of the projected increases in air temperatures which have consistently arisen from global climate change research. The impact of projected future climate on freshwater resources is most frequently evaluated through the use of modeling. While results from these modeling-based impact studies vary depending upon the particular area of study and the study methods, a number of common themes emerge from studies developed in snowmelt dominated systems in the western US. The most significant result is that the warm snowpack that exists throughout the Washington and Oregon Cascade mountains is particularly vulnerable to commonly projected increases in winter temperatures. Peak stream flow volumes, which characterize snowmelt peaks in snow-dominated watersheds, are commonly used to summarize and assess the snowpack dynamics.

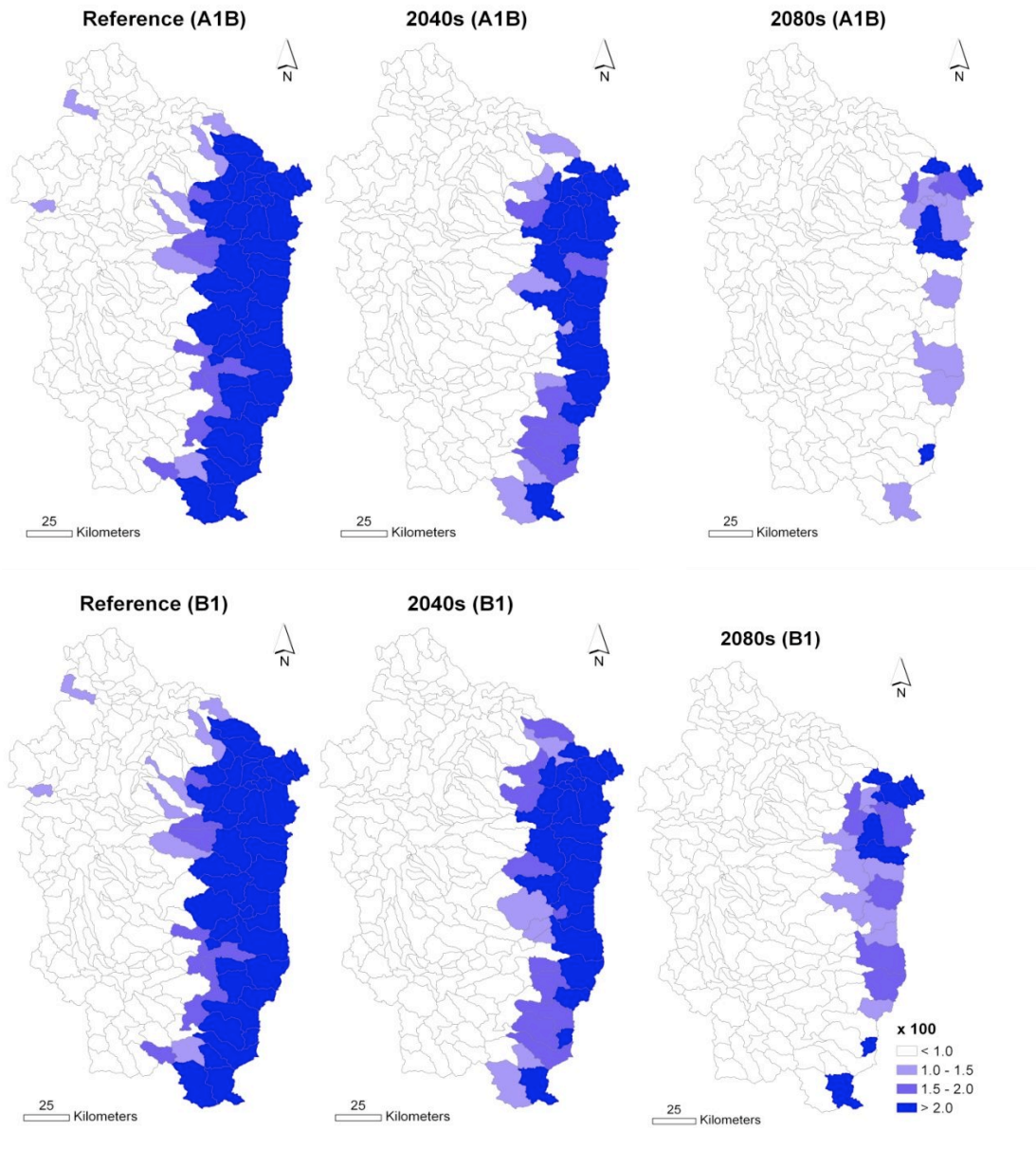
In one such study, Stewart et al. (2004) evaluated changes in the timing of peakflows under Business as Usual (BAU) emissions using PCM (Parallel Climate Model) and the VIC (Variable Infiltration Capacity) model of hydrology. They focused on the centroid of yearly stream flow as an indicator of snowmelt, and consistently projected statistically significant earlier peak runoff values in Washington. Supporting this work, Barnett et al. (2005) suggest that in the snowmelt dominated regions of the Western US, spring peak streamflows are likely to consistently occur up to a month earlier by 2050. Using PCM and a BAU scenario, Dettinger et al. (2004) employed the PRMS hydrologic model to provide more direct estimates of the future snowpack. They found that for the American River basin, in California, the average April 1 snowpack will approach 15 percent of historical values at the end of the 21<sup>st</sup> century. More recent modeling work by Elsner et al. (2010) also supports the notion of continuing snowpack decreases, in this case in Washington, suggesting statewide decreases in April 1 snow pack of 27 - 29% by 2020,

37 - 44% by 2040 and up to a 65% decrease by 2080. They focus on two emissions scenarios and used both the VIC and DHSVM (Distributed Hydrology Soil Vegetation Model) hydrological models.

In the Willamette River basin, the ratio of April 1<sup>st</sup> SWE to Precipitation (SWE/P) declined substantially from the reference period of 1970-1999 under two GHG emission scenarios with a greater reduction in the 2080s. The decline in the ratio is most pronounced under the high emission A1B scenario (see Figure 3.13). This is a combined result of increase in precipitation falling as rainfall in winter and earlier snowmelt caused by rising temperature. Snowmelt, estimated by the PRMS model, was projected to decrease gradually over time. For example, models of the upper Mckenzie River sub-basins indicate a decrease in snowmelt of up to -52% for the 2040s and up to -78% for the 2080s relative to the reference period, 1960 - 1989 (Chang and Jung, 2010).

### **3.3.2 Spatial and Temporal Variations of Changes in Runoff**

Available research consistently projects reductions in winter snowpack in the Northwest US, as well as earlier runoff in snowmelt dominated basins, yet many regions in this area do not develop a winter snowpack and are rainfall dominated. While many of these lower elevation basins are influenced by higher elevation, snowmelt dominated areas, the runoff response is characterized by a wider range of variables, including potential changes in precipitation and groundwater contributions.

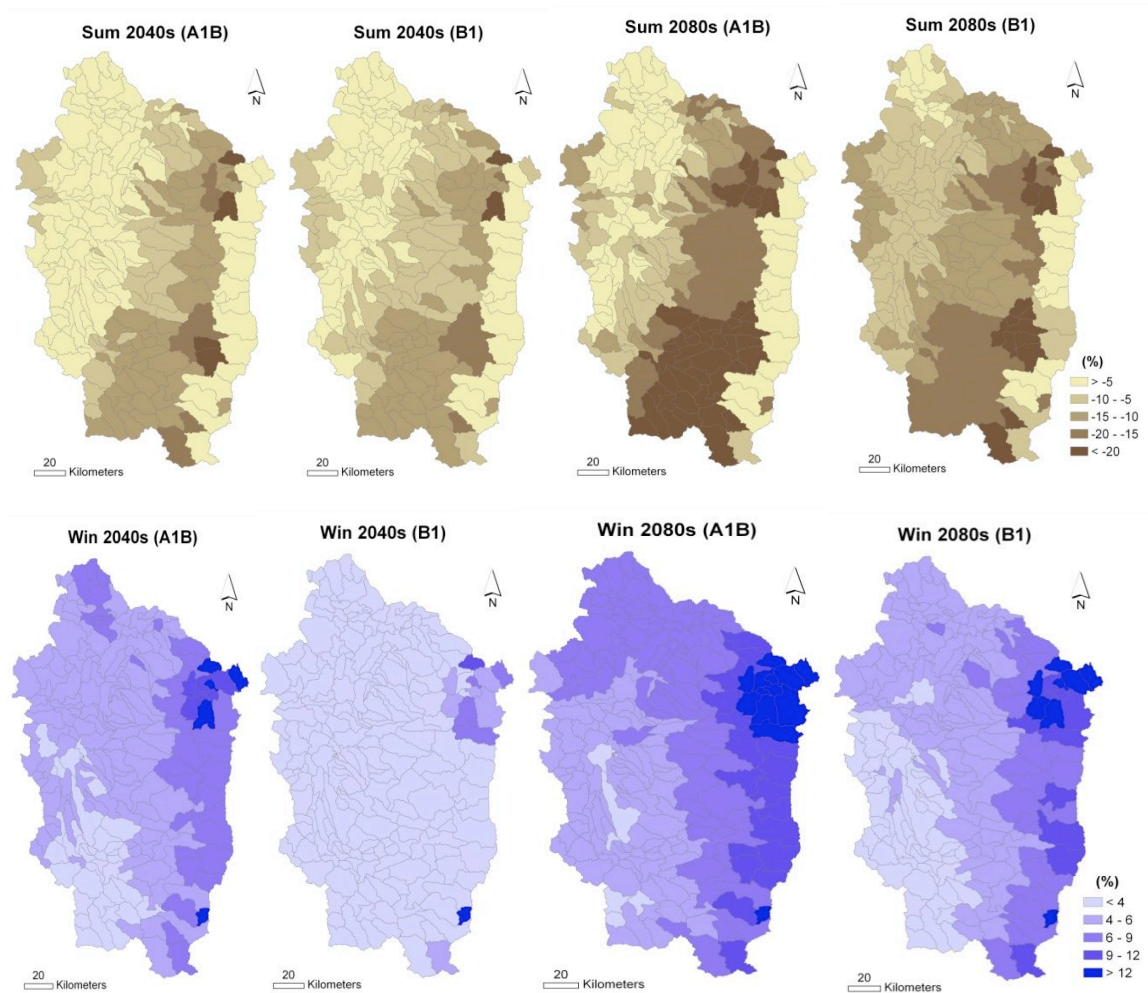


**Figure 3.13** Ensemble mean changes (averaged over eight GCMs) in SWE/P in the Willamette River basin for reference, the 2040s, and the 2080s by GHG emission scenario. The ratio is multiplied by 100 for representation, Source: Chang and Jung 2010.

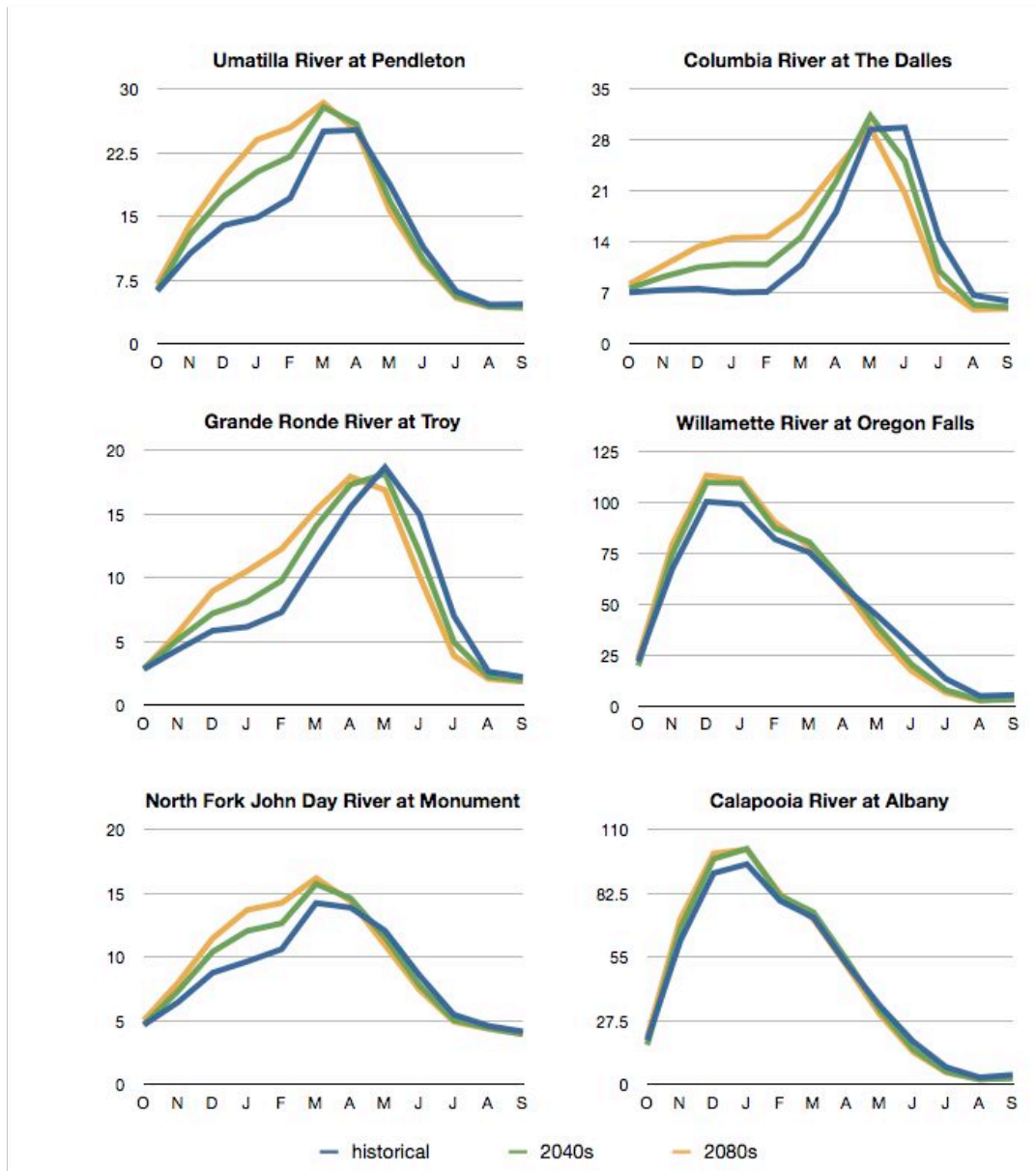
As the seasonal distribution of precipitation changes and temperature rises, watershed hydrology is likely to be modified at multiple spatial and temporal scales. Latitude and

elevation control the sensitivity of particular regions to a changing climate, primarily because of the strong relationship between these factors and the presence of winter snowpack. While seasonal runoff will be more affected by increases in temperature in snow-melt dominated basins (Graves and Chang, 2007), in rainfall-dominated basins it will be more affected by changes in precipitation (Franczyk and Chang, 2009a).

In the Willamette River basin, the complex topography and geology also partially control the sensitivity of each sub-basin response to changes in climate. In the Western Cascades, snow-water equivalent is predicted to decline and peak runoff is predicted to occur earlier by the 2080s. In the High Cascades, with relatively gentle slope and young volcanic rocks, summer runoff may be sustained by existing large groundwater reservoirs (Tague and Grant, 2009; Jefferson et al., 2006). However, the uncertainty of projected future runoff is high, particularly for the High Cascade basins where groundwater is a big component of the seasonal water cycle (Chang and Jung, 2010).



**Figure 3.14** Ensemble mean changes in summer runoff (upper panel) and winter runoff (lower panel) for the 2040s and the 2080s by each emission scenario (Source: Chang and Jung, 2010).



**Figure 3.15** Hydrographs of combined flow for selected locations in Oregon using VIC outputs (hybrid delta, ensemble mean of 10 GCMs, A1B scenario) credit Hamlet et al, 2010, Climate Impacts Group, [www.hydro.washington.edu/2860](http://www.hydro.washington.edu/2860).

The University of Washington Climate Impacts Group produced 297 hydrologic scenarios for the Columbia River Basin using the Variable Infiltration Capacity (VIC) model. For this assessment, combined flows were downloaded from the website for the A1B scenario for the historical period, the 2040s and the 2080s. Combined flow is average total runoff and baseflow as an average depth (mm). These hydrographs are constructed using an ensemble average of 10 GCMs that were downscaled using the hybrid delta method. To read more about the project,

downscaling techniques, and to download the data, visit the project website at <http://www.hydro.washington.edu/2860/>.

The six Oregon sites used for this assessment were selected based on two factors: their spatial distribution and their Nash-Sutcliffe efficiency. An effort was made to select sites that were distributed well across the larger Columbia River Basin and the state. Additionally, each site selected for this assessment had a Nash-Sutcliffe efficiency of 0.5 or greater. Nash-Sutcliffe efficiency is used to determine the predictive capabilities of a hydrologic model. The coefficient is a number between 0 and 1. The closer to 1 that the coefficient is, the better the model is at simulating flows. For applications such as these, a N-S efficiency of 0.5 is considered good.

Each hydrograph shows, with varying degrees of magnitude, a shift in streamflow largely consistent with climate projections. In snowmelt-dominated sites such as the Columbia River at the Dalles and the Grande Ronde River at Troy, flows are projected to increase in the winter months and decrease in the summer months through the 21st century. Peak flow shifts earlier into the spring at both sites in this scenario. At sites where the peak flows occur in the wetter winter months (Willamette and Calapooia), flows are projected to increase in the winter and decrease slightly in the summer. Both the Umatilla and North Fork John Day River project a significant increase in winter flows, but only a slight decline in summer flow. Diminished summer flows have implications for many sectors including agriculture, water resources and recreation, among others.

While changes in winter runoff volume and timing are commonly reported as potential impacts of projected temperatures, increased variation in hydrological response is also a potential response. Hamlet and Lettenmaier (2007) simulated runoff response and flood risk to explore impacts of documented (Mote et al., 2005) 20<sup>th</sup> century temperature increases. They used the VIC hydrological model and while they note significant variability in the flooding response, the results suggest that much of this variability can be constrained by regional differences in midwinter temperatures. In cold areas with a winter snowpack, flood risks have decreased, and in warm rainfall-dominated areas, flood risk appears to have significantly increased. Mote et al. (2003) also project an increased volume and earlier peak of winter runoff due to a lack of snowpack storage and an increase in rainfall (as opposed to snowfall), and also predict decreases in summertime low flows. They attribute the decreases in low flows directly to the lack of projected spring snowmelt peak. While changes in peak flows have significant implications, the associated changes in low flows are of potentially greater consequence in that water use is at a maximum during the summer period, while at the same time water availability is, even in the coolest years, at a minimum. The balance between these two quantities is more fully explored in other sections of the report, and we note here that it is an important component in the distribution runoff pathways, and that modifications to it may have potentially far-reaching effects.

While there are no significant trends in winter precipitation intensity in the Willamette River basin since 1972 (Praskievicz and Chang, 2009a), according to the IPCC fourth assessment report, climate change is likely to bring more extreme hydrologic events such as floods and droughts in the region. Urban areas are particularly vulnerable to these changes as impervious areas do not efficiently absorb storm water and infrastructure is densely concentrated (Chang

and Franczyk, 2008). A case study of Portland shows that climate change will bring more frequent storm events with a return period of less than 25 years, which means that nuisance flooding is likely to become more common at road cross-sections that have a history of chronic flooding (Chang et al., 2010a).

It is also important to recognize that these examples focus on basins in the Willamette River where precipitation is relatively abundant. In other regions of the state, different processes control the response (rainfall dominance, groundwater contributions, semi-arid hydrology, etc). Additionally, changes in water use by vegetation along with management-based adaptation strategies would also be important features of any future impacts work. An impact assessment for the state would need to be significantly broadened in scope to capture the large degree of hydrologic variability and possible secondary responses to climate change from vegetation and management expressed statewide.

### **3.3.3 Interactions Between Climate and Land Surface Hydrology**

The interactions between climate system and land surface hydrology are rather complex in the Willamette River basin. While elevation is a primary control of basin runoff, other basin characteristics such as geology and topography also affect basin runoff. Elevation is an important determinant of change in basin runoff because it affects the amount of precipitation falling as snow in winter and the snowmelt rate in spring. While winter runoff change is more sensitive to changes in winter temperature than winter precipitation in high elevations, the relative influence of winter temperature declines with elevation, and winter precipitation becomes more important in projecting future winter runoff in low elevations (< 1000m). This is associated with whether the basin runoff generation is dominated by either rainfall or snowmelt, suggesting that the elevation threshold may be associated with other basin characteristics such as geology. Geology could buffer the sub-basin hydrological response to climate change. Basins in the High Cascade Range with significant groundwater exchange may be less sensitive to changes in climate than those in the Western Cascade Range in the near term 2040s (less than 10% reduction in summer runoff) (Chang and Jung, 2010).

### **3.3.4 Uncertainty in Projecting Future Runoff**

Uncertainty is an inherent component of projections related to future runoff. It is an additive property of the modeled system, with each individual component contributing to the overall predictive uncertainty of the system, and as such the degree of uncertainty associated with each model component should be evaluated as a mechanism to communicate confidence in projected results. There are several sources of uncertainties in climate change impact studies. The GCM structural uncertainty is the main source of uncertainty as recognized in several studies (Praskievicz and Chang, 2009b; Graham et al., 2007). Although many investigations have shown that the highest uncertainty is attributed to the GCM's structure, the other sources are not negligible (Wilby et al., 2005; 2006; Wood et al., 2004). Other uncertainty sources include the emission scenarios, the downscaling methods, the hydrologic model structure and the hydrologic model parameters.

The importance of each source of uncertainty depends on hydrologic characteristic of the basin under study (Kay et al., 2009; Prudhomme, 2007). For example, two sub-basins of the Willamette watershed, one rain-snow dominated and one rain-dominated, showed different sensitivities to uncertainty. The snow-dominated basin was more influenced by uncertainty in hydrologic parameterization than the rain-dominated basin, although climate model uncertainty was still the main source of uncertainty in both basins (Chang and Jung, 2010).

To date, many hydrologic models have been used to project the possible consequences of the climate change on streamflow, ranging from simple conceptual lumped models to comprehensive physically-based distributed models – e.g. NWSRFS (Nash, 1991), WatBal (Yates, 1996), macro-scale hydrological model (Arnell, 1999), VIC (Lettenmaier, 1999), MODFLOW (Kirshen, 2002), CATCHMOD (Wilby et al., 2005), PDM (Kay et al., 2009) and PRMS (Jung and Chang, 2010) among others. Most of the hydrological models show reliable and accurate results under historical climate conditions (natural variability). However, they have often projected mixed results in runoff change even under identical climate change conditions. This could be attributed to differences in the models' structures (Bae, 2009; Bloeschl and Montanari, 2010; Kay et al., 2009; Wilby et al., 2006). Bae et al. (2010) employ three semi-distributed models to investigate uncertainty resulting from hydrologic model selection; they conduct their study using 13 GCMs simulations with 3 emission scenarios. They conclude that monthly and seasonal runoff change simulated by a single hydrological model is within  $\pm 10\%$  difference from those of a multi-model ensemble except in the low flow season.

Elsner et al. (2010) acknowledge the need to evaluate the uncertainty around model-derived hydrologic projections. While they do not provide estimates of predictive uncertainty, a sensitivity analysis using simulated runoff to estimate precipitation elasticity, or the fractional change in runoff as compared with a fractional change in precipitation, is developed. They also calculate modeled temperature sensitivity as the percent change in projected runoff for a 1 degree increase in temperature. The sensitivities are estimated for 12 different basins in Washington and represent 2 different hydrologic models. The results indicate low sensitivity across this range of simulations, providing additional quantitative evidence that the uncertainty of climatic projections dominates the overall uncertainty of impact projections.

Hawkins and Sutton (2009) state that the uncertainty in regional climate predictions varies with time but there is no constant positive trend because emission scenario uncertainty increases over time but GCM and internal variability uncertainties decrease. Also, the uncertainties vary across the seasons. In the summer, small changes in flow are much more significant than they would be in the high-flow wet season.

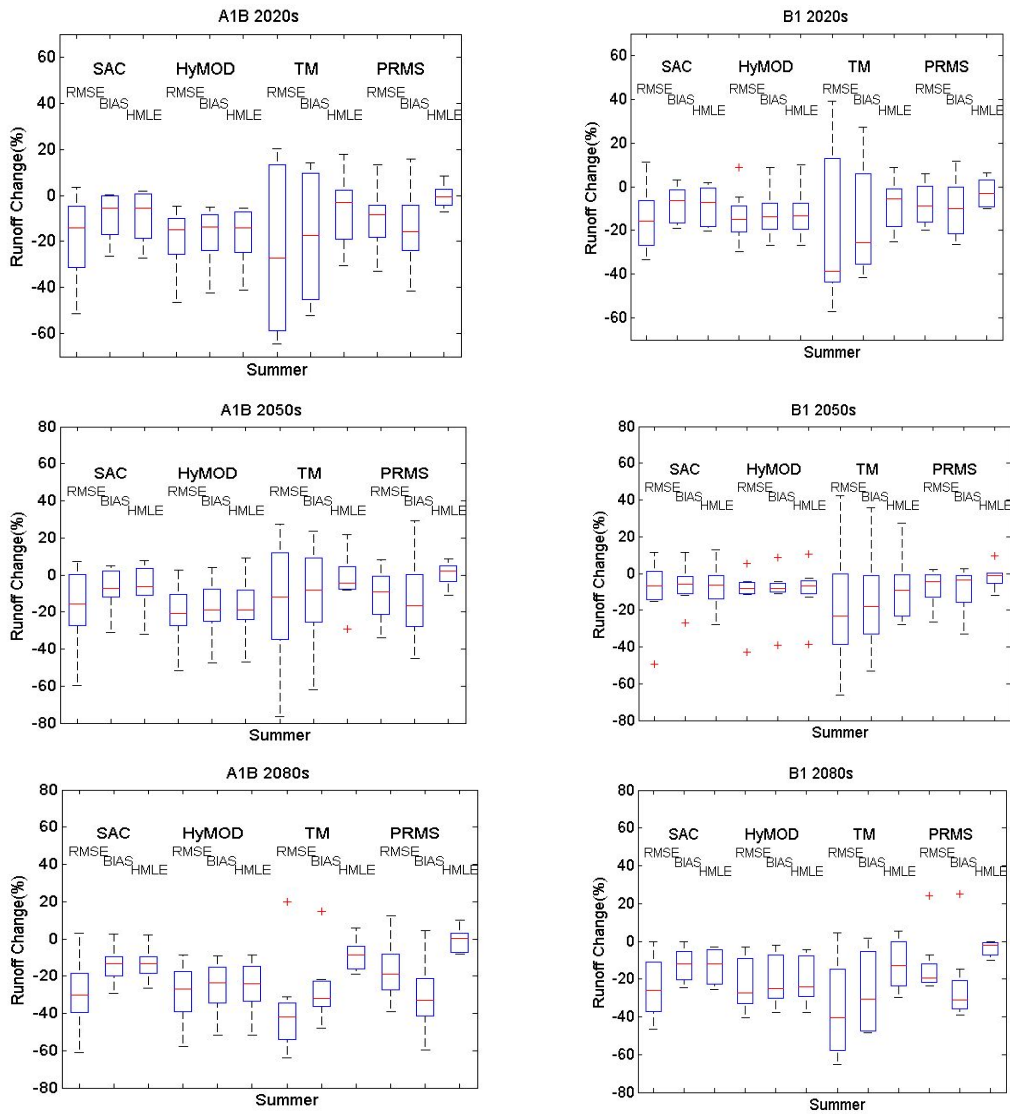
The uncertainty associated with hydrologic model selection was studied over the Tualatin river basin (Najafi et al., in review). Figure 3.16 shows the results of each model based on 8 GCM forcing data that are expressed as bias percentage between the future and reference periods. The figures show the runoff results for the winter (Dec-Jan-Feb) and summer (June, July, August) respectively for the two A1B and B1 emission scenarios. The TM model's (the simplest model) summer result shows the highest uncertainty due to the GCMs compared to the other hydrologic models simulations. The uncertainties vary between models for different emission scenarios and time periods. Therefore, the hydrologic model structural uncertainty would be

another considerable uncertainty in addition to the climate model, downscaling and emission scenario as the main sources of uncertainty reported in the literature.

The representation of vegetation response to water availability in most hydrologic models is a further source of model uncertainty in hydrologic projections under climate change scenarios. The dominant tree species in Oregon forests are capable of significant adjustments of transpiration rates in response to environmental factors, and these adaptations are not included in most hydrologic models. In addition, vegetation may undergo succession in response to changes in air temperature and/or soil water availability, further altering vegetation water use and hence streamflow, in ways not currently captured by hydrologic models.

As projections of future impacts of climate change on hydrology continue to develop, it is important to recognize uncertainty; but perhaps more important to recall, as outlined by Bloeschl and Montanari (2010), that while projections of future conditions will always be uncertain, the presence of uncertainty does not indicate a lack of understanding.





**Figure 3.16** Runoff change relative to the reference period obtained by four hydrologic models with different complexities (source, Najafi et al., in review)

## 3.4 Potential Changes in Groundwater Hydrology

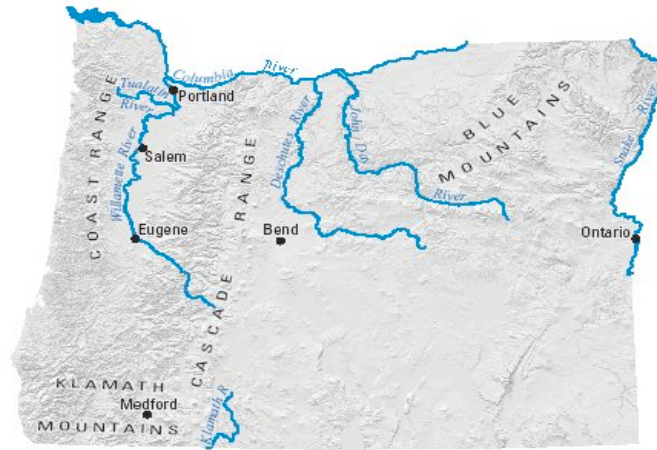
Projected future changes in temperature and precipitation will affect groundwater hydrology. Projected changes in climate will result in alterations of the timing and amount of recharge, increases in evapotranspiration, lowering of heads in boundaries such as streams, lakes, and adjacent aquifers, sea-level rise, and increased pumping demand. Increase pumping demand due to climate change will be exacerbated by population growth. This section presents a brief overview of groundwater hydrology, summarizes ways in which groundwater systems can be affected by projected climate changes, describes the likely response in key geographic settings in Oregon, and suggests directions for future research.

### 3.4.1 Overview of Groundwater Hydrology

Groundwater originates as precipitation that infiltrates into the ground. The infiltration of rainfall or snow melt into the groundwater system is called recharge. The largest amount of recharge typically occurs in upland areas where precipitation is greatest, although recharge can occur anywhere that precipitation exceeds evapotranspiration and available storage in the root zone. Water percolates downward until it reaches the water table, which generally defines the top of the region in which rock materials are completely saturated with water. In areas where streams are above the water table, leakage from streams can also recharge the groundwater system. Groundwater can also be recharged artificially through deep percolation of irrigation water, particularly in areas irrigated using surface water, and leakage from irrigation canals. Once in a groundwater system, water moves through permeable geologic materials in response to gravitational forces at a rate proportional to the permeability of the material through which it is moving and the hydraulic head gradient (which can be thought of as the slope of the water table). Groundwater eventually discharges back to the surface typically through springs or as diffused seepage to streams, lakes, and wetlands. In areas where the water table is very close to land surface, plants with roots extending to the water table can also be an avenue of discharge. Groundwater can also be removed artificially through wells. Groundwater discharge can occur naturally almost anywhere the water table, or saturated zone, intersects land surface including in uplands, where it supports perennial flow in low-order streams, and in lowlands and major stream valleys.

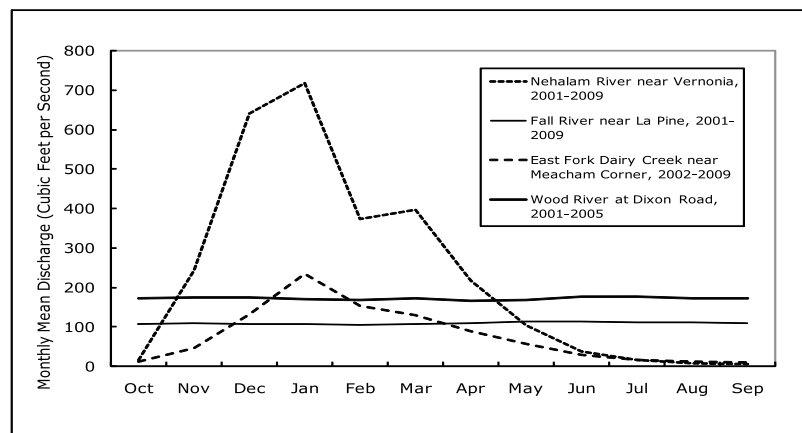
Groundwater discharge is an important component of streamflow along with surface runoff. Most critically, groundwater is the principal source of streamflow in the late summer and fall when there is little precipitation or snowmelt to supply runoff. In cold regions and at high altitudes, groundwater maintains winter flows critical to many groundwater dependent ecosystems, for example maintaining winter flows over salmonid redds. The portion of streamflow supplied by groundwater is known as baseflow. The proportions of groundwater and runoff in a stream vary seasonally, but also depend on the geology. Streams in areas of very permeable rock with substantial groundwater systems (as is common in parts of the Cascade Range) (figure 3.18) may consist almost entirely of groundwater discharge and have only a small component of runoff. Such streams are termed “groundwater-dominated,” and they are common in young volcanic areas. Groundwater-dominated streams have constant flows with very small seasonal variation (figure 3.18). Streams in relatively impermeable areas such the

Coast Range, in contrast, have a very small component of groundwater and are runoff dominated. Runoff-dominated streams have large seasonal variability and commonly go dry, or nearly so, in the late summer (figure 3.18).



**Figure 3.17** Selected physiographic and geographic features in Oregon

Because groundwater systems are recharged by precipitation, they are sensitive to changes in the amount, timing, and form of precipitation. Potential negative responses to climate change could include lower water levels in wells (water table elevations) and reductions in groundwater discharge to streams. Lower water table elevations can reduce the amount of water available for human uses by reducing the saturated thickness of aquifers and the amount of water in storage. Reductions in groundwater discharge to streams limit water available for human uses (such as municipal and agricultural diversions) and the in-stream needs of aquatic ecosystems.



**Figure 3.18** Mean monthly discharge of selected runoff dominated streams (dashed lines) and groundwater dominated streams (solid lines) with overlapping periods of record in Oregon. Nehalem River and Dairy Creek data from the U.S. Geological Survey, Fall and Wood River data from the Oregon Water Resources Department.

Because groundwater systems are recharged by precipitation, they are sensitive to changes in the amount, timing, and form of precipitation. Potential negative responses to climate change could include lower water levels in wells (water-table elevations) and reductions in groundwater discharge to streams. Lower-water table elevations can reduce the amount of water available for human uses by reducing the saturated thickness of aquifers and the amount of water in storage. Reductions in groundwater discharge to streams limit water available for human uses (such as municipal and agricultural diversions) and the in-stream needs of aquatic ecosystems.

Alexander and Palmer (2007) summarized studies of the impacts of climate change on groundwater resources in eight regions in the US and Canada. Most of the studies involved model analyses and incorporated multiple climate models and emission scenarios. Results differ between models, but tend to show that recharge varies in proportion to precipitation. Groundwater systems can be affected by changes in total precipitation, as well as changes in the spatial and seasonal-to-daily distribution of precipitation. Other climate-related factors that are shown to be important include changes in stream stage, increases in evapotranspiration, and increases in groundwater pumping.

#### *3.4.2.1 The response of groundwater systems to climate warming*

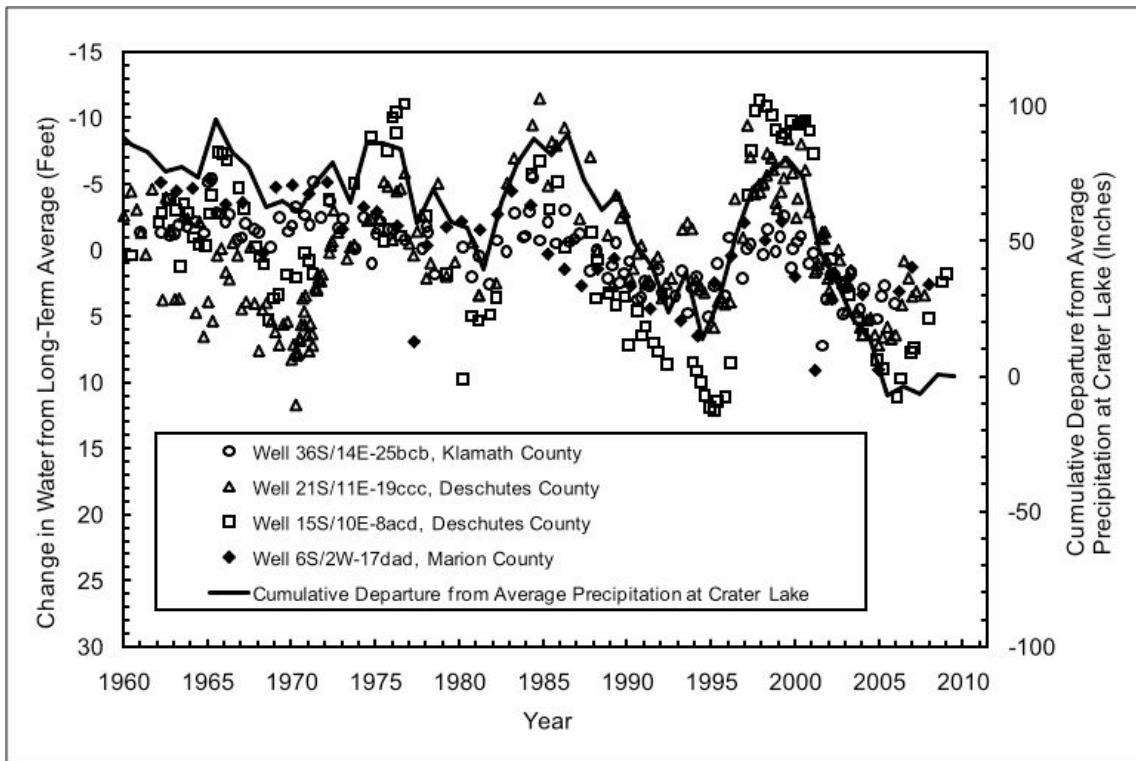
As surface hydrologic processes respond to climate change, so will groundwater recharge. The same rainfall and snowmelt events that drive runoff also provide groundwater recharge. Most groundwater recharge in Oregon occurs in place, meaning at the location where rainfall or snow melt occurs. Groundwater recharged from anthropogenic sources, such as deep percolation of irrigation water and canal leakage, is usually secondary to in-place recharge at the watershed scale. The close relation between runoff and groundwater recharge is demonstrated by Manga (1997), who successfully uses runoff as a proxy for groundwater recharge in models of groundwater-dominated streams in the Oregon Cascades. This means that changes in the timing of runoff that will occur under warmer climate conditions will result in changes in the timing of groundwater recharge. This is of practical importance where the timing of discharge of groundwater-fed streams is important for reservoir operations or irrigation.

Increased evapotranspiration due to warmer temperatures may also result in reductions in total annual recharge, especially at lower altitudes, as less water will percolate below the rooting depth of plants (Dettinger and Earman, 2007a). Variations in recharge resulting from changes in evapotranspiration are likely to vary geographically. Studies in the Yakima Basin of Washington show a 20% reduction of groundwater recharge (and stream discharge) in some subbasins resulting from a 3.6 °F increase in temperature (J.J. Vaccaro, U.S. Geological Survey, written commun., 2010). Preliminary results from modeling studies in the upper Deschutes Basin in Oregon suggest that total annual basin-wide changes in recharge resulting from warming will be much smaller (M. Scott Waibel, Portland State University, written communication, 2010).

#### *3.4.1.3 The response of groundwater systems to changes precipitation*

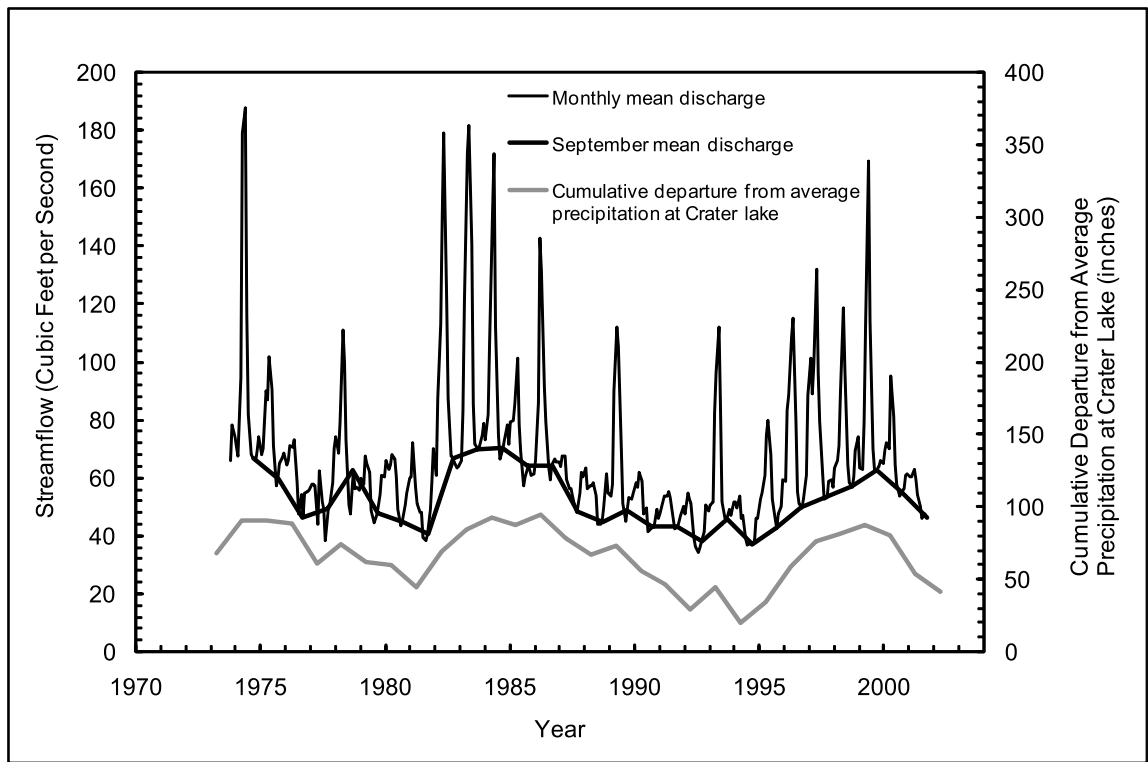
In general, increases or decreases in total precipitation will be reflected in groundwater recharge. The relation between total precipitation and groundwater can be seen by

comparing the cumulative departure from average precipitation and long-term water level trends in wells (figure 3.20). Fluctuations in upland recharge areas can range from several feet to tens of feet in response to, and generally coincident with, decadal drought cycles. This suggests that groundwater levels in many aquifers will reflect any long-term changes in total annual precipitation more or less as they occur. Historic streamflow records show that groundwater discharge to streams also varies with annual precipitation (figure 3.21). If precipitation decreases, groundwater levels will decline and discharge to streams will diminish proportionally. If average annual precipitation increases, groundwater levels will rise and discharge to streams will increase. However, the effects of increased groundwater recharge resulting from the small projected increases in precipitation in Oregon are likely to be offset by other factors such as increases in pumping demand and evapotranspiration resulting from warmer temperatures.



**Figure 3.19** Comparison of water level fluctuations in selected wells and cumulative departure from average precipitation at Crater Lake Oregon. Well data from U.S. Geological Survey and Oregon Water Resources Department.

Changes in the seasonal distribution of precipitation will affect seasonal water table fluctuations and of groundwater discharge to springs and streams. If seasonal shifts are sufficiently large and total annual precipitation remains constant, the result could be less annual recharge in some areas. This is because some shallow aquifer systems, such as in parts of the Willamette Valley, fill to capacity and recharge during the winter is already “rejected” and shunted off to streams (Conlon et al., 2005). Increased winter precipitation, therefore, may not result in increased groundwater recharge.



**Figure 3.20** Monthly mean discharge of the Williamson River near Lenz, Oregon. Note the relation between the September mean discharge (a proxy for baseflow) and the cumulative departure from average precipitation at Crater Lake.

### 3.4.2.3 Other factors influencing the response of groundwater to climate change

Groundwater recharge can be affected by factors other than changes in precipitation and evapotranspiration. Studies have also shown that recharge can be affected by changes in the temporal and spatial distribution of frozen ground (Jyrkama and Sykes, 2007) and rainfall intensity (Mileham et al., 2009) resulting from climate change.

In addition to changes in recharge, other factors will influence the way in which groundwater systems respond to climate change. Aquifer systems in alluvial deposits that are in direct hydraulic connection to streams can be affected by the lowering of stream and lake stages resulting from diminished flows. Lower stream and lake stages can result in lower water levels in adjacent aquifers. Reduced streamflow may also result in reduced irrigation diversions and in less artificial recharge from deep percolation of irrigation water and canal seepage. Artificial recharge may also be reduced by conservation measures such as the use of more efficient irrigation methods or lining irrigation canals.

Sea-level rise resulting from climate change also could affect groundwater in coastal regions. Sea level is an important boundary condition affecting water levels in the extensive sand-dune aquifers along the coast such as found near Coos Bay, Reedsport, Florence, and in Clatsop County (Rinella et al., 1980; Brown and Newcomb, 1963; Hampton, 1963; Frank, 1970). A rise in mean sea level will result in a comparable rise in water-table elevations in sand dune aquifers as well as alluvial aquifers hydraulically connected to tidally influenced estuaries. This could result in water-level rises and expansion of groundwater-fed lakes and wetlands in sand dune areas and other low-lying coastal settings. Sea level rise will exacerbate any existing saltwater intrusion problems, as will warming-related increases in groundwater pumping in coastal areas.

Groundwater systems are also susceptible to the effects of increased water demand resulting from climate change. Warmer temperatures typically result in increased groundwater pumping by both municipalities and irrigators. Diminished late season streamflow predicted by most analyses will reduce the surface water available for irrigation which will also increase demand for groundwater. The very small increase in precipitation projected by the ensemble average of climate models for Oregon is unlikely to offset increased pumping due to warmer temperatures and diminished late-season streamflow.

### **3.4.2 The Influence of Geographic and Geologic Settings on the Response of Groundwater Systems to Climate Change**

The response of groundwater systems to climate change will vary with geographic and geologic settings. Principal variables that will influence the response of groundwater systems to climate change include the permeability of the underlying geologic deposits, the geographic setting within the watershed (upland versus lowland aquifers), and the degree to which recharge originates as snow.

The permeability of geologic materials is the most basic factor controlling the presence or absence of groundwater systems and how those systems will respond to climate change. Low permeability units such as the marine sedimentary rocks Coast Range, pre Cenozoic rocks Klamath Mountains, and Mesozoic and early Cenozoic rocks of the Blue Mountains Province in northeastern Oregon, have generally low bedrock permeability and do not host large regional groundwater systems. Aquifers in such areas are largely limited to localized zones of bedrock fractures and alluvial deposits in valley bottoms. The largest impacts to the limited groundwater systems in such settings are likely to result from increased pumping demands and increased ET due to warmer conditions (Loáiciga, 2003; Hanson and Dettinger, 2005; Dettinger and Earman, 2007a). Streams in low permeability areas have very limited baseflow and typically go dry, or nearly so, in late summer and fall (figure 3.19). Late season water needs in such areas are commonly provided by storage in reservoirs that are filled during the winter and spring.

Areas dominated by permeable material such as fractured lava or extensive coarse-grained sedimentary deposits typically contain substantial groundwater systems that can be large enough to be of regional importance (Gannett et al., 2001, 2007; Tague and Grant, 2004). Such areas include the younger (high) Cascade Range, volcanic areas of central and eastern Oregon, and large sedimentary basins such as the Willamette Valley and Portland basin. Most large river basins in Oregon include both high permeability and low permeability areas. An exhaustive

analysis of the potential response of groundwater to climate change in geographic settings across the state is beyond the scope of this chapter. Instead, this section discusses the probable response in selected settings to provide general insights. For simplicity of discussion, regional groundwater systems are divided into upland and lowland settings in the following sections. The processes described in upland and lowland settings, such as recharge and discharge, occur at a range of spatial scales.

#### *3.4.3.1 Groundwater systems in upland settings*

Upland settings where permeable deposits dominate recharge areas tend to have substantial groundwater systems and a large proportion of groundwater-dominated streams (and associated groundwater dependent ecosystems). The most prominent permeable upland in Oregon is the geologically youngest region of the Cascade Range, often known as the “High” Cascade Range which encompasses the upper parts of the Deschutes, Klamath, and Willamette Basins. The importance of groundwater to the hydrology of basins flanking the Cascades has been recognized for many decades going back to the work of Russell (1905), Meinzer (1927) and Stearns (1929, 1931). More recent work characterizing the importance of groundwater contribution to streams emanating from the Cascades includes that of Grant (1997), Gannett et al. (2001, 2003, 2007), Tague and Grant (2004, 2009), and Jefferson et al. (2006, 2007).

Many permeable upland areas in Oregon, and in the Cascade Range in particular, rely on snowmelt for a large part of their groundwater recharge. As was previously described, warming will result in a shift in the form of precipitation toward less snow and more rain, and consequently more runoff in the winter, earlier (and less) snow melt in the spring, and less runoff during the summer. The timing of groundwater recharge will shift in the same manner as runoff. The shift in timing of recharge will affect groundwater-dominated streams, increasing winter flow and reducing late season flow (Manga, 1997; Tague et al., 2008). Runoff-dominated streams are expected to experience larger changes in the seasonality of flow than groundwater-dominated streams. This is because the groundwater system acts as a reservoir, storing seasonally variable recharge and releasing it to streams at a more constant rate throughout the year. Groundwater discharge from permeable upland areas, therefore, has the potential to moderate the effects of warming to some degree (see, for example, Tague et al., 2008; Tague and Grant, 2009; Chang and Jung 2010; Mayer and Naman 2010). Although groundwater-dominated streams may experience small percentage reductions of late season flow, the changes may be volumetrically large (Tague et al., 2008; Chang and Jung, 2010). In runoff-dominated low-order streams, a small-volume / large-percentage reduction in flows may be catastrophic for some groundwater dependent ecosystems, particularly if those reductions cause perennial streams to become ephemeral.

While the effects of changes in the seasonality of recharge may be moderated by groundwater storage in permeable uplands, such areas will respond to changes in total annual precipitation. Water levels and groundwater discharge to streams will vary in proportion to any long-term increases or decreases in total precipitation. Total recharge likely will also be reduced by increased evapotranspiration under warmer conditions.



### 3.4.2.2 Groundwater systems in lowland settings

Groundwater recharge in lowland areas (such as the Willamette Valley, Portland Basin, and stream valleys and lake basins in central and eastern Oregon) will respond differently from uplands to warming and to possible changes in the seasonality of precipitation. Moreover, additional climate-related stresses may affect groundwater in lowland areas. Natural recharge in lowland areas is primarily from rain and intermittent snowmelt and does not rely on large, spring snowmelt events. Therefore, changes in the form of precipitation are not likely to have as large an influence on the seasonality of recharge in lowland areas as they will in upland areas. Most climate models do, however, project a shift in the timing of precipitation toward wetter fall and winter seasons and dryer summers (Mote and Salathé, 2010). These shifts will affect seasonal groundwater fluctuations, possibly resulting in lower water levels in wells in the summer which could increase pumping costs and limit well yields. This is an important consideration for irrigation and municipal wells. As mentioned previously, if the shift toward winter precipitation is sufficiently large and total annual precipitation remains the same, total annual recharge could diminish in shallow aquifers that reach capacity and “reject” recharge during the winter.

Groundwater is much less likely to moderate the effects of climate change on streams originating in lowland settings than streams originating in permeable uplands for several reasons. Recharge rates in lowlands areas are generally less because of the smaller amount of precipitation, groundwater discharge to streams from lowland areas is generally less than in upland areas, and groundwater originating in lowlands generally makes up a smaller component of streamflow. For example, groundwater-dominated streams rarely originate in lowland areas except at the bases of uplands.

Groundwater systems in lowland areas are more susceptible to increases in pumping than upland areas. Farms and cities, the largest users of groundwater, tend to be located in lowlands. In addition, some lowland groundwater systems may be susceptible to changes in boundary conditions. Shallow alluvial aquifers in lowland stream valleys tend to be hydraulically connected to streams, and, because of the low head gradients, groundwater levels can be influenced by stream stage over significant areas (for examples in the Willamette Valley see Conlon et al., 2005). Decreases in stream stage resulting from smaller late-season flows could result in proportional water-level declines in hydraulically connected aquifers.

### 3.4.2.3 Columbia River Basalt Group aquifers

Aquifers in the lava flows of the Columbia River Basalt Group constitute a unique class of aquifers in Oregon. Because of their high transmissivity, Columbia River Basalt Group lavas are productive aquifers. However, these aquifers are susceptible to large pumping-related water level declines due to their low specific storage and recharge that is limited by low vertical permeability. Columbia River Basalt aquifers underlie much of north central Oregon and parts of the Tualatin and northern Willamette valleys.

Poorly-confined aquifers at shallow depths in the Columbia River Basalt Group allow infiltration of water and are often in a state of dynamic equilibrium with climate, and the

temporal variations caused by seasonal recharge events and decadal drought cycles are apparent in water-level trends (Conon et al., 2005; Vaccaro et al., 2009; Kenneth E. Lite Jr., Oregon Water Resources Department, oral communication, 2010). Highly confined aquifer systems such as found at depth in the Columbia River Basalt Group, in contrast, have very limited recharge. Consequently, climate signals are often not prominent in water-level data in Columbia River Basalt wells deeper than about 600 feet (Conlon et al., 2005; J.J. Vaccaro, USGS, written communication, 2010). Water level fluctuations in such highly confined systems are usually dominated by anthropogenic influences such as pumping, and, in some areas, head changes due to progressive interconnection of aquifers at different depths by wells (Burns et al., 2009). In an analysis of water level trends in the Yakima Basin in Washington, Vaccaro et al. (2009) show that water level declines are largest in deeper aquifers, indicating diminished recharge with depth. Generally speaking, climate signatures are apparent in upper basalt zones but less so in deeper zones (John Vaccaro, USGS, written communication). Therefore, climate change will affect Columbia River Basalt aquifers to different degrees (or at least with different timing) depending on depth. In deep basalt aquifers, the effects due to changes in recharge are likely to be small in comparison to the effects of increased demand, particularly if average annual precipitation remains largely unchanged.

### **3.4.3 Strategies for Improving the Understanding of, and Responding to, Changes in Groundwater Hydrology Resulting from Climate Change**

Several actions could be taken to improve the understanding of the probable response to groundwater systems in Oregon to climate change and to help in development of adaptive management strategies. Efforts should include additional analysis of historic data to improve understanding the relation between groundwater systems and climate across the state, improved monitoring of groundwater to quantify the current and future response to climate variability, and continued development of hydrologic models to improve understanding of the linkages between climate and groundwater and to improve predictive capabilities.

Considerable information is contained in historic records of groundwater levels and streamflow; these records could be evaluated along with historic meteorological data to improve understanding of the coupling of climate and groundwater. Such an analysis could provide new insights, highlight particularly vulnerable regions or hydrologic settings, and provide useful information for development of new models.

Monitoring of groundwater and streamflow in Oregon has historically been done for specific regulatory or management purposes so present networks, while supplying considerable valuable information regarding the possible effects of climate change, are not optimally suited for that purpose. Hence, water level trends in monitored wells are often dominated by pumping effects that overwhelm the climate signature. The US Geological Survey (USGS) has developed a groundwater climate response network to “portray the effect of climate on groundwater levels in unconfined aquifers or near-surface confined aquifers that are minimally affected by pumping or other anthropogenic stresses” (Cunningham et al., 2007). Of the 500 wells in the national network, eight are in Oregon. It is possible that many of the hundreds of wells presently monitored by the Oregon Water Resources Department (OWRD) and the USGS for

other purposes would be suitable for including in a climate response network. It is probable that there are aquifers that are not presently included that should be monitored.

Considerable information on the state of groundwater systems can be provided by monitoring the groundwater discharge to streams and springs using standard stream gaging techniques. Many gaging stations throughout Oregon, operated primarily by the USGS and OWRD, can be used to estimate discharge from some major aquifer systems. These estimates can be compared to climate records as in Figure 3.20 to provide insights into climate/ groundwater connections. Most streamflow monitoring, however, is done to assist in operations of dams and reservoirs or for managing irrigation water. There are, therefore, many groundwater systems for which discharge is not monitored. A systematic review of stream gaging networks and large springs in Oregon could identify sites that would provide information on groundwater conditions as well as aquifer systems that are not presently adequately measured.

Developing networks specifically for monitoring changes in groundwater recharge caused by climate change is a topic of growing interest in the western US, however no standard techniques and protocols presently exist. Summaries of existing and emerging techniques for monitoring groundwater recharge are provided by Dettinger and Earman (2007b) and Earman and Dettinger (2008).

Insight into the probable hydrologic response to the range of projected climate changes in Oregon and the western US has come from modeling studies. Models not only provide important insights, but also predictive capability. Modeling studies of the hydrologic response to climate change in Oregon include work in the northern Willamette Valley by Graves and Chang (2007) and Franczyk and Chang (2009a), in the McKenzie River watershed by Tague and Grant (2009), and in the Deschutes Basin by Waibel et al. (2009). Some of these studies incorporate existing hydrologic models, developed for reasons other than climate change research, coupled with downscaled climate model output or other predictions of future climate. Continuation and expansion of modeling efforts will provide additional insights and predictive capability. Emerging techniques for coupled groundwater/surface-water models (such as the USGS GSFLOW code) are particularly promising. Groundwater models exist for a number of major basins in Oregon (for example, Morgan, 1988; Davis-Smith et al., 1988; Morgan and McFarland, 1996; Gannett et al., 2004) that could be coupled with climate models to gain insights into the hydrologic response of the basins to projected climate change. Coupling hydrologic models with management models using optimization techniques can help identify strategies for resource management under uncertain and changing conditions.

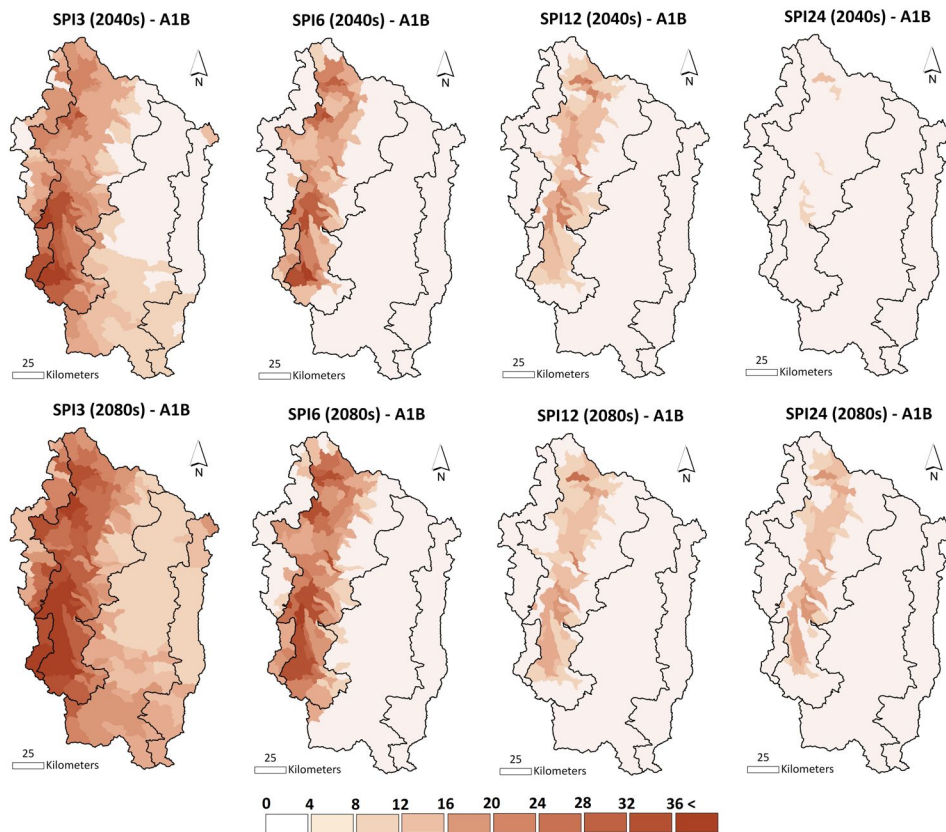
#### **3.4.4 Summary**

Groundwater systems in Oregon will be affected by warming and possible changes in the amount and seasonality of precipitation projected by climate models. The principal mechanisms for change in groundwater are expected increases in evapotranspiration, which will decrease groundwater recharge, and increase pumping of water from groundwater wells to compensate for increased evapotranspiration. Secondary mechanisms include small changes in groundwater resulting from small projected changes in precipitation and localized changes in sea level in coastal areas. Responses include changes in the timing, amount, and spatial

distribution of recharge, as well as changes in pumping demands and other boundary conditions. The response of groundwater systems will vary among geographic and geologic settings. All groundwater systems are sensitive to changes in the amount and timing of precipitation, from those in humid regions to systems in semiarid regions. Regional groundwater systems in the Cascade Range, important to streamflow in the adjacent basins, may moderate the effects of climate change somewhat but are likely to experience changes in the seasonal distribution of recharge. Lowland groundwater systems are probably most susceptible to increases in groundwater pumping resulting from warmer temperatures. Understanding the linkages between groundwater systems and climate can be improved with expansion of collection and analysis of groundwater data. Continued development of hydrologic models can improve understanding of the likely response of groundwater systems to the range of possible future conditions, and help in development of water management strategies.

## Case study: Possible future climatological drought in Willamette River Basin

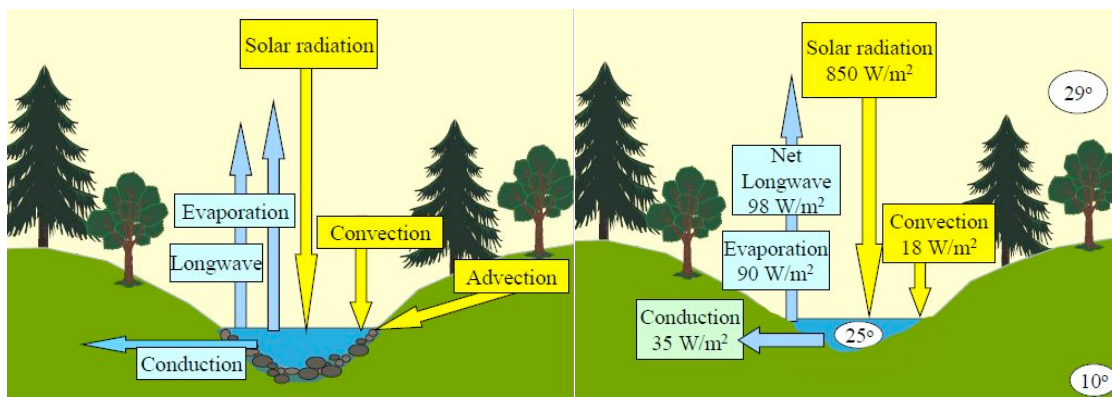
Drought is a natural hazard that can have severe impacts on regional water sector. The extreme seasonality of precipitation in the Pacific Northwest has induced frequent seasonal water shortage problem, especially at the rain-dominated region in summer. However, more winter rainfall and earlier snowmelt by increasing temperature is likely to increase drought risk at a transient region and snow-dominated region because of reduced water storage for summer use. We investigated possible changes in future climatological drought over the Willamette River Basin. The statistically downscaled 16 climate simulations derived from eight GCMs with two emission scenarios (Chang and Jung, 2010) were used to calculate relative Standardized Precipitation Index (SPI) (Vidal and Wade, 2009; Dubrovsky et al., 2009). The relative SPI can assess the spatial and temporal change of drought frequency at different lasting time scales, 3-, 6-, 12-, 24-month. Multimodel ensemble results projected increase in drought frequency under the A1B and B1 GHG emission scenarios. In particular, short-term 3- and 6-month droughts are likely to increase highly over the Willamette Valley region and the Western Cascade region for the 2080s (2070-2099) due to decreased summer precipitation. Long-term droughts, 12- and 24-month, however, are not projected to change except some of the Willamette Valley region because winter precipitation is projected to increase in these areas.



## 3.5 Impacts of Climate Variability and Change on Water Quality

### 3.5.1 Water Temperature

Although numerous studies have examined potential consequences of climate change on river flow (Arnell 2004; Payne et al., 2004), relatively few studies have investigated how river water quality might change in response to warmer air temperature and changing patterns of precipitation distribution (Murdoch et al., 2000, Chang et al., 2001). Water temperature is the most important indicator of stream health; it directly affects the amount of dissolved oxygen in water, which is critical for fish survival. Water temperature also indirectly affects the overall health of streams through its influence on in-stream biogeochemical cycles. In the Pacific Northwest (PNW), summer water temperature is critical for the survival of cold-water species like salmon. Studies have shown that ranges for cold-water fish would be displaced northward with a loss of habitat because cold-water species cannot adapt quickly to abrupt environmental changes (Mohseni et al., 2003).



**Figure 3.21** Major factors influencing stream temperature and example of heat budget for hot summer day at noon.

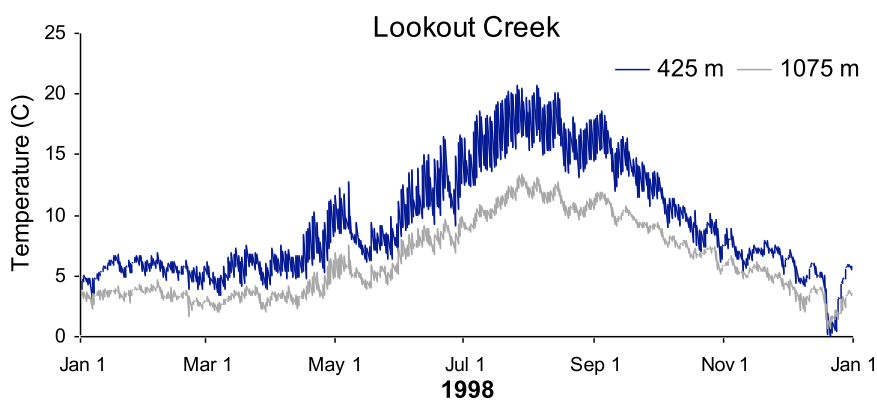
Changing climate could affect stream temperature through several mechanisms (Figure 3.21). Although air temperature and water temperature are correlated (Webb, 1996), variation in air temperature alone does not lead to major changes in stream temperature in Oregon streams (Johnson, 2003; Johnson, 2004). The largest effect of climate change on stream temperature may occur indirectly through climate-induced modification of riparian vegetation (although it might take a while), which provides shading for streams, and influences streamflow timing and amount. In the Willamette River basin approximately 35% of runoff comes from the snow pack. This results primarily from increased soil moisture earlier in the spring (Burns et al., 2007). Declining snowpacks could reduce spring and summer streamflow, which thus could increase summer stream temperatures. Low streamflows coincide with maximum summer air temperatures, and if streams become standing pools, temperatures can greatly increase. The degree of temperature change will depend on how much streamflow will decrease in the future

and the degree to which stream temperature depends on discharge. Stream discharge could further decline as elevated summer air temperature accelerates the rate of evapotranspiration, which will have harmful effects on freshwater habit of Pacific Salmon (Mantua et al., 2010).

Land use also affects stream temperature (Krause et al., 2004; Johnson and Jones 2000). A reduction of riparian buffers, whether from urban, agricultural or forest land use practices, and the shade they provide leads to increased levels of solar radiation and increased stream temperatures. Urbanized landscapes with high levels of impervious surfaces can absorb more heat energy than rural landscapes, which also increases surface air temperatures. This effect may be more pronounced during the spring and early summer months with runoff flowing over the hot surfaces into streams. These overland flows can cause short-term spikes in water temperature (Nelson et al., 2007).

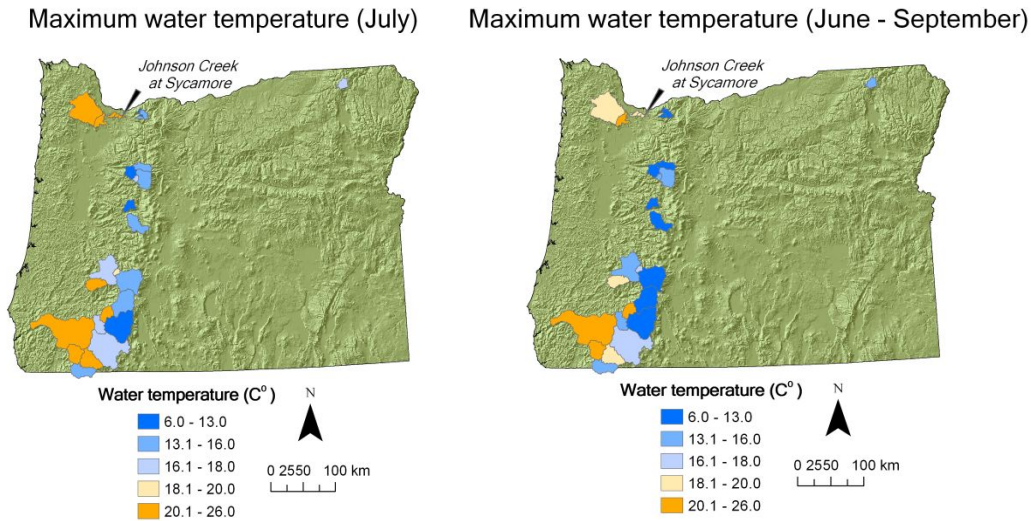
While there is a growing concern about potential changes in water quality resulting from climate change, only a few studies have investigated this topic in the Pacific Northwest (PNW). Based on an analysis of two PNW streams, Cristea and Burges (2010) showed that stream temperature increases depend on reductions in summer streamflows rather than increases in air temperature. Johnson and Jones (2000) documented a return to preharvest stream temperatures with recovery of riparian vegetation. Tague et al. (2007) examined water temperature variations in a High Cascade and a Western Cascade basin using historical water temperature data. Their results suggest that geology and the source of stream water controls summer water temperature dramatically, with less seasonal variations in water temperature in sub-surface flow- dominated High Cascade watersheds.

Water temperature in Oregon is highest in the summer, with forested headwaters generally having cooler temperatures than larger downstream sites (Figure 3.22). Winters are times of lowest temperatures, and maximum temperatures generally occur in July, August or September, depending on year-to-year weather patterns, discharge trends and timing of shading.



**Figure 3.22** Daily maximum and minimum water temperature during 1998 for 1<sup>st</sup> and 5<sup>th</sup> order Lookout Creek in the Cascade Mountains.

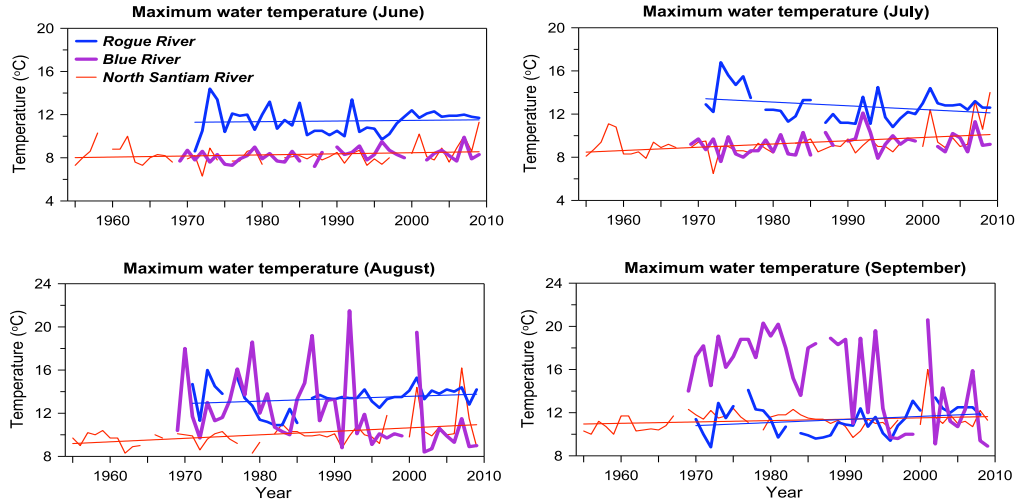
Figure 3.23 illustrates a general spatial pattern of maximum water temperature during summer (June to September) for selected stations for a period of 1999 and 2008. As shown in this Figure, most basins draining the Cascade Range experience low maximum water temperature, while urban and mixed watersheds (e.g., Johnson Creek and the Tualatin River Basin) exhibit higher than average water temperature. Basins located in southwestern Oregon also experience higher than average water temperature.



**Figure 3.23** Average annual maximum daily water temperatures for July and summer (June to September) for 31 basins in Oregon, 1999-2009.

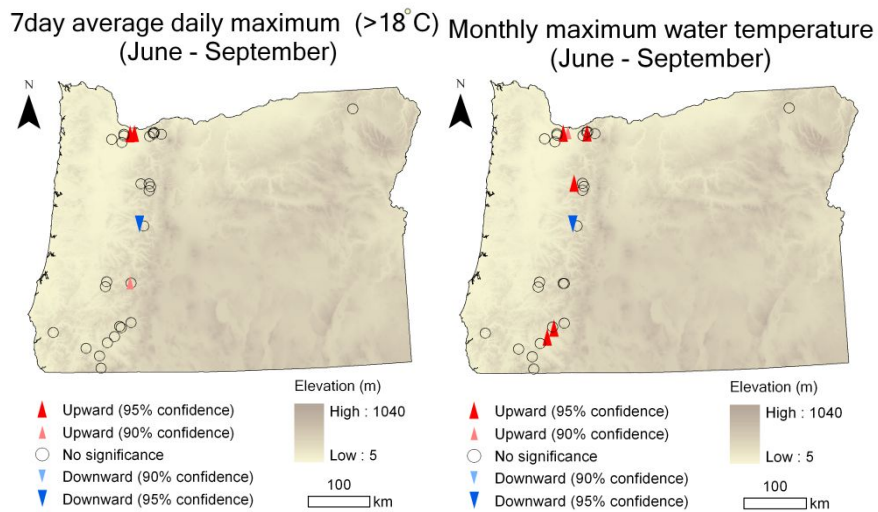
Long-term trends of water temperature in undisturbed watersheds are rare. Many sites with long-term data have been impacted during the period of record by upstream impoundments or land use changes, which confounds our ability to detect climate related changes. Data from stream gaging stations in the Rogue River basin (Rogue River near Mcleod, station #14337600) and in the Willamette River basin (Blue River at Blue River, station #14162200, and North Santiam River at Niagara, station #14181500) show general increasing trends in maximum water temperature for two of the three stations, particularly in the North Santiam River (Figure 3.25). High variability in August and September water temperature at Blue River appear to be associated with flow regulations in late summer months.



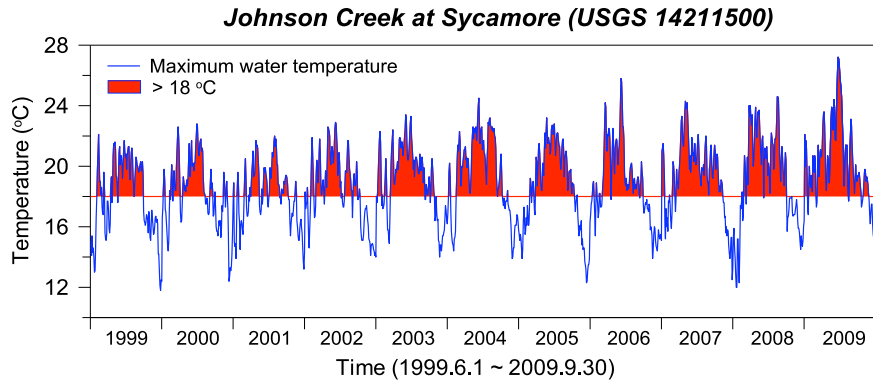


**Figure 3.24** Long-term trends of maximum water temperature for Rogue River near Mcleod, Blue River at Blue River, and North Santiam River at Niagara.

Figure 3.25 shows trends over time in maximum water temperature in summer, based on records from 1999 to 2009. Only 6 of 36 stations show increasing trends. According to Mann-Kendall's test, one station located in the Willamette Valley shows a downward trend in summer maximum water temperature. The 7-day average daily maximum temperature, currently used for assessing water temperature threshold for fish habitat (e.g., lethality and migration blockage conditions), increased at 5 stations which are all located in the Portland metropolitan area. As shown in Figure 3.26, the variability of water temperature in Johnson Creek increased over the past 10-year period, suggesting that the stream frequently exceeds the threshold level of 18°C. A comprehensive assessment would be required to determine the degree of disturbance to fish habitat in urban streams.

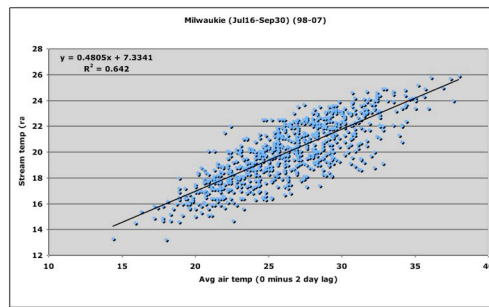


**Figure 3.25** Trends in maximum summer water temperature and 7-day average daily maximum temperature for 31 stations in Oregon



**Figure 3.26** Maximum water temperature for Johnson Creek at Sycamore, 1999-2009

A preliminary study of the three streams - Tualatin, Johnson and Clackamas River - in the Portland metropolitan area shows that the degree of landscape disturbance further elevates stream water temperature (Chang and Block 2009). While lagged air temperature can explain approximately 66% of variations in summer water temperature on average, the size of stream, the amount of flow, and the upland hydrological processes also affect water temperature variations (see Figure 3.27).



**Figure 3.27** Relation between streamflow and water temperature and lagged air temperature and water temperature at Milwaukee in Johnson Creek, 1998 - 2007.

Major controls on stream temperature are riparian vegetation (through shading) and streamflow (which influences heat exchange). Climate warming may increase stream temperatures by reducing riparian vegetation, or by reducing snowpack and spring and summer discharges. Low elevation watersheds in areas of agricultural or urban land use, which are already temperature limited, may be most susceptible to climate-warming-induced increases in stream temperature.

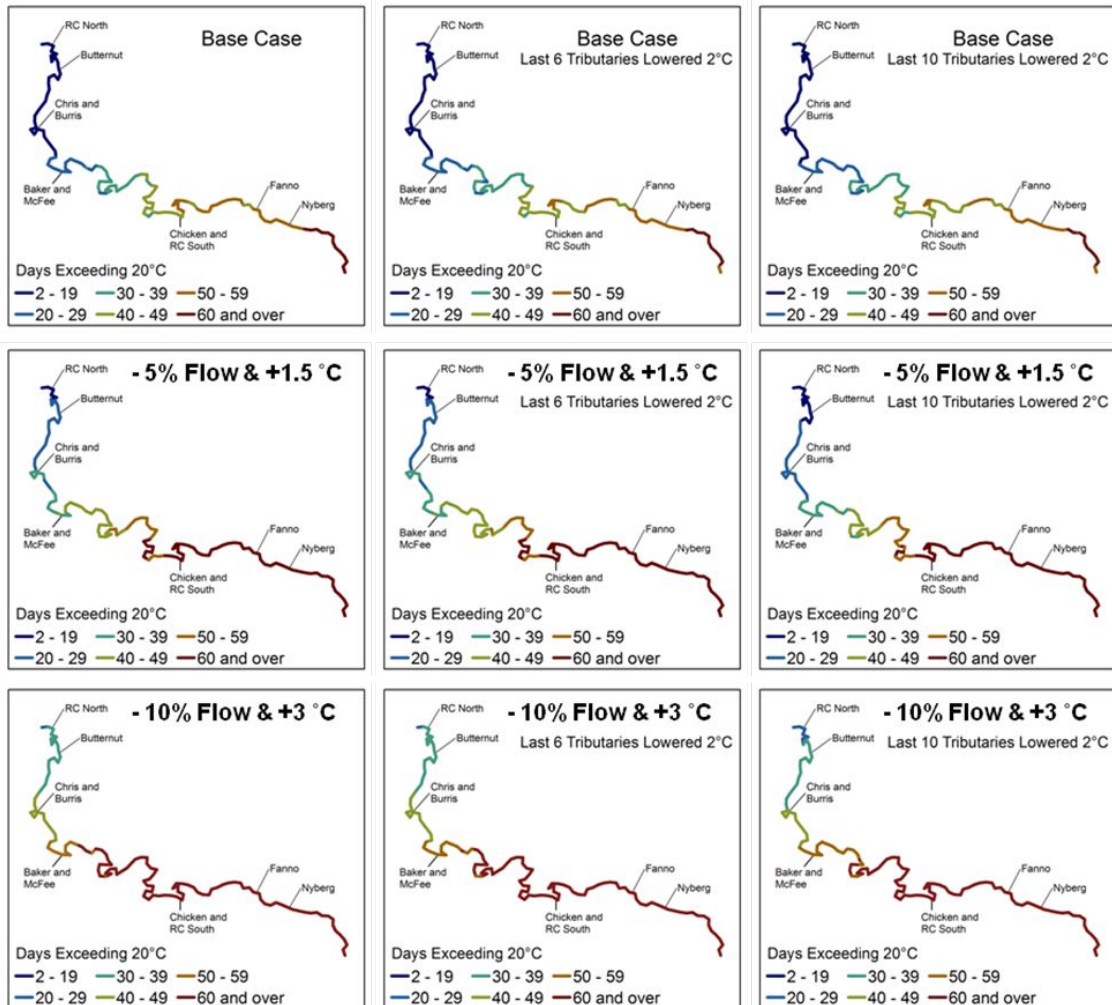
Figure 3.28 shows potential changes in water temperature in the mainstem of the Tualatin River located in the Portland metropolitan area. These results are based on CE-QUAL-W2 simulations for 154 segments in the lower Tualatin River under three combinations of temperature, flow, and riparian scenarios. The nine maps show the number of days that 7-day daily average water temperature exceeds 20°C between May 15 and October 15 under each scenario. Under the

baseline scenario (top left), only the lower segments of the drainage experience water temperature above 20°C. Under water temperature reduction scenarios, with reductions due to revegetation in tributary riparian zones, only a few immediate segments are affected. Under 5% flow reduction and 1.5°C air temperature rise scenarios (representing the 2040s), segments with water temperatures in excess of 20°C for more than 60 days expand to include some upstream areas. Under 10% flow reduction and 3°C air temperature rise scenarios (which represents the 2070s), they expand further into upstream areas. Riparian vegetation scenarios have the most direct impact on middle segments of the drainage under the highest warming scenario.

In summary, there is little evidence to date of increasing stream temperatures over time in Oregon, except in urban streams, where temperatures may have increased because of cumulative loss of shading from riparian vegetation associated with urban and suburban development. Only a few dozen long-term records of stream temperature exist in Oregon. Existing studies have demonstrated that stream temperatures depend on riparian vegetation cover as well as air temperatures and discharge, which are inversely related. Future changes in stream temperature in response to climate change in Oregon will depend on the degree to which warming results in a reduction of late summer streamflow and how warming influences riparian vegetation. The resulting effects are complex. Warming temperatures may increase late-summer evapotranspiration from riparian vegetation, potentially reducing late summer flow; smaller snowpacks and earlier snowmelt may further reduce late summer streamflow. If streamflow in late summer is reduced, with no changes in riparian vegetation cover, stream temperatures may increase. However, increases in riparian vegetation cover (from stream restoration) could partly counteract these effects. In addition, stream temperature increases from typically forested headwaters, where groundwater contributions are important, to typically agricultural or urban downstream areas, so stream temperatures in downstream areas may be more sensitive than headwaters to future climate-related warming.

### **3.5.2 Sediment and Nutrients**

As sediment and phosphorus loadings typically increase during high flow events, changes in flow variability are expected to alter temporal variability of sediment and phosphorus loadings. A case study in the Tualatin River basin (TRB) of Oregon illustrates that winter sediment nutrient loadings are expected to increase under climate change scenarios as winter flows are projected to increase (Praskievicz and Chang, 2011). Although diminished summer flow is likely to reduce summer nutrient loading, the annual load is expected to increase further with urban development scenarios.



**Figure 3.28** Change in water temperature under climate change and tributary riparian vegetation scenarios (Source: Chang and Lawler 2010).

However, conservation-oriented development could reduce erosion and phosphorus loading substantially compared to conventional development. The combination of climate change and urban development scenarios generally produce hydrological and water quality results that track the results from climate change alone, suggesting that the water resource impacts from climate change are more significant than those from land use change in the TRB. The development and conservation scenarios do differ in their hydrological and water quality outcomes, thus representing a potential opportunity for local adaptation to climate change by pursuit of sustainable forms of urban development.

## 3.6 Impacts of Climate Variability and Change in Water Demand

Municipal water demand patterns have progressively become a greater concern to urban water resource managers due to changes in climate and the expansion of urban areas in many parts of the world during the 20<sup>th</sup> and early 21<sup>st</sup> centuries. The recent Intergovernmental Panel on Climate Change report (IPCC) also projected an increase in temperature and spatial and temporal variability of precipitation, which may increase water demand but reduce seasonal water supply (Kundewicz et al., 2007). Although many North American cities have recently implemented conservation measures which have reduced water consumption per capita (Gleick, 2003), growing municipalities located in arid or semi-arid regions or areas prone to drought are increasingly apprehensive about the sustainability of their water resources (Morehouse et al., 2002; Kenney et al., 2008). Even for cities located in relatively temperate climates, such as the Pacific Northwest of North America, potential seasonal changes in runoff due to climate change pose another stress in the sustainability of water resources (Palmer and Hahn, 2002; VanRheenen et al., 2003; Palmer et al., 2004; Graves and Chang, 2007). Residential water consumption is a key factor that could affect water availability at the local and regional scale (Gutzler and Nims, 2005; Balling and Gober, 2007).

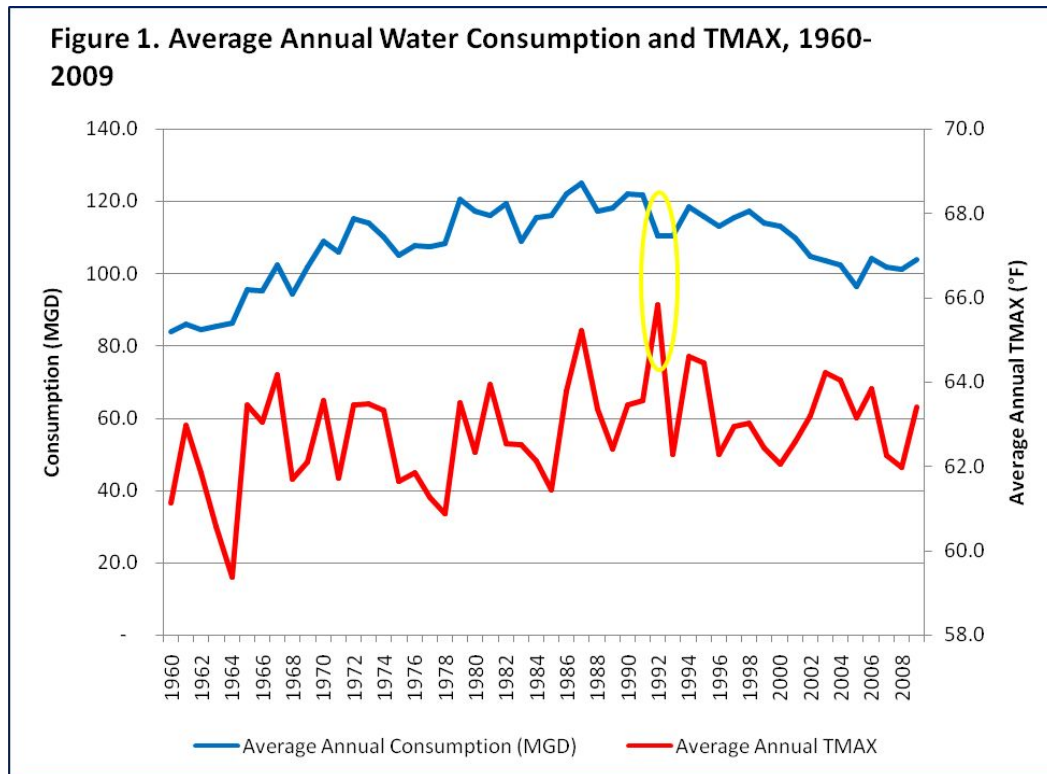
While previous studies suggest the existence of threshold values of climate variables that affect the sensitivity of urban water consumption, few examined the complex relation between water consumption and climate variables at multiple temporal scales. Water consumption research is typically constrained by a lack of detailed data to draw from; however, a rich dataset of long-term daily water data was available for the preliminary investigation of Portland water consumption. To draw meaningful inferences on water consumption as it relates to climate variability and projected climate change, multi-scale analysis is needed. Multi-scale temporal analyses allow us to project short-term and long-term water demand forecasting based on the fluctuations of climate variables. Water resource managers need not only seasonal climate but also daily weather information as they relate to water supply and demand (Steinemann, 2006).

Here we examined the relationship between urban water consumption and climate variables at daily, monthly, seasonal, and annual scales using 50 years of historical water production data from Portland, Oregon as a case study. Additionally, we also used customer demand monitoring data for a finer temporal analysis at a household level for one specific summer year. This study is a unique investigation concerning the sensitivity of urban water consumption to climate variables as the scale of analysis changes. It will provide useful climate information for urban water resource managers as it relates to water consumption. Urban water managers may be able to use such information to establish proactive plans under increasing pressure from climate change (Ruth et al., 2007; Praskievicz and Chang, 2009c).

### 3.6.2 Inter-annual Climate Variability and Water Consumption

Water consumption in the Pacific Northwest is highly dependent on weather variations. The annual consumption pattern shows increase in water consumption in warmer and drier months, and in warmer and drier years. Figure 3.29 shows average annual water consumption by retail

and wholesale customer classes of the Portland Water Bureau (PWB) along with maximum daily temperature, averaged over the year, measured at the Portland Airport (PDX) weather station. Although consumption is related to population, conservation, land use, and other economic and demographic factors, the inter-annual fluctuations in consumption also are related to maximum air temperature. One exception is the spike in temperature in 1992, which coincided with a dip in consumption. This dip was the result of mandatory curtailment imposed by the PWB during the summer of 1992, when a water shortage occurred due to lack of access to the existing groundwater supply along the Columbia River South Shore, an issue which has now been resolved.



**Figure 3.29** The relation between average annual water consumption and average annual maximum temperature.

Consumption has an inverse relationship with total annual precipitation, however, not as strong as that of temperature. Figure 3.30 shows dips in average annual consumption in years that are very wet.

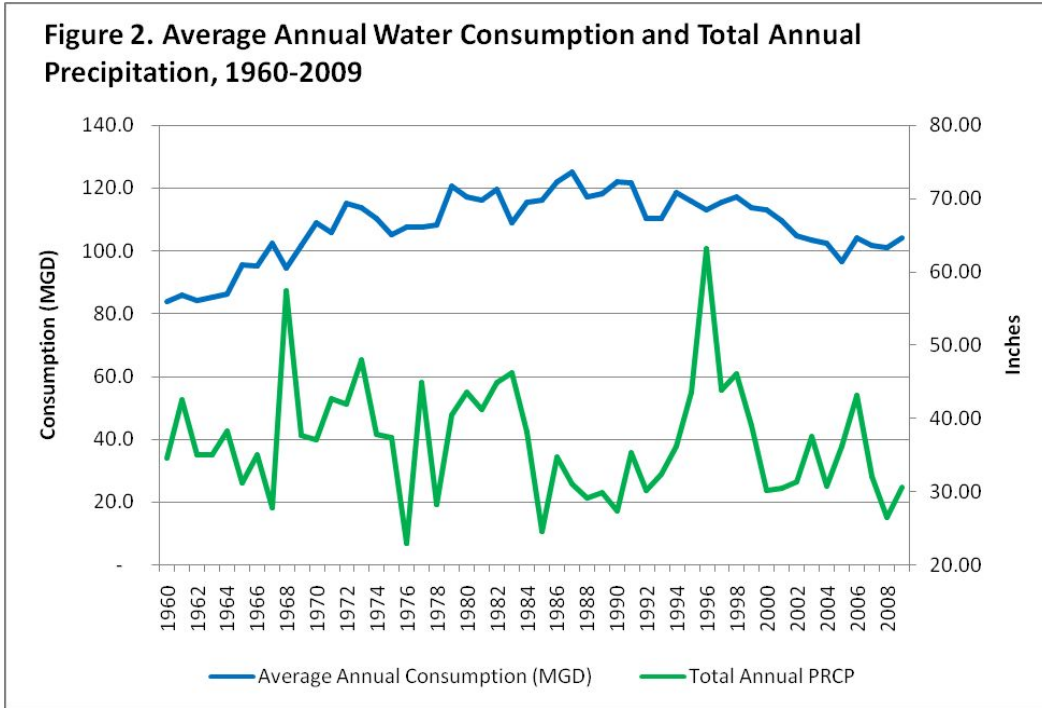
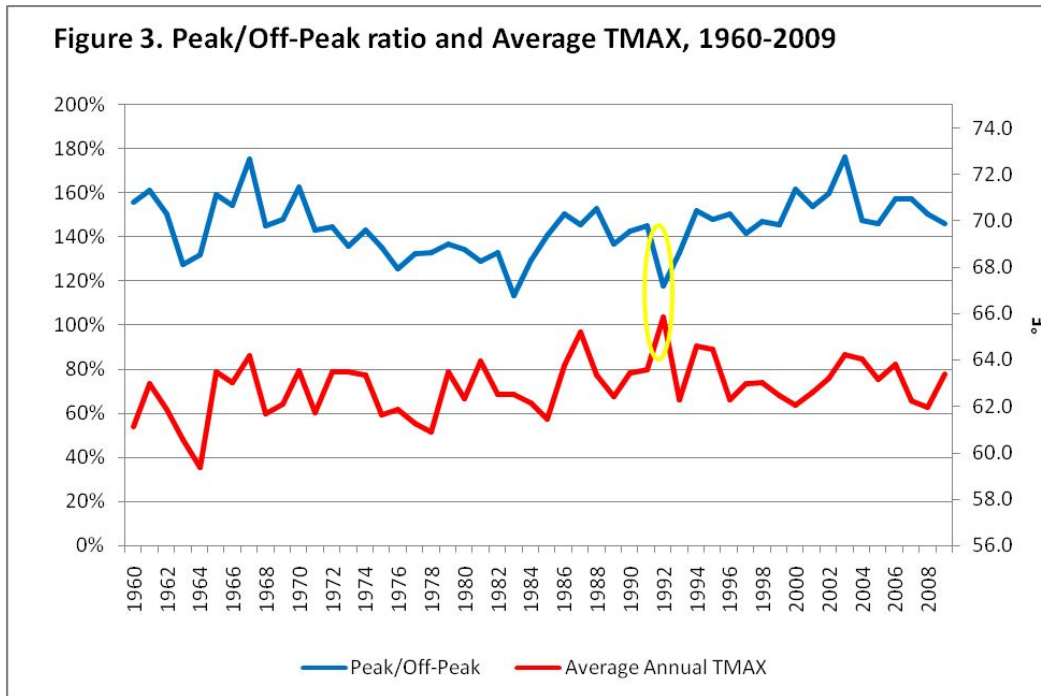


Figure 3.30 Average annual water consumption and total annual precipitation, 1960-2009

### 3.6.3 Seasonal Climate Variability and Water

Water consumption shows a strong seasonal pattern in the PWB service area. The Bureau recognizes June to September as peak season based on empirical data observations. The annual figures over the 1960 - 2009 period show higher consumption during peak season relative to off-peak in the range of 113% - 176%. Although peak season consumption also depends on economic and demographic factors, it is affected by inter-annual climate variability as well. Figure 3.31 depicts the Peak/Off-Peak ratio and maximum daily temperature, averaged over the year. Again, with the exception of 1992, spikes in the relative peak-off-peak consumption mostly coincide with those of the TMAX.



**Figure 3.31** Peak/off-peak ratio and average maximum temperature, 1960 - 2009. The peak/off-peak ratio is water consumption in June to September (dry season) divided by water consumption in October to May (wet season).

### 3.6.4 Daily weather variability and water consumption

Daily fluctuations in consumption are closely related to daily fluctuations in weather. In fact, a simple regression of daily consumption on maximum daily temperature and total daily precipitation shows that 51% of variation in daily water consumption can be explained by total daily temperature and precipitation. Obviously, part of the explanatory power is due to seasonal patterns in both consumption and weather. That is, no matter how hot or cold the summer months are, there will be increases in water consumption due to change in the season. The daily effect of weather above and beyond the seasonal effect can be measured by considering the deviations of daily temperature and precipitation from their historical mean. A more sophisticated regression model, which includes seasonal, economic, demographic, and weather variables in form of deviations from historical means, shows how variations in consumption can be disaggregated to show the effects of these variables. A model developed by PWB shows that daily weather variations explain about 13% of the daily variations in consumption, above and beyond seasonal changes.

There was also wide variation in the average amount of water used by individual households from day to day. Overall, the average daily volume of water used by a household was greater in summer months than in winter months. This corresponds with Portland's cool, wet winters and dry, temperate summers. Average daily household water consumption was also greater on weekend days, which is logical given our sample of residential properties: some residents likely



spend much of their weekday time out of the home at work or other locations. Consequently, water-consumptive activities of maintenance (washing clothes and cars) and recreation (gardening and water play) are more likely to take place on weekends.

A multilevel model results suggest that the most important determinants of household water consumption is daily maximum temperature, followed by day of the week (weekend or not), building size and building age. These factors correspond to other previous studies in the same region (Shandas and Parandvash, 2010; Chang et al., 2010). A model suggests that water use increases by 27 liters/household for every 1° C increase with an increase in daily maximum temperature. It requires an 86.5 ft<sup>2</sup> increase in building area to increase water use by an amount equivalent to a 1° C rise in daily max temperature. Larger houses have a greater water consumption than smaller houses on hot days. Thus the larger the house, the greater the increase in water use with rise in daily maximum temperature.

### **Case study: water demand in the city of Hillsboro: a spatially-explicit assessment**

Urban residential water consumption is significantly affected by both interannual seasonal climate variability and periods of drought. In Hillsboro, Oregon, a rapidly growing suburb of Portland, a statistical analysis of single-family residential water records for the period 2004-2007 found that water consumption throughout the entire study area exhibited significant sensitivity to interannual climate variation (House-Peters et al. 2010). Sensitivity to interannual climate variability was manifested as increased household water consumption during the summer season, as compared to the winter season, due to increased external water use for irrigation, pool maintenance and car washing during hot, dry weather. Furthermore, sensitivity to interannual climate variability was spatially heterogeneous throughout the study area. Census blocks displaying the largest magnitude of increased summertime water use, up to 2.2 times greater than winter use, had newer and larger homes, higher property values, and more affluent and well-educated residents. This research also examined water consumption during a drought summer in 2006 when the study area recorded only half as much precipitation as the 30-year mean and exceeded the 30-year mean's average maximum temperature by one degree Celsius (National Climatic Database, station #353908). Although water use across the entire study area did not demonstrate sensitivity to the drought conditions, particular census blocks were highly sensitive to the drought, consuming up to 1.85 times more water for external purposes during the drought summer than an average summer. Interestingly, during the summer characterized by reduced precipitation and higher maximum daily temperatures, external water use was found to be more dependent on physical property characteristics and less dependent on socio-economic characteristics. These results suggest that strategic urban planning and neighborhood design may be able to reduce stress to the water supply system during peak summer demand and future drought episodes.

### 3.6.5 Conclusions

Statistical analysis of daily water consumption per capita in the studies cited above shows that determining which climate factors are the most influential to consumption per capita is highly dependent on the scale of study. While both precipitation and temperature are significantly associated with water consumption at all scales, the influence of temperature is stronger than that of precipitation on water consumption at the monthly scale. Other hydro-climatic and social behavior variables, such as humidity and social activities, could be also potential factors that affect the variations in water consumption. As soil moisture depends on both precipitation and evaporation, it is important to include humidity as part of water demand modeling, particularly outdoor water use such as lawn irrigation and recreational activities. Changes in lawn irrigation behavior thus can also be an important factor that might influence irrigation water demand (House-Peters et al., 2010). At a daily scale, our multilevel model can provide more nuanced information about the interacting effects of water use, structural attributes, day of the week, and temperature. These results imply how changing temperatures and demographics can lead to development patterns that exacerbate or conserve regional water resources.

This multi-scale analysis of urban water consumption illustrates complex interactions between urban water consumption and climate variables depending on the scale of analysis. It demonstrates what climate information would be useful for short and long-term water consumption forecasting. Urban water resource managers may be able to use such information for establishing proactive water resource management strategies under increasing pressure from potential climate change. While many municipalities in Oregon have prepared water management and conservation plans with supply focus (Bastasch, 2006), now is a time to put climate change into water resources planning at multiple levels.

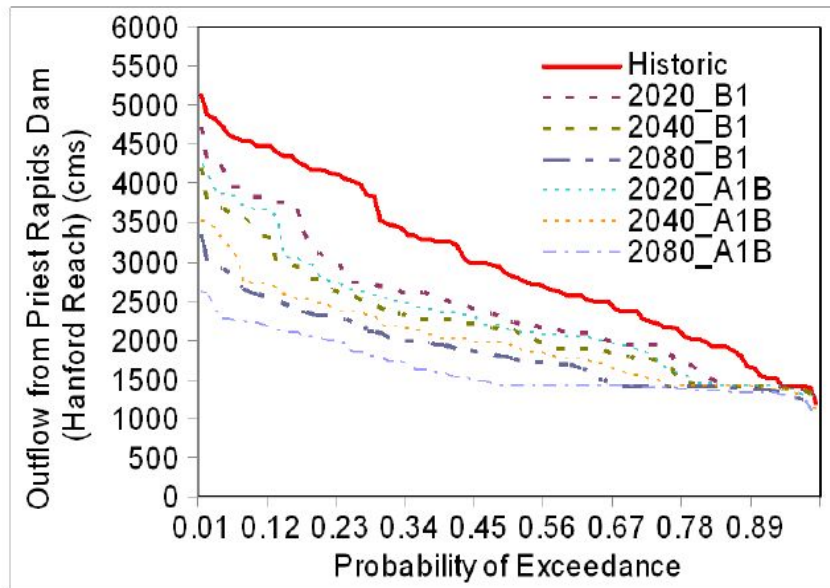
## 3.7 Projected and Observed Impacts of Climate Change on Hydrosystems

Oregon is blessed with a varied and ecologically diverse environment; consequently, parts of the state are either too wet or too dry to support many human activities without modifying the natural water supply. These modifications include an extensive series of engineering projects, including reservoirs, dikes and levees, and diversions, to meet a number of sometimes conflicting objectives for Oregon's hydrosystems, including flood control, irrigation and municipal supply, hydropower production, recreation, and recovery of threatened and endangered species. Meeting these objectives in the future is likely to become increasingly difficult as climate and land use change, combined with population growth, alter the demands on and supplies of the water system.

A number of groups have investigated the projected impacts of a changing climate on hydrology and streamflow that represent changes in supply (Udall and Bates, 2007; US Geological Service, 2005; Stewart et al., 2005; Regonda et al., 2005; National Assessment Synthesis Team, 2001; Knowles et al., 2006; Ray, 2008; Baxter and Hauer, 2000; Warren et al. ,

1964). Also relevant are projected changes in water demands (NWPPCC, 2005; Voisin et al., 2006).

These changes in supply and demand are likely to have important impacts on water infrastructure and the built environment. Regional frequency results indicate that an increased frequency of higher streamflow events (i.e. Figure 3.32) can be expected for most areas of the PNW region, though this pattern is expected to vary spatially (Rosenberg et al., 2009a; Kunkel et al., 1999; Pryor et al., 2009; Madsen and Figdor, 2007). Small basins with a large proportion of their area at the midwinter or transient snow line are likely to be most vulnerable to climate changes (Mote et al., 2003).



**Figure 3.32** Predicted changes in extreme events for the Columbia River Basin. Figure reprinted from Hamlet et al., 2009.

Despite the value of trends projections from GCMs, the variability between GCMs challenges the design of some urban infrastructure (Rosenberg et al. 2009b). As an example, the variability between models represents one characteristic challenge in designing new and retrofit infrastructure (e.g. stormwater) based on the magnitude of the 24-hour extreme. Further, the anticipated changes are likely to be beyond what the current water infrastructure can reliably manage. For example, achieving a reduction of winter flood risk with future increases in peak flows will likely require strengthening dikes and levees, restoring floodplains, improving flood forecasting, changing reservoir management, improving emergency management, and modifying land use policies and flood insurance. With regards to low flows, it is projected that a reduction of summer water will require diversification and development of water supplies, reducing demand, improving efficiency, operational changes at reservoirs, increasing water transfers between users, and increasing drought preparedness (Binder et al., 2009). Thus, maintaining water infrastructure in future climates and land uses is likely to require new design

and management approaches to address the potential challenges posed by uncertain changes in both supply and demand.

In this section we further explore these potential impacts of climate and land use changes on water infrastructure in Oregon, leading to questions regarding: How might water management objectives (e.g. hydropower production, flood protection, recreation, municipal and irrigation supply, and instream flows) be impacted by climate change? What indicators and measurements are relevant to evaluating climate change impacts on meeting water management objectives? What adaptation strategies are groups considering and what tradeoffs may be necessary for new water management objectives?

### **3.7.1 Impacts on Water Infrastructure**

A number of climate-related impacts could have important consequences for water infrastructure and management. For example, fish recovery plans may need to be revised, fire risk may increase due to vegetation shifts, infrastructure (e.g. crossings, conduits, landslide risks) could be impacted by increased peak flows, and water and/or reliance on groundwater could increase.

In some areas, impacts to water infrastructure include (also see Miller and Yates, 2007).

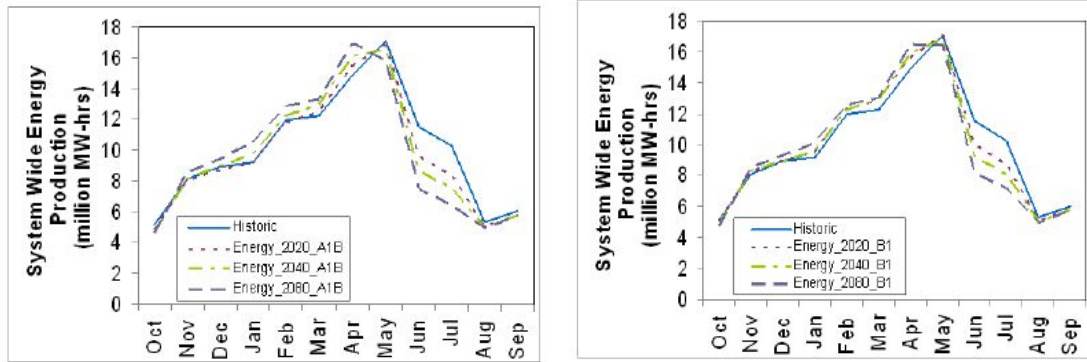
- intrusion of bromine/iodine from seawater, leading to problems meeting disinfection by-product rule compliance (AWWA, 2001)
- increasing potential for floods to exceed stormwater systems, leading to water contamination from combined sewer overflows (Ashley et al., 2001)
- increased potential for floods to damage infrastructure (Filion, 2000)
- increased fire frequency leading to increased sediment loads to water treatment plants

Recent work has focused on the development of hydrological projections for the PNW in the context of water resources management (Vano et al., 2009a and 2009b; Wiley and Palmer, 2008; Trayham, 2007; Polebitski et al., 2008). Together, these studies indicate that shifts in hydrology towards higher flows in fall are likely to variably impact dam operating objectives. For example, Wiley et al., (2008) predicted that April snowpack will decline from 2000 to 2040 and that peak snow accumulation will shift from March to earlier in the year. This is anticipated to result in a decline in fall reservoir storage. In another example, Vano et al., (2009a) used downscaled GCM A1B and B1 emission scenarios as inputs to DHSVM to produce streamflow simulations for the 2020s, 2040s, and 2080s. These results were then input into water resources model run at a daily time step. Their results project a transition from a double peaked hydrograph (December and mid-May snowmelt peak) to a single peak in December (elevated winter runoff). By early April to the end of March, all future scenarios show less water than historical conditions, due to earlier snowmelt. Despite this change, reliability (the ability of the system to meet demands including instream flow and consumptive use) remains at 100% for

historical simulations of Seattle, Tacoma, and Everett reservoirs and only drops below 98% for the warmest and driest scenarios (CCSM3 and ECHO\_G). However, in their models, reliability decreased markedly if increases in demand are factored into analyses.

Most models agree that instream flow requirements will be increasingly difficult to meet in the more distant future as demands increase and available storage declines. In Puget Sound reservoirs, Vano et al. (2009a) and Wiley and Palmer, (2004) found that instream flows in summer will not be significantly impacted by climate change in the near future as instream flow requirements set by the Habitat Conservation Plan (SPU, 2000) are lower than typical observed flows. However, instream flows are projected to be adversely impacted for the most severe climate scenarios for the 2020s and for A1B and B1 scenarios in the 2040s and 2080s. Without substantial infrastructure changes, tradeoffs are likely to be necessary between hydropower generation, instream flows for fish, reservoir storage, and flood protection. For example, regarding instream flows, the Hamlet et al. (2009) studies suggest that the use of larger reservoir storage will be required to mitigate/supplement summer low-flows for reducing tradeoffs between fish flows and firm energy resources. Along these lines, Payne et al. (2004) found that trade-offs were unavoidable in the winter due to limited reservoir storage level.

It is likely that changing supply and demand of water will require reconsideration of established rule curves to more reliably meet flood protection, instream flows, and hydropower objectives. For example, projections (Figure 3.34) indicate that increased potential for hydropower production exists through the winter months while decreased production is likely through the summer months as we move further into the future. These results are based on simulation of streamflow for the Columbia River Basin (Hamlet et al., 2009) using the VIC hydrologic model (Liang et al., 1994) and methods described by (Elsner et al., 2009). Their objective was to investigate adaptive responses with regard to flood control, using fixed (assuming no change in demands) energy targets for firm and non-firm energy. They found that, for the 2020s, winter hydropower increases 0.5-4% and summer hydropower decreases 9 - 11%, with net decreases of 1 - 4%. By the 2040s, winter production will increase 4% and summer production will decrease 2.5 - 4%. By 2080s, winter production will increase 7 - 10% and summer production will decrease 18 - 21%. The largest reductions in hydropower generation, as compared with 20<sup>th</sup> century values, are likely to occur July-Sept, coincident with peak seasonal air conditioning loads (Voisin et al., 2006; Westerling et al., 2008).



**Figure 3.34** Projected Impacts to hydropower production on the Columbia River. Simulated long-term mean, system-wide hydropower production from the Columbia River basin for A1B scenario (top panel) and the B1 scenario (bottom panel). Figure reprinted from Hamlet et al., 2009.

Mote et al. (2003) found that the reliability of energy production remains high in future scenarios but that reliability of flood control diminishes with increased precipitation (Figure 3.34).

In addition to direct changes in flow, synergistic changes in water temperature are likely to influence reservoir operations (Battin et al., 2007; Mantua et al., 2010). Thermal stress periods are predicted to be minimal until 2020s and then subsequently increase (Mantua et al., 2009). These stress periods will occur during reduced summer flows and are likely to influence both dam operations and infrastructure needs (e.g. temperature control devices). The complex and variable nature of hydrologic, and consequent ecosystem changes, suggests that current strategies and regulations that govern operations of reservoirs in static and uncoordinated ways may inhibit the necessary flexibility required to manage water resources in a changing climate.

### 3.7.2 Adaptations and Tradeoffs

As agencies and communities adapt to a changing climate, tradeoffs are going to be inevitable. Some of these tradeoffs will be specific to the local hydrogeology and climate while others will be based on social values or existing legal requirements (e.g. ESA). For example, while hydropower is a very inexpensive energy source and accounts for 70% of energy use in the PNW (Hamlet et al., 2009; Binder, 2009) the amount of hydropower generated is controlled by water availability and not demand (Hamlet et al. 2009). Thus, some are considering additional storage (Snover et al., 2007) to meet competing water demands. Indeed, important trade-offs between fish flows and firm energy resources in winter may require the use of much larger reservoir storage (Hamlet et al., 2009; Barnett et al., 2004). In one example, researchers (Payne et al., 2004) examined tradeoffs in alternative reservoir operation strategies. They found that greater storage to capture earlier reservoir refill could help meet instream targets, though at a cost (9 - 35% loss) of firm hydropower production.

### 3.7.2.1 *System optimization*

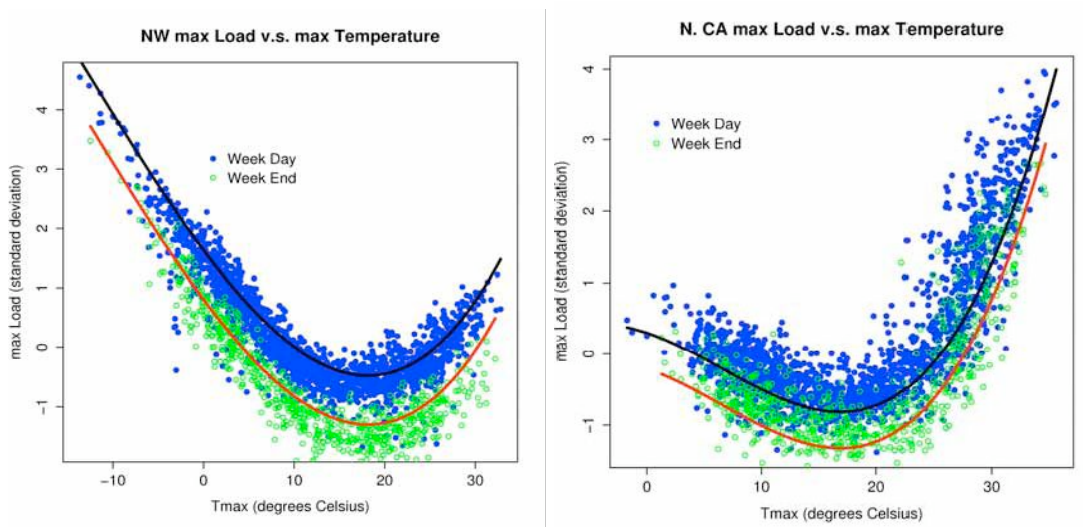
Optimization has been applied to evaluate tradeoffs in operations for multiple-reservoir, multi-purpose hydrosystems for many years (Needham et al., 2000). However, some major challenges exist in basing operations solely on optimization outcomes. Labadie (1997) reviews reservoir optimization models, with discussion on the lag between theoretical developments and implementation. Some of these challenges include establishing relative value or priority among multiple objectives, scaling and time steps/lags (changes in flow now vs. responses of ecosystems vs. other costs/benefits), defining and measuring system health/impairment and response/performance. These factors require a high degree of model complexity, which significantly increasing costs of model development, ease of use, the reliability of its output (Van Lienden and J. Lund, 2004), and the difficulty in addressing deviations and risk. Further, an increase in the frequency of extreme events (floods or droughts) will make it more difficult to meet multiple objectives under an optimized system. For example, reservoirs in the Willamette Basin, designed to meet flood protection, municipal water supply, and Biological Opinions requirements are generally in concert. However, during high flow events, conflict between objectives could occur when, for example, ramping rates required by the Biological Opinions may not be met to satisfy flood protection objectives.

### 3.7.2.2 *Current planning and design practices*

Fundamental challenges emerge for water managers when applying the results of GCMs in water infrastructure design. These challenges result from the current design paradigm for water resources engineering, which is based on frequency distributions of precipitation and runoff and assumes stationarity. For example, design of stormwater infrastructure is frequently based on precipitation events of 1-hr to 24-hr duration, and 2 to 25 year return frequency (Osman, 1993). Predictions at this scale are especially important in urban areas, where smaller lag-to-peak and flashy streams are common (Rosenberg et al., 2009). Continuing to design stormwater facilities in this way may require GCMs to be downscaled to hourly precipitation timestep and low spatial resolutions (e.g. ~20km) before input into rainfall-runoff models (Rosenberg et al., 2009), a process that is highly vulnerable to uncertainty. The alternative is the development of a new design paradigm that is not based on frequency distributions. Advantages of various downscaling approaches in the Pacific Northwest have been reviewed (Salathé et al., 2005), and Avise et al., (2006) present some advantages of using regional climate models for various impacts applications. Neither solution has been comprehensively demonstrated or is without uncertainties. Thus, managers will need to consider the resolution of data required for hydrodynamic and management models and either downscale (with a quantitative understanding of uncertainty) or adjust their management models to operate at a coarser scale.

A second challenge regarding engineering design practices is the assumption of stationarity. In addition to key challenges in assuming hydrological stationarity (Milly et al. 2008), nonstationarity in ecological and social drivers is also likely. For example, planning for future energy demands is challenged by unpredictable changes in carbon pricing and policies that may influence where and when power is produced from reservoirs, the availability of alternative energy supplies, the increased importance of managing reservoirs for temperature in both the

summer and winter, changes in populations and/or demographics, and the lack of stationarity in ecological systems' responses to changing landscapes and hydrology.



**Figure 3.35** Nonlinear relationships between maximum daily temperature and peak energy demand in the PNW and Northern California. (Figures from Westerling et al., 2008).

An example of nonstationarity in social drivers is demonstrated by Hamlet et al. (2009), who investigate the uncertainty in the relationship between daily maximum temperature and peak energy demand in the PNW and northern California. By investigating projected increases in population, heating degree days, cooling degree days, and air conditioning market penetration, this research attempted to address heating and cooling energy demand indices (for residential, not industrial use) for three projected climate periods (2010 - 2039, 2030 - 2059, 2070 - 2099) using IPCC emission scenarios A1B and B1. Their studies projected that peak electricity demand in summer in the PNW would likely remain similar to current demands, but would be higher in CA (Figure 3.35). Their work also emphasized a highly non-linear relationship between demand and maximum temperature. For example, despite warmer temperatures, heating energy demand is projected to increase with increasing population: 22 - 23% for the 2020s, 35 - 42% for 2040s, and 56 - 74% for 2080s. Cooling energy demands will increase by a factor of 2.6 - 3 for the 2020s, 4.6 - 6.5 for 2040s, and 10.8 - 19.5 for 2080s. This work also identified key sources of error in these analyses to be 1) decadal scale precipitation associated with the PDO, and 2) population growth predictions and related heating and cooling energy demand.

### 3.7.2.3 Addressing uncertainty in water resources impact assessment

In this unpredictable water future, water resource management may become increasingly complex as new objectives and multi-facility coordination requirements are added to reservoir rule curves and water infrastructure. This complexity will be driven by a number of key uncertainties, including the loads and market price of power, hydrologic variability, water demands, environmental and biological requirements, aging infrastructure, and science and



policy changes. These uncertainties pose important challenges to the management of hydrosystems.

The uncertainty in climate and hydrology is important for a number of management decisions around water infrastructure, including Biological Opinions, ESA and NEPA, flood risk management, FERC relicensing, evaluating resource adequacy and rates, infrastructure studies and policy (e.g. 2014/2024 Columbia River Treaty) reviews. While decision making under uncertainty is not new (Loucks et al., 1981), the non-linearity of changes associated with climate change presents some new challenges in a) using, interpreting, and communicating data based on climate projects, b) grasping the scope of policy/economic changes, c) resolving inconsistency in timesteps between social change and environmental change, d) meeting new and varied demands on the water system, and d) identifying control points in social-economic-ecological systems. Using dam operations as a specific example, uncertainties in reservoir operation models include fisheries objectives (flow augmentation and spill), forecast errors, hydropower loads, and runoff distributions. These challenges are further complicated by inconsistencies between the temporal and spatial scales of GCM and water resource models. Some (Barsugli et al., 2009) argue that GCMs need better model agreement on key parameters, a narrowing of the range of model output, and climate model output that matches the spatial and temporal resolution needed for water utility models, improved short-term climate model projections that fit water utility planning horizons.

Model uncertainties emerge from a variety of sources, including both the projections of future climate and the hydrologic response to changing climate. Based upon work in the United Kingdom, Kay et al. (2006) suggest that the largest source of uncertainty in estimated future runoff is introduced by the choice of GCM, followed by the chosen emission scenario, and then by the hydrological model which produces estimates of future runoff. This ranking of uncertainty has been supported by others (Praskievicz and Chang, 2009b; Bloeschl and Montanari, 2010) who have suggested that the greatest uncertainty emerges from the fact that the GCM projections cannot be evaluated against measured data for the future. Hydrological models, on the other hand, can be evaluated against historical conditions, and calibrated to ensure that the model captures measured dynamics, albeit historical, of the hydrological system.

The assessment of uncertainty in climate and hydrological predictions is becoming an integral component of climate forecasting (e.g. Solomon et al. 2007). The most common implementation of uncertainty analysis in climate modeling focuses on the utilization of an ensemble of climate results, including both multiple emissions scenarios and the results from multiple GCMs, as input into a single hydrological model. A variety of studies have utilized this model for impact assessment in California and Washington watersheds (Vano et al., 2009a and 2009b; Miller et al. , 2003; Hayhoe et al., 2004; Leung et al., 2004; Dettinger, 2004; Maurer and Duffy, 2005; Maurer, 2007). This procedure makes direct use of the uncertainty methods that are commonly employed by the atmospheric modeling community and climate change impacts research. In addition, Bloeschl and Montanari (2010) make the case that uncertainty introduced into water resource assessment through hydrological modeling should also be acknowledged and quantified. Techniques exist for evaluating hydrological model uncertainty (e.g. Beven and Freer, 2001; Vrugt et al., 2003), which can support climate change planning and designs.

### 3.7.3 Evaluating vulnerability of infrastructure to climate change

Measuring and communicating the impacts of climate change on water infrastructure is critical as water resource managers reflect on future infrastructure needs and risk. Several metrics may be useful in evaluating the vulnerability of water infrastructure across basins, political governances, and management approaches. Indirectly, measures of a landscape's hydrologic sensitivity to climate change may include percent of watershed with transient snow (resulting in a two peaked hydrograph due to rain and snow) (Swanson et al. 1992), and Hydrologic Landscape Regions (Wiggington et al. in review), which are based on measures of seasonality, climate, aquifer permeability, terrain, and soil permeability.

More directly, minimum reservoir storage, as the ratio of annual runoff to total storage, is another measure of system vulnerability or stress. Studies by Vano et al. (2009a, 2009b) indicate that active storage capacity drops by 50, 25, or 10% in October, when reservoir storage is typically lowest, under the A1B and B1 scenarios as compared to historic conditions. This could result in lower reservoir storage available late spring through early fall in the future. Similarly, Mote et al. (2003) found that basins with higher storage-to-flow ratios may be less vulnerable to stress than those with minimal storage. Another direct measure of storage vulnerability is the projected timing of reservoir filling. Medellín-Azuara et al. (2007) predict that dry-warm climate scenarios, given projected water demands and land use for 2050, will increase the seasonal storage range, with peak storage occurring around one month earlier.

### 3.7.4 Conclusions

As Oregon's population and economic activity increase over time, and as changes in climate increasingly impact the hydrological and ecological systems of Oregon, management of water resources will become increasingly complex. Difficult decisions regarding tradeoffs, modifications to current water infrastructure, and coordinated, thoroughly-analyzed operations of hydrosystems are going to be necessary.

## 3.8 Conclusions and Recommendations

As illustrated by several case studies, climate change will affect various sectors of water resources in Oregon in the 21<sup>st</sup> century. First, the amount and seasonality of water supply is expected to shift as seasonal distribution of precipitation changes and temperatures rise. While annual total precipitation may not change or even increase under some climate change scenarios, hotter summers accompanied by reduced precipitation will decrease stream flow. Although there are no anticipated spatial patterns of precipitation and temperature change across the state for the 21<sup>st</sup> century (temperature is projected to increase uniformly across the region), significant regional variations do exist. Models suggest that spring and summer streamflow in transient rain-snow basins, such as those in the Western Cascade basins, will be sensitive to these changes in precipitation and temperature; analyses of existing long-term streamflow data in western Cascade basins reveal declining spring streamflow, but no changes

in summer or winter streamflows, since the 1950s. The High Cascade basins that are primarily fed by deep groundwater systems are expected to sustain low flow during summer months despite declining snowpacks, although the absolute amount of summer flow will decline. Basins in the east of the Cascades underlain by the Columbia River basalts are expected to have low summer flow in a distant future as groundwater recharge declines over time. April 1 snow water equivalent (SWE) will decline and the center timing of runoff will become earlier in transient rain-snow basins as snowpack is projected to decline consistently in the 21<sup>st</sup> century.

Second, water temperature is projected to rise as air temperature increases in the 21<sup>st</sup> century, particularly in urban streams where natural riparian vegetation is typically lacking. A decline in summer streamflow is expected to exacerbate water temperature increases, because the low volume of water will absorb solar radiation or blackbody radiation from the streambed and banks more quickly than during times with larger instream flows. Changes in water temperature can have significant implications for stream ecology and salmonid habitat in many Oregon streams. Lower order streams in transient rain-snow basins and in semi-arid eastern Oregon will be the most vulnerable to rising summer air temperature and diminished low flow. A new dam or reservoir might be required to maintain environmental flow in summer.

Third, as shown in the Portland water use study, when other demand factors are constant, increases in temperature alone would result in higher demands for peak season water. While demand during winter months is expected to remain constant, urban water demand is positively correlated with air temperature, particularly among single family residential (SFR) households. These impacts are also evident at multiple scales, including the household, neighborhood, and region. At the regional scale, urban land uses have different water demands, and will have varying impacts on water availability. Overall, people living in single-family residential areas are the largest consumers of water. At the neighborhood scale, the density of development helps to predict future water use, where higher density residential developments have lower water demand. Finally, at the household scale, the results of empirical research in the Portland region suggests a coupling of structural attributes (e.g. building and lot area) and temperatures that affect water demand. For the competing demands on regional water resources, if this development had contained smaller homes, and higher densities, other land uses would likely have more total water available.

Uncertainty is still high in projecting future changes in runoff, urban water demand, and water quality in Oregon. While the main source of uncertainty stems from the choice of global circulation models, additional sources of uncertainty include GHG emission scenarios, downscaling methods, hydrologic model structure and parameterization, and impact assessment methods. Multi-ensemble models that take into account all sources of uncertainty with different weights might provide a means of quantifying different sources of uncertainties. Communicating uncertainty to water resource decision makers is another challenge for adaptive water resource management in a changing climate. While a more sophisticated hydrologic impact assessment model yet to be developed, climate adaptation strategies can be implemented at multiple spatial scales.

Since one objective of land use planning is to coordinate regional activities, planning is one tool that may be helpful in meeting the future water needs of the State. Currently, land use and

water resource management agencies have limited coordination in their responsibilities. The analyses provided here suggest that two characteristics of land-use plans, namely zoning and public involvement, can be instrumental to improving the coordination between land and water management agencies. Zoning can be used to link types of future development (e.g., for 2030 and 2040) to include a combination of infill, expansion, connecting existing developments, with explicit identification of water demands on different land uses in the region. To date, few plans have explicitly included dimensions of water management. Outreach and education campaigns can help inform the public about the relationship between water demand and supply, but can also assist in adapting to a future with increasingly limited resources. The details of those plans and the precise nature of the outreach and education campaigns will require further investigation, and will likely be part of the second assessment of Oregon's water resources.

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## 4. Climate Change and Agriculture in Oregon

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### Summary and Knowledge Gaps

Oregon agriculture is as diverse as the geography and climate of the state. However, while this diversity is an economic strength, it creates a wide range of sensitivity issues to climate change factors that does not produce a “one-size-fits-all” assessment protocol or universal response. Most crop systems have been maximized for optimal production and sustainability through the years, and exist in a narrow temperature niche - one that may no longer be optimal under a warmer climate. The warming of the past century has already had an effect on the growing season; Oregon’s wine regions have seen the length of the frost-free period increase by 17 to 35 days.

In a changing climate:

- Availability, quality and cost of water will likely be the most limiting factor for agricultural production systems under the scenario of a warmer climate. Many Oregon irrigation systems are fed by snowmelt and stored in reservoirs. With a rise in temperature, irrigation demands are projected to increase.
- Perennial cropping systems are more vulnerable to climate change than annual systems. Research is needed to select drought resistant and robust temperature tolerant crops.
- There may be new opportunities for agriculture under a warmer climate but additional research on irrigation technologies, new crop adaptations, and associated management of new invasive plant pathogens will likely be needed.
- Crops will be vulnerable to invasion risk by pests and diseases that thrive in a warmer climate, increasing stress on plants. Warmer winter temperatures will allow insects to survive over the winter.

Agriculture is also contributing to the climate change problem. It is estimated that 8.6% of all human caused greenhouse gas emissions are from the agriculture sector (USGCRP 2001). There are opportunities for mitigation in the sector, through the use of different tillage practices, nitrogen management strategies and livestock diet management. Oregon needs to conduct studies on specific crops/commodities and how they will

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function in a changing climate. Most of the available studies on climate change effects to Oregon crops/commodities is largely speculative, drawing from studies conducted in other states (California and Washington).

## 4.1 Introduction

Agriculture is extremely vulnerable to climate change as most crop systems have been optimized to fit a given climate niche allowing for economically sustainable quality and production. These climatic niches range from fairly broad conditions suitable for crops such as wheat or corn, to more narrow conditions suitable for specialty crops such as berries and wine grapes. Agriculture responses to changing climates reflect the interaction between temperature, water availability and timing, and increasing carbon dioxide concentrations. As such, understanding agricultural impacts from climate change necessitates integrated studies examining the combined effects of these three factors.

As agriculture is a highly climate sensitive sector, climate change impacts are likely to have a significant impact on the growth and productivity of plants and livestock, cropping and grazing seasons, and the spread of pests and diseases (Mearns, 2009). Projected warming is expected to result in a displacement of current agricultural zones, with likely movements northward (Northern Hemisphere), toward the coast, and higher in elevation. Higher temperatures are also likely to reduce the amount of land appropriate for grazing in some regions, with implications for livestock productivity. In addition, warming may lead to greater irrigation requirements. For a rise in temperature of 1°C, irrigation demands are projected to increase by at least 10% in arid and semi-arid regions. These factors may contribute to lower agricultural yields, which may increase dependence on global grain markets and threaten food security, particularly of the urban poor, who are already heavily influenced by prices in global markets.

Furthermore, while changing climates clearly affect agriculture, the agriculture sector also affects climate through the emissions of greenhouse gases. It is estimated that agriculture in the United States contributes 8.6% of all human-produced greenhouse gas emissions (USGCRP 2001). Therefore, agriculture plays a dual role in climate change impact assessment whereby it can help mitigate impacts, but clearly needs to adapt to changes in climate so that future food supplies and regional economies can be maintained. Historically, people engaged in agricultural have adapted to a range of climate impacts over both the short and long term. Future adaptation is made more challenging by the large size of agricultural operations today, the long-term investments made in them, and the observed and anticipated rapid changes in climate. To help understand the range of impacts and increase resiliency in agriculture, scientists and governments will need to provide timely information and policies allowing for suitable adaptive responses.

## 4.2 Agriculture in Oregon

Oregon agriculture is as diverse as the geography and climate of the state. As of 2008, Oregon had 38,600 farms operating on 16.4 million acres with an average farm size of 425 acres (NASS 2009a,b). The average value produced per acre in 2008 was \$2260, representing a gross value of commodities and services produced in one year of nearly \$5 billion for agricultural sector production. Oregon agricultural commodity production is mostly crops (72.72%) followed by livestock and poultry products (21.67%), forest-farm products (2.64%), and fishery products (2.97%) (Table 4.1). Within the crop production sector, field crops represent 27.43%, greenhouse, nursery and tree farms 19.16%, seed crops 11.11%, fruit and nut crops 9.74%, and vegetable crops 5.27% (NASS 2009a). By value, Oregon's largest single commodity is greenhouse and nursery products followed by hay, grass seed (all types), cattle and cattle products, wheat, potatoes, and Christmas trees. In terms of national rankings for agricultural production, Oregon ranks first in fifteen different commodities with many berry and seed crops producing between 70 and 100 percent of the nation's overall production (Table 4.2). Total exports of Oregon agricultural commodities were \$1.6 billion in 2008 with wheat and wheat products, seeds, fruit and fruit preparations, and vegetables and vegetable preparations representing over 60% of the total (NASS 2009a).

**Table 4.1.** 2008 Oregon agricultural commodity sectors. (Source: NASS, 2009a)

Commodity Sector	% of all Commodities
All farm production (less fishery)	97.03
All crops	72.72
Greenhouse, nursery and tree farms	19.16
Field crops	27.43
Seed crops	11.11
Fruit and nut crops	9.74
Vegetable crops	5.27
All livestock and poultry products	21.67
Forest products, farm	2.64
Fishery products	2.97

**Table 4.2.** Oregon’s Top 40 Agricultural Commodities for 2008. (Source: NASS, 2009b)

Rank	Commodity	Value	Rank	Commodity	Value
1	Greenhouse & nursery products*	\$880,061,000	21	Sweet corn, all	\$34,864,000
2	Hay	\$613,311,000	22	Grass and grain straw*	\$34,004,000
3	Grass seed, all*	\$510,298,000	23	Crab landings	\$29,175,000
4	Cattle & calves	\$426,794,000	24	Snap beans, processing	\$26,418,000
5	Milk	\$412,482,000	25	Horses*	\$25,500,000
6	Wheat	\$340,178,000	26	Vegetable & flower seeds*	\$25,072,000
7	Potatoes	\$211,039,000	27	Mint for oil	\$24,544,000
8	Christmas trees*	\$122,765,000	28	Blackberries, all	\$22,941,000
9	Onions, storage	\$97,524,000	29	Shrimp landings	\$21,384,000
10	Pears	\$92,582,000	30	Hay silage*	\$20,068,000
11	Winegrapes	\$71,135,000	31	Mink	\$20,033,000
12	Eggs	\$64,974,000	32	Strawberries	\$16,768,000
13	Cherries, all	\$56,356,000	33	Raspberries, all	\$13,082,000
14	Hazelnuts	\$52,160,000	34	Tomatoes*	\$12,995,000
15	Corn, grain & silage field	\$52,137,000	35	Sheep & lambs	\$11,369,000
16	Blueberries	\$49,266,000	36	Tuna, albacore landings	\$10,651,000
17	Groundfish landings	\$43,587,000	37	Barley	\$10,463,000
18	Hops	\$37,991,000	38	Squash & pumpkins*	\$9,956,000
19	Apples	\$37,752,000	39	Watermelons*	\$8,865,000
20	Cranberries	\$36,600,000	40	Green peas, processing	\$8,768,000

While some of Oregon’s agricultural commodities are more broadacre crops such as hay or wheat, many of them are specialty commodities, which together represent quite different climate requirements and thresholds that need to be better understood to adequately assess climate change impacts.

### 4.3 Oregon Agricultural Sensitivity to Climate Change

Oregon’s agricultural diversity is an economic strength, but it creates a wide range of sensitivity issues to various climate change factors. Depending on the crop/commodity and its current climatic equilibrium, temperature or precipitation changes can either reduce or increase yields or quality. Few direct studies on climate, production and quality thresholds for Oregon’s major crops have been done. Most of the direct studies done are largely speculative, indicating that if a given crop/commodity exists within today’s climatic thresholds, projected climate changes would push them outside what is suitable. What is needed is much more direct and controlled studies of plant/animal growth characteristics, optimum climate requirements and variability thresholds for economic sustainability. For example, Lobell et al., (2006) and Lobell et al., (2007) have



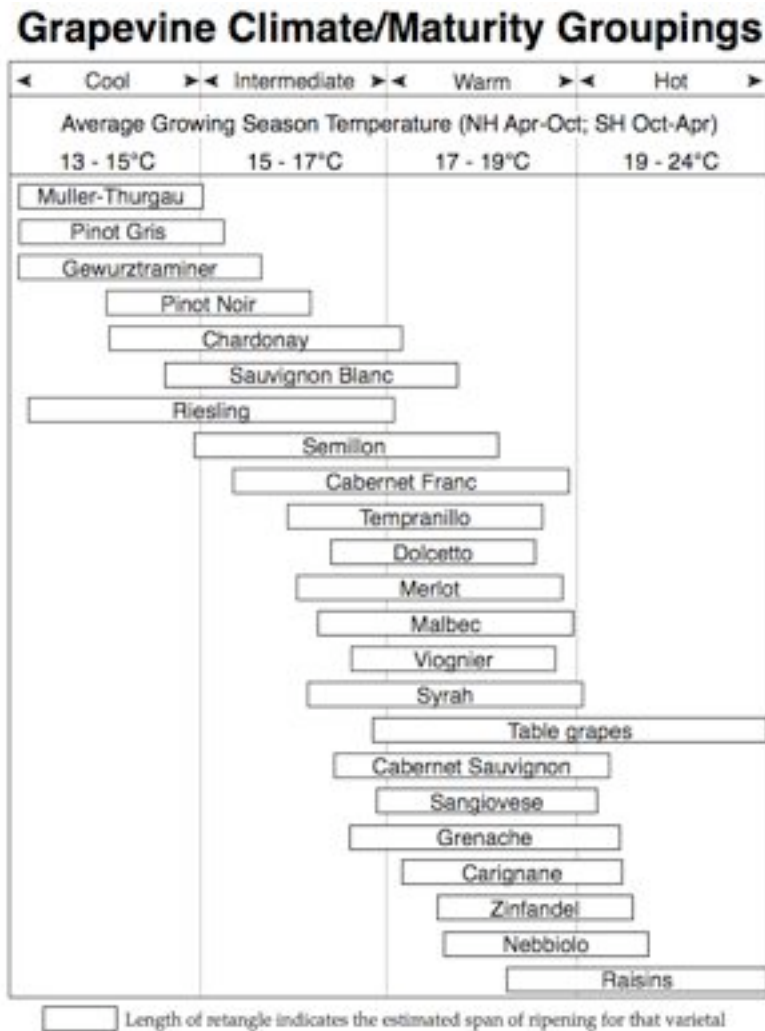
conducted studies on major crops in California revealing historical impacts and future sensitivities. These kind of studies need to be replicated for Oregon's climate and crops.

Good examples of impacts and sensitivity concerning Oregon agriculture include winegrapes and orchards. For winegrapes, research globally has shown that each variety has a relative narrow climatic optimum for both quality and economically sustainable production. For Oregon, no crop better illustrates climate sensitivity and risk associated with climate change than Pinot Noir, the state's marquee winegrape. Pinot Noir is typically grown in regions spanning from cool to lower intermediate climates with growing seasons ranging from roughly 14.0 - 16.0°C (Jones, 2006). Across this 2°C climate niche, Pinot Noir produces the broad style for which is it known with cooler zones producing lighter, elegant wines and warmer zones producing more full-bodied, fruit-driven wines. While Pinot Noir can be grown outside the 14.0 - 16.0°C growing season average temperature bounds, it is typically unripe or overripe and readily loses its typicity.

Changes in the climate of Oregon's wine growing regions since 1950 (especially the Willamette Valley) have provided longer and warmer growing seasons and less risk of frost (Jones, 2003, 2005). These changes have taken the Willamette Valley from a marginal wine climate (< 14°C) to one producing globally recognized high-quality wines (averaging 15°C or higher today). Similar changes have been seen in other wine regions worldwide (Nemani et al., 2001; Jones et al., 2005; Jones, 2006; White et al., 2006; Jones and Goodrich, 2008). However, due to the narrow niche Pinot Noir requires for optimum quality, further increases in temperature will likely move much of current acreage planted in the Willamette Valley outside of what is considered suitable for Pinot Noir (White et al., 2008). This would necessitate costly adaptation processes of replanting to different, warmer climate grape varieties (Figure 4.1), or moving to higher elevations, more toward the coast, or further north in latitude. Additional risks come from the marketing side, where changes in varieties or wine styles would require a substantial effort to inform consumers and maintain market viability.

Orchard-based crops provide another example of the potential economic impacts of climate change associated with rising temperatures. Like many crops, orchard fruits mature more quickly at higher temperatures. Earlier maturity, however, brings issues of both crop quality and its timing to market. Oregon apples and pears, for example, are sold into a global market in which crop quality and availability provide comparative advantages. Observations in Jackson County, where pears represent a large portion of the crop land, show pear bloom dates in the spring have been earlier in the year with lower frost impacts (G.V. Jones data). However, when frosts do occur, the trees are not as accustomed to the low temperatures as they used to be and minor frosts can be more problematic (Gu et al., 2008). In addition, the earlier start to the season has been followed by earlier harvests, which influence when the fruit goes to market, potentially creating disconnect with historic need. Further shifts to earlier and earlier harvests during warmer summers could both lower the quality of the fruit and shift the competitive environment in which Oregon producers must sell their crop. In addition,

winter chilling requirements for orchard crops in Oregon appear to still be sufficient, unlike California. There, chilling hours during winter have declined by as much as 30% since 1950 in areas of the Central Valley to the point of not making some orchard crops viable (Lobell et al. 2006; Luedeling et al. 2009). However, as climates continue to change, similar winter dormancy issues could mean trouble for Oregon's perennial crops.



**Figure 4.1.** Climate maturity groupings based on average growing season temperatures and the estimated span of varietal ripening potential occurring within and across the groups. Note the climate data depicted in Table 1 is derived from grids, not station data therefore values given may deviate slightly from any one station in a given region (Jones et al., 2004).

Potatoes are also sensitive to rising temperatures because warmer temperatures accelerate plant development and leaf senescence, and because higher temperatures during tuber bulking reduce translocation of carbohydrates from the plant to the tubers (Timlin et al., 2006). Adams et al. (1999) predicts potato yield decreases at sites across the United States with rising temperatures, with yield decreases as high as 50% with a 5 °C temperature rise, due to the sensitivity of potatoes to temperatures in tuberization

response. Yield increases as a result of CO<sub>2</sub> fertilization effect were insufficient to offset yield reductions. At the same time, the authors note there is a high degree of genetic variability in potatoes, suggesting further research may be able to help the potato industry adapt to changing climate conditions. Stöckle et al. (2008) also predicts significant potato yield decreases with modeled temperature increases, but increasing CO<sub>2</sub> concentrations compensated significantly for the yield reductions. Alva et al. (2002) finds high temperature during tuberization may contribute to lower tuber quality.

Increased variability in crop yields as a result of climate change is predicted to impact global cereal grain and oil seed trade (Reimer and Li, 2009).

#### **4.3.1 Livestock Production**

There will likely be both positive and negative benefits to livestock production from climate change. Milder winters may increase livestock survival and lengthen the available grazing season. A direct impact may come from increased or decreased availability of water for drinking. There are substantial costs incurred for water hauling or drilling of wells. There is an opportunity for expanded use of solar or wind powered pumping systems that might offset some water hauling or drilling costs in the long-term. A changing climate may require adaptation of water delivery systems to new areas and additional fencing to limit cattle access to creeks and riparian areas. A shift toward higher temperatures, drier conditions and less irrigation availability will influence water temperature. Increased water temperature can have a negative impact on any of a number of listed fish species (or other aquatic or riparian dependent species), and the resulting Endangered Species Act induced restrictions could have a substantial impact on production costs for livestock producers and others in agriculture.

On a similar note, hotter, drier climatic conditions, coupled with less irrigation could affect the timing and amount of forb production on rangelands, playas, meadows, etc. which could impact an important food source for sage grouse chicks during part of their life cycle. If bird populations decline, especially enough to trigger an ESA listing, restrictions will likely impact production costs for livestock producers. At certain times, insects are also an important component of sage grouse diets. If insects are negatively impacted by climatic change, sage grouse could suffer population declines and additional management restrictions could be imposed. In drier areas, grazing may need to be limited or foregone. There is a need to do research on developing new forages, livestock breeds resilient to temperature changes, and the development of new grazing or feeding strategies.

Climate change has the potential to influence the rate of increase and distribution of invasive plants species and to alter plant community distribution. Depending on the nature and magnitude of these changes, if they occur, both cost and capacity of production could be affected. Increases in atmospheric CO<sub>2</sub> has have impacted the retention of cheatgrass biomass and it seems likely that it this could have implications for fire disturbance (Ziska et al., 2005). This type of disruption can impact livestock

grazing opportunities (see Chapters 6 and 7).

### **4.3.2 Changes/Shifts in Growing Seasons**

There is much evidence pointing to a lengthening of the growing season globally of between 10 and 20 days in the last few decades (Linderholm 2006). The change is asymmetric and largely due to an earlier onset of spring instead of later ending of fall (Christidis et al., 2007). Growing season lengths are often defined by the period of time that is frost-free and Easterling (2002) finds that warming in the United States has resulted in a decrease in the number of frost days, an earlier date of the last spring frost, a later date of the first fall frost, which has resulted in a lengthening of the frost-free period during the last half the 20th century. Examining wine region climates across the western US, Jones (2005) finds longer growing seasons (38 days longer on average) and less risk of frost. Oregon's wine regions have seen the length of the frost-free period increase by 17 to 35 days.

Growing season shifts, or increases in growing season duration, can have mixed effects to regional agricultural production, benefiting some crops while harming others. Adams et al. (2006) models changes of yields and irrigation water demand for a variety of crops in California and finds warming during the growing season is generally beneficial to yields in cooler regions of the state, but is harmful to yields in the San Joaquin region. Models also predict crops in cooler regions benefit from additional degree-days of warming. However, longer and warmer growing seasons translate into generally higher irrigation water demands, although this is mitigated somewhat by the CO<sub>2</sub> fertilization effect.

Adams et al. (1999) also model the impacts of two climate change scenarios on cattle and forage production in Texas. Increased temperatures combined with the CO<sub>2</sub> fertilization effect have mixed results on forage production in different regions of Texas: production increases in some regions but decreases in others. Cattle production is affected by increased summer temperatures and associated stress to livestock, along with lower energy requirements for maintaining body heat in the winter. The authors predicted the net effect to cattle production in Texas to be negative.

### **4.3.3 Extreme Events and Agriculture**

Possible increases in the frequency and intensity of extreme daily precipitation events are likely to affect agriculture and aquaculture adversely and to threaten food security. Impacts can include damage to crops and infrastructure, delayed effects due to pests and diseases, as well as waiting periods of several years for uprooted trees and plants to be replaced and become productive. In turn, these can result in loss of crop and fishery productivity, food shortages, and elevated food prices in the absence of adaptation.

The costs of weather-related disasters in the U.S. have been increasing since 1960, and globally trending upward faster than population, inflation, insurance penetration, and

non-weather related event costs (Mills, 2005). It is difficult to estimate the impacts of natural disasters in Oregon to agriculture. Costs are not broken out by sector by the U.S. Federal Emergency Management Agency (FEMA) for specific disasters. While U.S. Department of Agriculture disaster payments to agricultural producers may provide some relative measure of disaster impacts, they are unlikely to provide a comprehensive cost of a disaster's impact to agriculture. This is because only certain crops are eligible for disaster payments or insurance programs, and cost-share payments may vary by program, not reflecting agricultural producers' matching investments for disaster response.

Droughts are one of the most costly natural disasters. Many counties in eastern and southeastern Oregon have experienced season-long or prolonged drought in recent years, with the Klamath Basin drought in 2001 being one of the most well-known as far as its impacts to agriculture. Droughts are likely to be exacerbated by earlier and lower spring snowmelt and runoff, which is occurring 7 - 10 days earlier than the historical average (Cayan et al., 2001). Estimates of economic impacts for natural disasters such as drought are difficult to reproduce because of the unique nature of drought, including its slow onset and significant secondary impacts (Kunkel et al., 2008). U.S. agricultural losses have been estimated at \$4 billion per year over the past 10 years, but it is unclear if they are directly related to crop production or other factors. Little to no official estimates exist for the livestock sector, as well as several other nonagricultural sectors (Kunkel et al., 2008).

Heat waves can also cause significant economic damage to crops and livestock. Even short-lived events can damage crop quality and reduce yields (Reilly, 2002). Reilly (2002) suggests breeding for cold tolerance during germination and heat tolerance during grain filling will probably mitigate some impacts of increases in temperature variability and some extremes, but this conclusion is mostly based upon research conducted on grain crops. Livestock are especially vulnerable to higher temperatures in the summer, but these losses will very likely be mitigated by warmer winter temperatures in the state (Hauser et al., 2009).

Some types of natural disasters may decrease in frequency under changing climatic conditions. Over the last ten years, most land areas in the United States had lower numbers of severe cold snaps than any other ten-year period. In addition, a decrease of frost-free days has been observed in the U.S., with a more pronounced decrease in the West (Kunkel et al., 2008). Depending on the timing of cold snaps, this trend may decrease damage to Oregon's crops, but it may also increase the likelihood of survival of insects and other pests. In addition, if a crop experiences a rapid swing between high and low minimum temperatures, winterkill can result (Reilly, 2002).

Nationally, the frequency and intensity of heavy precipitation events is on the rise. The most pronounced changes have taken place in other parts of the U.S. outside the Pacific Northwest. There is some indication these events may increase in the Pacific Northwest. The Northwest is located in a transitional area where some models show increasing precipitation and the others show the opposite. However, the projected upward winter

temperature trend suggests more precipitation will likely fall as rain rather than snow (Chapter 1 - Climate). This pattern, combined with earlier snowmelt, could mean less summer water availability for irrigation and other natural resource needs.

Interannual variability will continue to dominate precipitation (particularly winter) in the Pacific Northwest. Historically, the El Niño Southern Oscillation and La Niña phenomena have resulted in periods of drought and heavy precipitation in the Pacific Northwest. Changing precipitation patterns are predicted to cause significant increase in crop losses, but better forecasting could partially offset these losses (Reilly et al., 2002).

#### **4.3.4 Adaptability of Oregon Agricultural Producers to Changes in Climate**

Agriculture is considered one of the sectors most adaptable to changes in climate. Typically, agriculture producers are an adaptable group, however, increased heat and water stress, changes in pest and disease pressures, and weather extremes will pose adaptation challenges for many crop and livestock production systems.

Probably the biggest advantage Oregon agricultural producers have relative to changes in climate are that those in agribusiness continually adapt to variations in climate, otherwise they would not be successful. As a result adaptation by farmers should allow them to maintain quality and production levels in the face of short-term and modest warming. However, if warming is very rapid and compounded by less and less availability of water, then the ability to adapt is much lower. This has been seen in Australia where a multi-year drought episode, and government policies that failed to manage water appropriately and inform stakeholders, has brought near collapse to the wine industry in many regions. Surveys out of California and Australia, reveal growers deem site factors are essential to quality and these include climate and access to irrigation. They also believe their ability to adapt to changes in climate becomes increasingly difficult with greater warming unless there are better understanding of their system and government policies that are proactive.

#### **4.3.5 Changes in Crop Diseases and Pests**

While agricultural crops are responding to changes in climate, so are plant diseases, pests, weeds, and vertebrates. Climate change is expected to enhance invasion risk from many crop diseases, pests, and weeds (Bradley et al., 2009; Sutherst et al., 2007) ultimately increasing the stress on crop plants and requiring more attention to pest and weed control. In addition to the direct impact on plants growing in both managed and natural ecosystems, a changing climate will affect pathogens causing diseases, reduction in productivity, and often death of their hosts. It is expected that changes in temperature, precipitation and other environmental factors will have both direct and indirect impacts on host-pathogen interactions. These will be host and pathogen specific and it is not possible to make accurate general predictions. There are, however, numerous examples of how plant disease occurrence and spread appear to be closely tied to prevailing climatic factors and evidence that global climate change is already impacting the occurrence of some diseases (Anderson et al., 2004; Bergot et al., 2004; Harvell et al.,

2002; Woods et al., 2005). In the long-term, one expects the increases in some diseases to be balanced out by decreases in others (Coakley et al., 1999; Scherm and Coakley, 2003). Unfortunately, in managed ecosystems, the speed of climate change and the often long growing cycle (e.g., fruit trees, grape vineyards, and forests) are likely to result in significant and difficult to manage economic losses for some crops before adjustments can be made (Garrett et al., 2006). If an annual crop such as wheat is hit severely by disease one season and it looks like disease pressure will be high again the next, one may be able to choose another cultivar resistant to the pathogen or another crop. If a perennial grass or mint field develops a soil borne root disease, the only option may be to remove and replant with another crop. In the case of perennial cropping systems, e.g., vineyard or hop yard, the use of predictive models and chemical control can help manage the response. There are several examples of agricultural diseases important in the Pacific Northwest that may be impacted significantly by a change in temperature or precipitation patterns. Downy mildew on grapes has not been found in Oregon since the late 1930s. Downy mildew is thought to be related to a generally unfavorable climate. However, a very similar pathogen occurs on Boston Ivy, a closely related species, and the potential exists for this pathogen to re-emerge in Oregon. Research out of Italy suggests additional sprays (currently 7 - 10 are used) might be needed to control this disease with the most likely climate change scenarios expected (Salinari et al., 2006). In contrast, powdery mildew does occur on grapes in Oregon, but is fortunately an easier disease to manage. Spider mites are an example of a plant pest that may increase in severity under warmer and drier conditions. Following a particularly mild winter in 2005, voles reached epidemic numbers in the Willamette Valley and wreaked havoc on grass fields and vineyards. The following winter was unusually wet and cold and the vole populations rapidly returned to normal. This example serves as a reminder of how vulnerable perennial cropping systems may be to pests favored by unusual climatic conditions.

Rising temperatures allow both insects and pathogens to expand their ranges to regions where they were once not found (Kamata et al., 2002). In addition, warmer winter temperatures allow more insects to survive over the winter, whereas colder winters once controlled their populations. The absence of normal low winter temperatures across Canada may be directly related to the increase of pine bark beetles across Canada. Furthermore, changes in climate have the potential to disrupt the natural enemies of some crop pests (beneficial insects), ultimately producing greater overall crop vulnerability (Campanella et al., 2009; McEvoy and Dauer, 2009; Hatfield et al., 2008; Thomson et al., 2010).

Warmer temperatures may also allow for additional generations of insect pests within a single growing season. Stöckle et al., (2008) models codling moth populations under baseline conditions and four Global Climate Model (GCM) projections and finds earlier emergence of adults in spring coupled with warmer temperatures in summer would result in most apple-growing locations in Washington state experiencing a complete third generation hatch. These results suggest additional costs to apple growers from additional pheromone and sprays per season. Altermatt (2010) reviews European datasets documenting the number of generations of 263 European butterflies and moths

per growing season and finds higher frequencies of second and subsequent generations in many species, suggesting a higher risk of outbreaks for some agricultural and forest pests. Furthermore, changes in climate have the potential to disrupt the natural enemies of some crop pests (beneficial insects), ultimately producing greater overall crop vulnerability (Thomson et al., 2010).

The warmer, wetter fall and winter seasons projected for the Pacific Northwest may have similar impacts on plant pests. Stöckle et al. (2008) predict warmer and wetter falls and winters will result in greater numbers and growth of winter and annual weeds, such as volunteer potato.

Higher temperatures and atmospheric CO<sub>2</sub> concentrations may affect the effectiveness of existing pesticides on diseases, plant pests, and insect pests. Ziska et al. (1999) and Ziska and Goins (2006) find glyphosate loses its effectiveness on weeds grown at CO<sub>2</sub> levels likely occur in the future.

#### **4.4 Indirect Effects of Increasing CO<sub>2</sub> on Agriculture**

Carbon dioxide is essential to plant growth and evidence suggests total crop yields may rise when averaged across the globe due to effects of CO<sub>2</sub> fertilization (Drake et al., 1997). Even with the advent of more realistic field experiments (e.g., Free-air concentration enrichment - FACE) few impact studies have been done outside of broadacre crops such as wheat, corn, and soybeans.

Kimball (1983) reviews 430 prior studies evaluating crop response to higher CO<sub>2</sub> concentrations. C3 crops (most crops, including wheat and soybeans) respond with yield increases up to 30% under doubled CO<sub>2</sub> concentrations. C4 crops (corn, sorghum, sugar cane) having much lower yield increases, around 7%. Kimball et al. (2002) summarizes crop yield impacts under free-air CO<sub>2</sub>-enriched environments.

In addition to increasing plant growth and biomass production, higher carbon dioxide concentrations can mitigate drought stress to certain crops by causing partial stomatal closure. Hatfield et al. (2008) review a variety of studies demonstrating reduced crop stomatal conductance under CO<sub>2</sub>-enriched environments. Fleisher et al. (2008) find that in potato plants under drought stress, plants grown in elevated CO<sub>2</sub> conditions produce higher yields, suggesting that CO<sub>2</sub> enrichment will mitigate drought-induced yield reductions. Curtis and Wang (1998) review studies of woody plants and find elevated CO<sub>2</sub> decreases stomatal conductance less in woody plants than in herbaceous plants. Kimball et al. (2002) reviews FACE experiments and notes elevated CO<sub>2</sub> levels stimulate growth in plants under water stress as much as plants in well-watered conditions.

Models evaluating climate change impacts to agriculture have generally shown reduced crop yields from changing climate conditions, but significant mitigation of yield losses because of the CO<sub>2</sub> fertilization effect. Stöckle et al. (2008) models yields for several types of crops under increasing temperatures and higher CO<sub>2</sub> levels. Temperature increases



are generally detrimental to crop yields, but CO<sub>2</sub> fertilization greatly reduces these effects. In some cases, the net effect of a temperature increase and CO<sub>2</sub> fertilization on crop yields is positive.

Rising atmospheric CO<sub>2</sub> levels can have both positive and negative impacts on crop quality depending on other factors such as temperature, water, and nutrient availability. Wolfe (1994) notes that fertility and growing conditions need to be good in order to maximize potential benefits from higher CO<sub>2</sub> concentrations. Research on the effects of increased CO<sub>2</sub> levels has been carried out since the early 1980s, often in controlled situations, to assess the effects to crop quality and yield (Mearns, 2009). When nutrient supplies are limited, the quality of the crop, especially grain protein content, may decline (Bazzazz and Fajer, 1992). Ziska and Goins (2006) observe a significant vegetative response of soybeans to higher CO<sub>2</sub> concentrations, but no consistent effect on seed yield. Bindi et al. (2001) evaluates the response of winegrapes to enriched CO<sub>2</sub> and documents higher biomass and fruit production, with little change in fruit and wine composition. Studies in rangelands find lower nitrogen concentrations in shortgrass steppe, tallgrass prairie, and mesic grassland at elevated CO<sub>2</sub> levels (Owensby et al., 1993; Hungate et al., 1997; King et al., 2004; Wan et al., 2005; Gill et al., 2006), which presents significant implications for forage quality.

Even under conditions with good nitrogen availability, plant and grain nitrogen quality may decline under higher CO<sub>2</sub> concentrations. In their review of FACE experiments, Kimball et al. (2002) find an average decrease in grass leaf nitrogen concentration of 9% under elevated CO<sub>2</sub> levels and ample water and nitrogen, and under low soil nitrogen conditions, an average leaf nitrogen concentration of 16%. Kimball et al. (2001) finds a 3% decrease in wheat grain nitrogen concentration under good conditions, and a 9% decrease under low soil nitrogen conditions. The authors report that low soil nitrogen by itself cause serious reductions in nutritional and baking quality and elevated CO<sub>2</sub> makes the situation worse.

Some experiments predict greater plant nitrogen uptake to maintain carbon to nitrogen ratios and less long-term nitrogen availability, limiting long-term growth (Luo et al. 2006). Kimball et al. (2001) note FACE experimental results show a wide range of effects on nitrogen removal under higher CO<sub>2</sub> concentrations, both positive and negative, depending on the crop.

Researchers have documented some interesting secondary effects to crops due to the CO<sub>2</sub> fertilization effect. Coviella and Trumble (1999) and Hunter (2001) note insects sometimes feed more on leaves having lower nitrogen content in order to obtain sufficient nitrogen. Free-air concentration enrichment (FACE) experiments show 57% more insect pest damage to soybeans in higher CO<sub>2</sub> concentrations, which researchers hypothesize is due to increases in levels of simple sugars in leaves. Aphid populations have also been shown to increase under higher CO<sub>2</sub> concentrations, independent of temperature changes (Bezemer et al., 1998; Doherty et al., 1997; Salt et al., 1996).

It is possible crop response to higher CO<sub>2</sub> levels may be temporary. Some experiments

predict greater plant nitrogen uptake to maintain carbon to nitrogen ratios and less long-term nitrogen availability, limiting long-term growth (Luo et al., 2006).

## **4.5 Water Availability and Irrigation Requirements**

The most pressing limitation to future agricultural production may be the quantity, quality and cost of water. In addition to shifts in temperature, changes in precipitation are likely which will alter the variability, timing, frequency, intensity, and spatial coverage of rainfall. Since many agricultural production regions rely on rain-fed production systems, these changes may have severe impacts on agricultural production. Extreme daily and prolonged rainfall during planting seasons could damage seedlings, reduce growth, and provide conditions promoting plant pests and diseases. Moreover, the resultant rise in the frequency and intensity of floods may result in soil erosion and flooding of agricultural lands leading to greater crop losses in more vulnerable regions. On the other hand, drought combined with higher temperatures may lead to greater evaporation, reduced availability of water for agriculture, and added thermal stress on plants. Oregon has substantial experience with water limitations as a result of drought. The Klamath Basin has been particularly hard-hit in the need to respond to competing water demands. Boehlert and Jaeger (2010) provide an excellent review of the issues faced in that region (see Chapter 8).

For irrigation managed cropping systems small changes in water availability will necessitate the need for more water and greater efficiencies in irrigation infrastructure. For a rise in temperature, irrigation demands are projected to increase. Moreover, decreases in water from snow- and glacial-melt could, over time, impact smallholder irrigation systems and hence food production. However, shifts in the amount and timing of precipitation (e.g., snow falling later, melting earlier) will likely have greater impacts, at least in the near term.

In California, history has shown farmers increasingly employ new water conservation technologies as drought becomes more severe (Cavagnaro et al., 2005). Examining the past resiliency of Oregon agricultural producers in dealing with climate-related events, one can speculate that the same would hold true for Oregon.

In recent years, toxic algal blooms appear to be more frequent and widespread in Oregon. Additional research is needed on how to predict and limit these toxic blooms which can lead to illness and death of livestock and other animals (See Chapter 7).

## **4.6 Mitigation Capacity of Oregon Agricultural Producers:**

There are several types of mitigation opportunities in Oregon agriculture: soil carbon

sequestration, reduction of nitrous oxide emissions through nutrient, manure, and irrigation water management; reduction of methane emissions from livestock diet and manure management, and reduction of energy consumption.

Soil tillage buries and mixes crop residue into the soil to prepare a seedbed for crop planting. Tillage accelerates oxidation of organic matter within soil, thus contributing to greenhouse gas emissions that negatively impact air quality and global climate-related processes (Reicosky, 1997). In contrast, conservation tillage systems plant directly into crop residues (no-till, or direct seeding) or only till part of the soil area (zone-till). Long-term research trials comparing conventional tillage with conservation tillage show significant improvements in soil quality in conservation tillage, including elevated levels of soil carbon sequestered in organic matter (Johnson and Hoyt, 1999).

Other research shows little difference between the overall sequestration benefits of conventional vs. no-till agriculture (Blanco-Canqui and Lal, 2008), but the two tillage systems result in carbon being stored in different locations within the soil. Under conservation tillage, organic matter remains near the soil surface, while under conventional tillage organic matter is distributed deeper into the soil. Liebig et al. (2005) summarize the available literature regarding soil organic carbon and carbon dioxide, nitrous oxide, and methane fluxes in cropland and rangeland in the western U.S. continuous no-till cropping. Generally, continuous no-till cropping and grazing increases soil organic carbon in the top 10 - 30 centimeters of the soil.

Conservation tillage is not widely practiced in Western Oregon for a number of reasons, primarily due to the extended cold and wet periods in the spring that often interrupt planting schedules, particularly when crop or cover crop residues remain on the soil. Scientists at Oregon State University (OSU) are collaborating with farmers to evaluate the potential of using zone tillage to overcome some of the obstacles associated with conservation tillage on both organic and conventional farms. Less tillage will directly reduce carbon emissions because of reduced equipment use (Luna and Staben 2002, 2003), and indirectly by reversing the loss of carbon from the soil. Conservation tillage has the potential to stabilize losses of organic carbon from soil, and may allow farmers in Oregon to capture carbon from the atmosphere and sequester it in organic matter within the soil.

Scientists at the Columbia Plateau Soil Conservation Research Center (CPSCRC) at Pendleton, operated jointly by Oregon State University and the USDA-Agricultural Research Service (ARS) have conducted several long-term experiments to evaluate carbon sequestration potential in low rainfall areas of eastern Oregon. This research suggests that permanent grass cover promotes the highest rate of carbon storage in the top 30 centimeters of soil, and that no-till results in net carbon storage in the top 30 centimeters of soil, but the overall carbon sequestration potential of these soils is relatively low (Albrecht et al., 2008). Nevertheless, the carbon accumulated in the upper soil profile boosts soil tilth and quality, and strategies that increase carbon near the soil surface will help agricultural producers adapt to warmer temperatures and other consequences of climate change.

In the summer of 2009, ARS researchers at the CPSCRC also published the results of a ten-year study evaluating several cropping patterns on soil organic carbon up to 150 centimeters in soil depth (Gollany et al., 2009). One of the findings in the study is that soil organic carbon levels increase significantly throughout the soil depth evaluated under a continuous wheat no-till system.

Studies in other parts of the United States show nitrogen management strategies such as proper application rate matched to crop needs, proper timing, and using slow-release forms of fertilizer can reduce nitrous oxide emissions associated with fertilizer application (Snyder et al., 2007; Halvorson et al., 2009). Emissions rates vary widely by soil and location, and soil emission rates for Oregon have not yet been researched.

Livestock diet and manure management can affect methane and nitrous oxide emissions. Odongo et al. (2007) find that adding an ionophore, monensin, to the diet of lactating dairy cows achieves long-term reduction of methane emissions. Some other studies also find long-term benefits from monensin, while others find only short-term effects. Many fertilizer application strategies that reduce greenhouse gas emissions also apply to manure management strategies, such as applying the right amount of nitrogen for the crop, and timing the application appropriately.

Agricultural producers in Oregon have implemented a variety of energy efficiency and renewable energy strategies to reduce electricity, natural gas, propane, diesel, and gasoline use, directly and indirectly reducing carbon dioxide emissions. No comprehensive assessment of the amount of reductions or the potential for further reductions currently exists. This year, USDA National Agricultural Statistics Service plans to conduct the first on-farm renewable energy survey, so it is possible that additional energy and agriculture statistics will be available for Oregon in the future.

Some other states, such as Washington, have conducted assessments of the greenhouse gas mitigation potential by agricultural producers, but no comprehensive assessments have been conducted in Oregon.

## **4.7 Adaptation options**

Recommendations from the Climate Change Integration Group (2008) specific to Oregon agriculture include:

- Introduction and study of more heat and drought tolerant species and animal breeds
- Developed genetic tools for adaptation
- Avoid over-management that could lead to greater risk
- Short-term: adaptive management
- Long-term: new crop varieties
- Foster no-till soil management
- Improve water-use efficiency and infrastructure

- Develop more accurate seasonal to annual climate forecasting

The International Food Policy Research Institute (Nelson et al., 2009) summarizes the top eight policy and program priorities for agriculture:

1. Design and implement good overall development policies and programs.
2. Increase investments in agricultural productivity.
3. Reinvigorate national research and extension programs.
4. Improve global data collection, dissemination, and analysis.
5. Make agricultural adaptation a key agenda point within the international climate negotiation process.
6. Recognize that enhanced food security and climate-change adaptation go hand in hand.
7. Support community-based adaptation strategies.
8. Increase funding for adaptation programs.

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## 5. The Potential Effects of Climate Change on Oregon's Vegetation

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### Summary and Knowledge Gaps

There is clear evidence from the paleoenvironmental record that Oregon's vegetation has responded to climate changes over past millennia. Recent research indicates that plants have also responded to climate changes over the last century, with relatively large and more rapid changes occurring since the mid-1970s. Twentieth-century vegetation changes in Oregon that may be the result of changing climate include earlier flowering dates for some plant species and increased tree mortality in some old-growth forest stands. Evidence from studies in the California Sierra Mountains and elsewhere indicates that some tree species are shifting their distributions significantly upward in elevation, and this response would be expected to occur in mountainous regions of Oregon as well.

Some model simulations of future vegetation changes in Oregon indicate that high elevation areas of subalpine forest and alpine tundra as well as areas of shrubland in eastern Oregon will contract under projected future climate changes. These projected vegetation changes would reduce critical habitat for species of management concern, such as greater sage-grouse (*Centrocercus urophasianus*). The paleoenvironmental record indicates that plant species respond individually to changing climate. As species distributions change, the current associations of plant species in Oregon may be affected. Some model simulations indicate that the species composition of western Oregon forests may already be changing and that the rate of change will increase during the 21<sup>st</sup>-century.

Disturbance events will continue to play a critical role in the dynamics of Oregon's vegetation. Recent forest dieback in the western United States, empirical studies, and model simulations indicate that the frequency and magnitude of some disturbance events, such as drought, wildfire, and insect outbreaks, may be changing. Model simulations indicate that more frequent, large fires could become increasingly common in western Oregon forests.

Oregon's forests currently store substantial quantities of carbon and could store more under forest management practices that increase the time between harvests and/or reduce the amount of carbon that is harvested from forests. Carbon is also stored in wood products that are harvested from Oregon's forests, but wood products are unlikely to provide for substantial increases in stored carbon under current manufacturing, use, and disposal practices. The more

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carbon that is stored in Oregon's forest, the greater the potential carbon releases that may occur in the future in response to disturbances, such as fire. Management activities carried out in response to climate changes, such as thinning of forests to reduce moisture stress on the remaining trees, would also remove carbon from the forests.

Plant population genetics and life-cycle characteristics will play an important role in determining how plants respond to climate changes. Future climate changes are projected to occur relatively rapidly, making it difficult for plants to genetically adapt to climate changes or to disperse to areas of more suitable climate, although microclimate diversity in Oregon's mountainous terrain may provide suitable climate conditions for some species over relatively short distances. Adaptive management strategies may assist plants in adapting to future climate changes, but will be challenged by the long life-cycles of many Oregon forest tree species.

There are a number of important knowledge gaps in our understanding of how plants may respond to climate change. Some species in Oregon, particularly important commercial species such as Douglas-fir (*Pseudotsuga menziesii*), have been well studied. However, we know relatively little about many plant species, their sensitivities to climate and climate change, and their interactions with other species, including insects and diseases. The need for additional information is particularly important with regard to invasive species in Oregon, including how invasive species will interact with native species and the ability of invasive species to alter disturbance regimes, such as fire. The potential for CO<sub>2</sub>-induced increases in plant water use efficiency are not well known, but could be critical for ameliorating plant drought-stress for some species. The roles of nutrient limitations in carbon sequestration and responses to disturbances also remain critical uncertainties.

Uncertainties in projections of future climate changes, particularly our ability to project changes in the amount and variability of precipitation, limit our ability to project how plant species will respond to climate change. The potential for future climate changes to produce spatially extensive, multi-year droughts is of particular concern. As projections of future climate change improve in quality and resolution, we will be better able to simulate the potential response of plant species to changes in climate. Similarly, improvements in vegetation and ecosystem models, including modeling efforts that integrate data from vegetation monitoring and vegetation spatial distribution modeling, as well as an explicit consideration of disturbances, will also improve vegetation simulations. The potential for rapid climate and ecosystem changes and associated uncertainties may require new adaptive management approaches.

## 5.1 Introduction

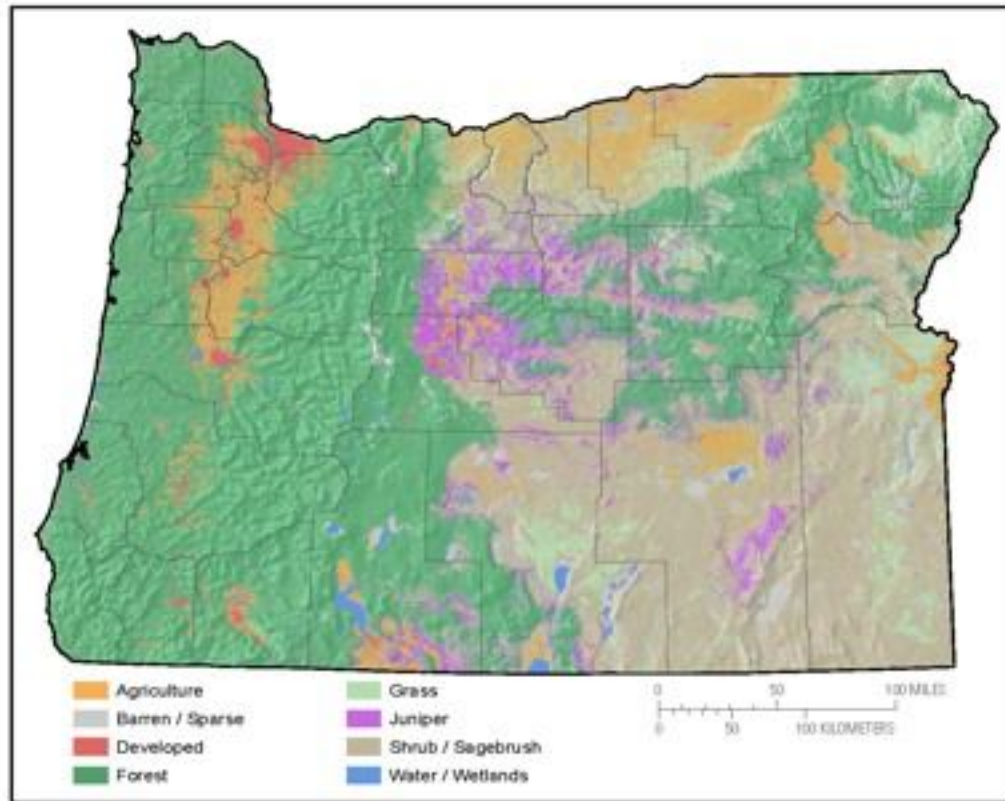
Oregon's vegetation is remarkably diverse, ranging from the old-growth temperate rainforests west of the Cascade Range to the arid shrublands and grasslands of eastern Oregon. Vegetation directly contributes to the environmental, economic, and cultural well-being of the state. Plants provide habitat for wildlife, including threatened and endangered species such as the marbled murrelet (*Brachyramphus marmoratus*). Oregon's forests support the state's logging and wood products industries, its rangelands support ranching communities and livestock industries, and vegetation of all types contributes to the recreation and tourism activities in the state. Oregon's forest and rangeland areas are the source of over 80% of the state's water (Brown et al., 2008). The region's vegetation is also culturally important. It provides many of the first foods (Et-twaii-lish, 2005) and sacred places used by local tribes, and is central to many of the iconic landscapes reflected in Oregon's art and literature.

Potential future climate changes will affect vegetation across Oregon. As climate changes, the species composition, spatial distribution, and productivity of Oregon's vegetation may change. In this chapter we provide a brief overview of some of the potential effects of future climate change on Oregon's terrestrial vegetation. Additional information may be found in the references cited throughout the text as well as in the numerous national and regional climate change assessments that encompass Oregon. These resources include the Intergovernmental Panel on Climate Change's Assessment Reports and Special Reports (e.g., IPCC, 2007), three Assessment Reports on climate change impacts for the U.S. (e.g., Karl et al., 2009), and a Synthesis Report on "Forests, Carbon, and Climate Change" produced as a joint effort of the Oregon Forest Resources Institute, Oregon State University, and the Oregon Department of Forestry (Cloughesy, 2006).

## 5.2 Vegetation Responses to Climate Change

### 5.2.1 Oregon's current vegetation

Oregon's vegetation is strongly influenced by climate and topography. Along the Oregon coast, the Pacific Ocean affects local climate conditions that support maritime species, such as Sitka spruce (*Picea sitchensis*) and shore pine (*Pinus contorta* var. *contorta*). Further inland, vegetation varies along the west slope of the Cascade Range from oak woodlands in the Willamette Valley to mixed conifer forests dominated by Douglas-fir (*Pseudotsuga menziesii*) at mid-elevations, to high elevation mountain hemlock (*Tsuga mertensiana*) and true fir (*Abies* spp.) stands. On the east side of the Cascade Range, ponderosa pine (*Pinus ponderosa*) and western juniper (*Juniperus occidentalis*) woodlands give way to steppe and shrubland vegetation in drier locations of eastern Oregon (Figures 5.1 and 5.2). These natural patterns in the distribution of vegetation are modified by human activities, including urbanization, agriculture, road building, logging, grazing, and fire suppression.

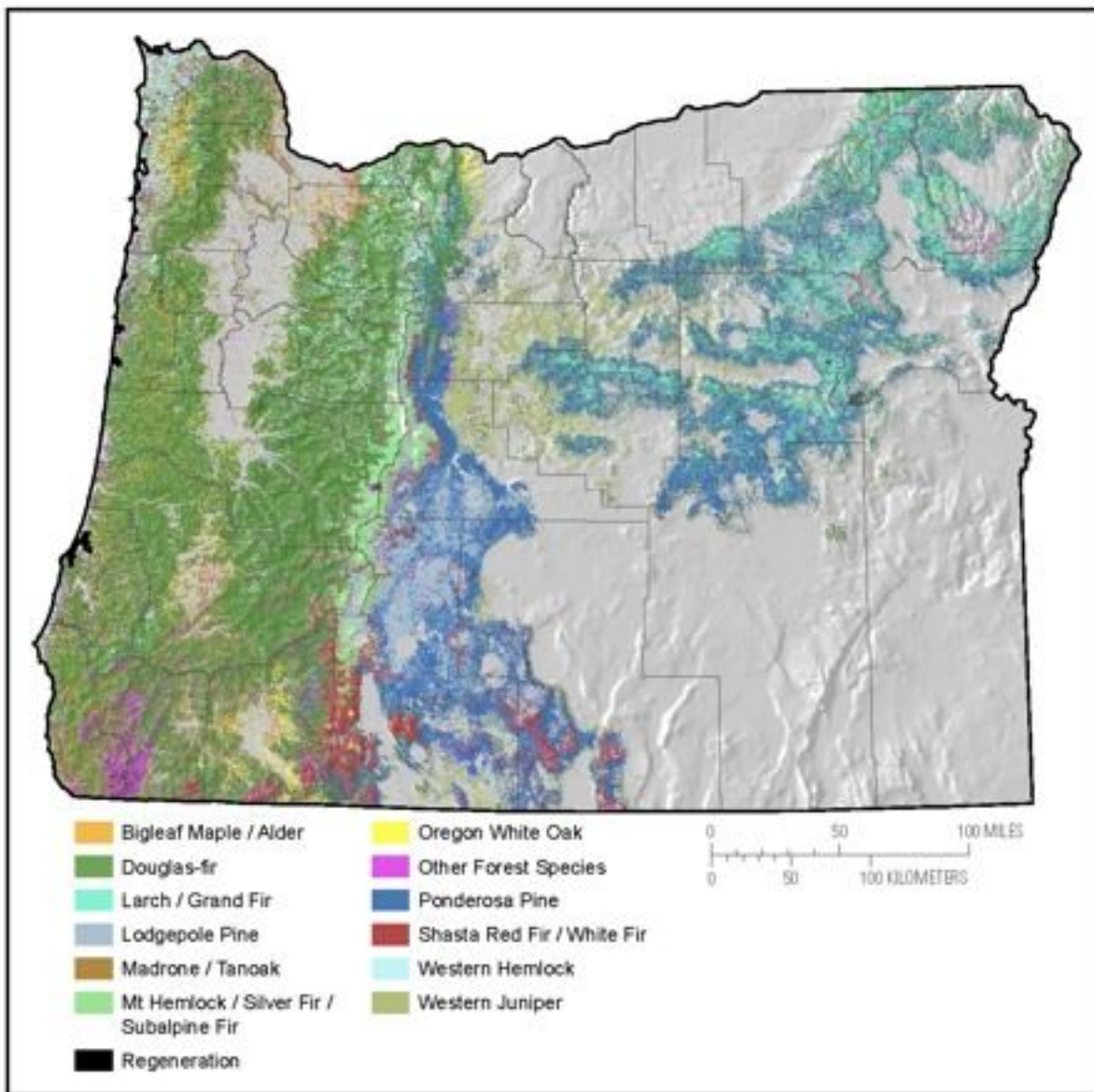


**Figure 5.1** Land cover map of Oregon (Oregon Department of Forestry, 2010). Data: GNN Vegetation Imputations (LEMMA Laboratory, USFS PNW Research Station, Corvallis, Oregon); Ecological Systems (Oregon Institute for Natural Resources, Oregon State University); Development Zone Study (Resource Planning Program, Oregon Department of Forestry). (Figure: R. T. Peltier, USGS)

### 5.2.2 Past vegetation changes

Our understanding of how Oregon’s vegetation may respond to future climate changes is based, in part, on studies of how vegetation has responded to past climate changes. Many studies of paleovegetation changes have been carried out in Oregon, including reconstructions of vegetation patterns from pollen found in lake sediments (e.g., Worona and Whitlock, 1995), tree-ring analyses of the relationships between tree growth and climate (e.g., Pohl et al., 2002), and investigations of past fire occurrence using fire scars from trees (e.g., Weisberg and Swanson, 2003). These studies provide evidence of how vegetation has responded to past climate changes over time periods ranging from centuries to millennia (Whitlock and Bartlein, 1997). Worona and Whitlock (1995) analyzed pollen from the sediments of Little Lake in the Oregon Coast Range (near Blachly, Oregon), which provide a record of vegetation change going back ~42,000 years. This pollen record indicates that the current Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and western red cedar (*Thuja plicata*) forests of Oregon’s Coast Range developed in the last ~5600 years, possibly in response to cooling climate conditions during this time period. Charcoal from past fires found in the sediments of Little Lake (Long et al., 1998) and Taylor Lake (south of Warrenton, Oregon; Long and Whitlock, 2002)

indicate that fires in the region also became less frequent during this same time period, as would be expected under cooler climate conditions.



**Figure 5.2** The distribution of dominant tree species in Oregon as modeled using the gradient nearest neighbor (GNN) method. Data: GNN Vegetation Imputations (LEMMA Laboratory, USFS PNW Research Station, Corvallis, Oregon); Ecological Systems (Oregon Institute for Natural Resources, Oregon State University); Development Zone Study (Resource Planning Program, Oregon Department of Forestry). (Figure: R. T. Peltier, USGS)

On shorter timescales, many research efforts are focused on identifying vegetation responses to recent climate changes that have occurred over the last century. Particularly important for understanding the potential effects of climate change on plants are changes in phenological events, such as the flowering dates for different plant species. Cayan et al. (2001) analyzed flowering data for honeysuckles (*Lonicera* spp.) and common purple lilacs (*Syringa vulgaris* f.

*purpurea*) in the western U.S., including data from Oregon, and reported earlier first bloom dates in the 1980s and 1990s as compared with data from the 1960s and 1970s. They attributed these earlier bloom dates to increased spring temperatures across the region at the end of the 20th-century. In a more recent study, van Mantgem et al. (2009) identified an increase in tree mortality rates in the western U.S. since the 1950s that they attribute, in part, to increased drought stress on trees resulting from increased temperatures during this time.

Both the Cayan et al. (2001) and van Mantgem et al. (2009) studies used data from long-term vegetation monitoring efforts, which are critical for identifying vegetation changes over time in response to climate changes. A number of long-term vegetation monitoring efforts are under way in Oregon. These efforts include the U.S. Forest Service's Forest Inventory and Analysis Program (<http://fis.fs.fed.us/>), the National Park Service's Inventory and Monitoring Program (<http://science.nature.nps.gov/im/index.cfm>), and the U.S.A. National Phenology Network (<http://www.usanpn.org/>). Long-term vegetation data are also being collected at many individual research sites, such as the H.J. Andrews Experimental Forest near Blue River, Oregon (<http://andrewsforest.oregonstate.edu/>).

### **Case Study 1. Mapping plant species distributions in Oregon**

A recent effort to model and map existing species distributions across ownerships within Oregon, Washington, and parts of California is being conducted through the Landscape Ecology, Modeling, Mapping and Analysis (LEMMA) project team (U.S. Forest Service Pacific Northwest [PNW] Research Station and Oregon State University). The mapping is integrated with ongoing sample-based forest inventories conducted by the Forest Inventory and Analysis (FIA) program at the U.S. Forest Service PNW Research Station, the Current Vegetation Survey of Region 6 (Oregon and Washington), USDA Forest Service, and the U.S. Bureau of Land Management (BLM) in western Oregon. The project uses gradient imputation (Gradient Nearest Neighbor [GNN]; Ohmann and Gregory, 2002) to map detailed vegetation composition and structure for areas of forest and woodland. GNN uses multivariate gradient modeling to integrate data from FIA field plots with satellite imagery and mapped environmental data. A suite of environmental variables associated with each sampling plot is assigned to each pixel in a digital map based upon interpretations of satellite imagery and topographical information. From multivariate statistics using these variables, regional maps can be constructed for many of the same vegetation attributes available for FIA plots. The 2000-era species distribution maps produced with GNN (Figure 5.2) provide baseline information that will be compared with future inventory data to assess the rate and extent of future shifts in distributions of species.

## **5.3 Potential Future Vegetation Changes**

Climate has long been identified as a primary control on the geographic distribution of plants (e.g., Forman, 1964; Box, 1981). Research from a variety of ecosystems and spatial scales describes the effects that climate has on plant species distributions and ecosystem type (Neilson and Wullstein, 1983; Davis and Botkin, 1985; Overpeck et al., 1990; Guisan and Zimmerman, 2000). The paleoenvironmental record provides clear evidence that species respond individually to climate change and supports the current scientific consensus that the



geographical distributions of plant species will change as climate changes (Huntley, 1991; Pitelka, 1997; Jackson and Overpeck, 2000; Bachelet et al., 2001; Hansen et al., 2001; Shafer et al., 2001; Walther et al., 2002; Higgins et al., 2003; Sans-Elorza et al., 2003; McLachlan et al., 2005; Neilson et al., 2005b; Wang et al., 2006; Jurasinski, 2007; McKenney et al., 2007; Xu et al., 2007; Thuiller et al., 2008). The ranges of many North American tree species in relatively flat terrain may have to expand at rates of 3-5 kilometers per year in order to adapt to the climate changes that are projected for this century (Davis and Shaw, 2001; Iverson and Prasad, 2002).

One approach for investigating how plants may respond to future climate changes is to use vegetation models to simulate potential future vegetation changes. These models range from simple conceptual models of how plants may respond to temperature and precipitation changes to more complex statistical and process-based numerical models. Statistical models include various correlation or regression-tree approaches to simulate species distributions or species mixtures as well as more complex statistical models that simulate stages of forest growth and succession (McKenney et al., 2007; Iverson and Prasad 2001; Weisz et al., 2009; Henderson 2008). Although statistical models provide useful insights into vegetation responses to climate change, there are a number of important processes, such as many types of disturbance, which they often do not explicitly simulate. Furthermore, statistical models implicitly assume that observations of the past are also applicable under future conditions, which might not always be the case in a changing environment (see Williams and Jackson, 2007).

Mechanistic or process-based models are thus considered more robust models for simulating the complex and non-linear interactions of changes in temperature, humidity, precipitation and elevated atmospheric CO<sub>2</sub> concentrations projected for the future (Rastetter et al., 2003; National Research Council, 2009). A number of process-based models have been run for Oregon, including 3-PG (Coops et al., 2005) and MC1 (Neilson et al., 2005a). Process-based models often incorporate the physiological effects of elevated atmospheric CO<sub>2</sub> concentrations on plants, as well as the hydrological constraints on the distribution of vegetation density, which can be used to simulate the distributions of forests, savannas, shrublands and grasslands. Many of these process-based models also simulate the potential effects of disturbance on vegetation. It is particularly noteworthy that although these models differ in the various details of their construction, many produce qualitatively similar forecasts of the impacts of potential future climates on ecosystem distribution, function, and disturbances.

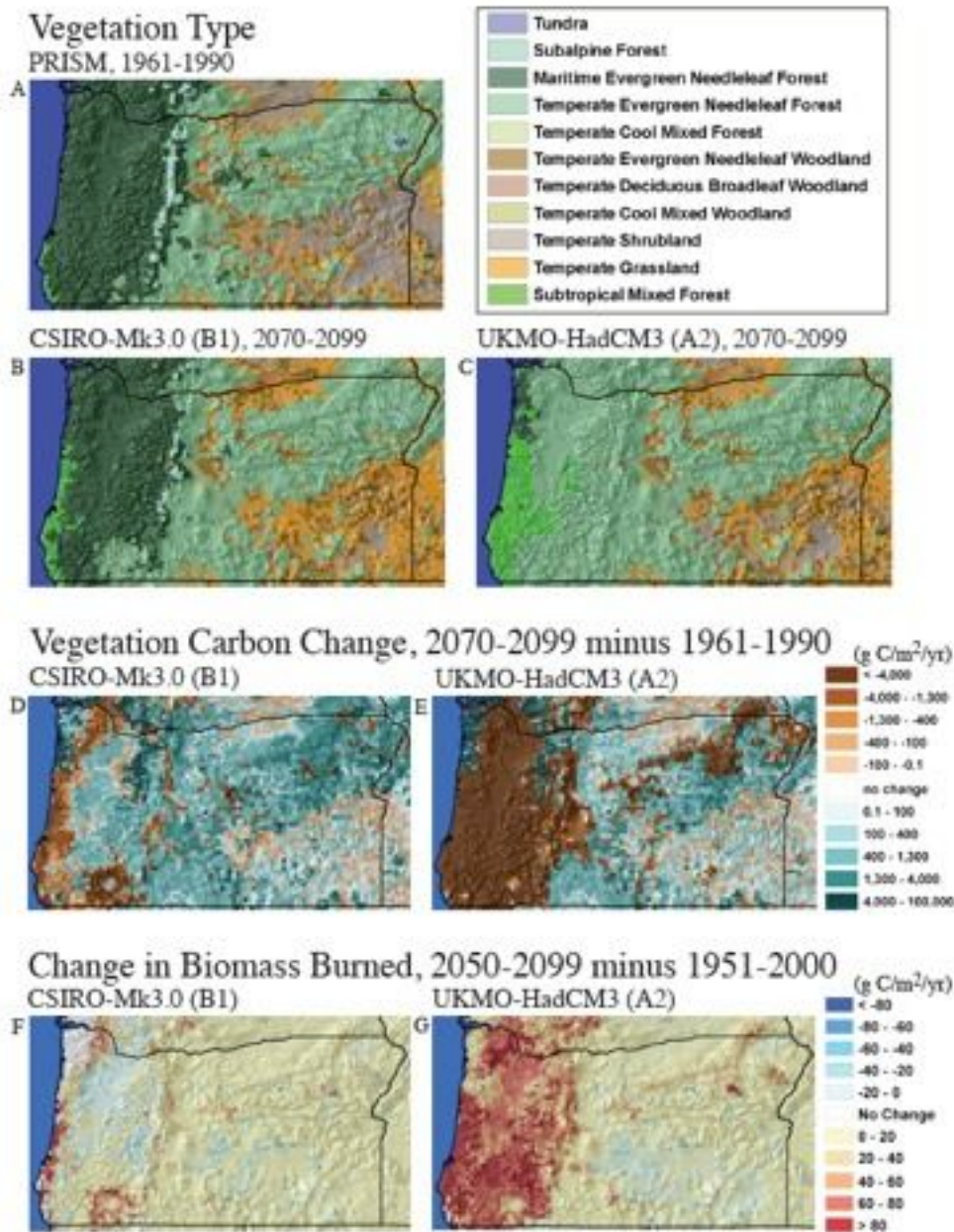
Figure 5.3 displays model output from MC1 (MAPSS-CENTURY, ver. 1, R. P. Neilson, U.S. Forest Service MAPSS Group; <http://www.fs.fed.us/ccrc/video/skamania-scale.shtml>), a dynamic general vegetation model that represents vegetation using plant functional types (e.g., needleleaf evergreen trees, shrubs, grass). Modern vegetation (Figure 5.3a) for Oregon was simulated by MC1 using PRISM historical monthly climate data for 1895-2002 (Daly et al., 2008). Future vegetation was simulated using climate data from two coupled atmosphere-ocean general circulation models (AOGCMs), CSIRO-Mk3.0 (Gordon et al., 2002) and UKMO-HadCM3 (Pope et al., 2000; UK Meteorological Office, Hadley Centre, 2006). These AOGCMs simulated future climates using the B1 and A2 future socio-economic scenarios (Nakicenovic et al. 2000) described in Chapter 1). The B1 scenario represents relatively low levels of greenhouse gas emissions and associated climate forcing for the end of the 21<sup>st</sup>-century while the A2

scenario represents relatively high levels of greenhouse gas emissions and associated climate forcing over the same time period.

Under the B1 emissions scenario, CSIRO-Mk3.0 simulates mean annual temperature increases of ~1-2 °C (~2-4 °F) and total annual precipitation increases of ~0-10% for the period 2070-2099 (30-year mean) as compared with 1961-1990 (30-year mean) data for Oregon. Under the A2 emissions scenario, UKMO-HadCM3 simulates mean annual temperature increases of ~3-5 °C (~6-8 °F) for the period 2070-2099 (30-year mean) as compared with 1961-1990 (30-year mean) data for Oregon. Total annual precipitation for 2070-2099 (30-year mean) is projected to decrease by ~0-15% in western and central Oregon and to increase by ~3-6% in easternmost Oregon.

In addition to responding to changes in temperature and precipitation, plants also may respond to changes in the concentration of atmospheric carbon dioxide (CO<sub>2</sub>), which plants use for photosynthesis. Human activities have increased the concentrations of CO<sub>2</sub> in the atmosphere and CO<sub>2</sub> levels are projected to continue rising for the foreseeable future (IPCC, 2007). Particularly in areas where moisture for plants is limited, increased concentration of atmospheric CO<sub>2</sub> may increase the efficiency with which plants are able to use water in the soil and may allow some plant species to expand their range in parts of the state, or to maintain their range under increasing drought stress (Morgan et al., 2004; Millar et al., 2006).

In future vegetation simulations produced by MC1, areas of subalpine forest and alpine tundra in Oregon are projected to decrease as temperatures increase at higher elevations (Figures 5.3b and 5.3c). Areas of shrubland in eastern Oregon are also projected to decrease, which could reduce sagebrush (*Artemisia* spp.) habitat (Neilson et al. 2005a). Sagebrush shrublands are considered important habitat for greater sage-grouse (*Centrocercus urophasianus*), a species of management concern in southeastern Oregon (Chapter 7). The future vegetation simulations project an expansion of forest and woodland into areas of eastern Oregon currently dominated by grassland and shrubland. This expansion occurs as the combined result of projected increases in precipitation, a longer growing season, and increased plant water-use efficiency produced by increased atmospheric CO<sub>2</sub> concentrations. Areas of mixed evergreen and deciduous forest are projected to expand in the Oregon Coast Range. This vegetation type represents a major floral and faunal transition from temperate to subtropical species, including broadleaf vegetation (some evergreen), and its increase could represent expansion of maple species (*Acer* spp.), madrone (*Arbutus menziesii*), oak species (*Quercus* spp.), and various pine species (*Pinus* spp.) that currently occur in southwestern Oregon and northern California (McLaughlin 1989). The simulated vegetation changes produce a decrease in vegetation carbon in western Oregon by the end of the century (Figures 5.3d and 5.3e). This decrease is partly the result of changes in vegetation (Figures 5.3b and 5.3c) and partly the result of projected increases in the amount of biomass burned by wildfires, particularly in western Oregon (Figures 5.3f and 5.3g). Eastern Oregon is simulated to gain ecosystem carbon as a result of the simulated expansion of forest and woodland vegetation, while experiencing more and larger wildfires at the same time (Millar et al., 2006).



**Figure 5.3** Vegetation types simulated by MC1 (MAPSS Group, contact: R.P. Neilson) on an 8-km grid for 1961-1990 using PRISM climate data (Daly et al., 2000) (A) and for 2070-2099 using climate data simulated by CSIRO-Mk3.0 under the B1 emissions scenario (B) and by UKMO-HadCM3 under the A2 emissions scenario (C). For each grid cell the vegetation type most frequently simulated during the model time period (i.e., the modal vegetation type) is mapped. Future changes in vegetation carbon calculated as 2070-2099 values minus 1961-1990 values (D, E) and future changes in biomass burned calculated as 2050-2099 values minus 1951-2000 values (F, G) were also simulated by MC1. Climate data from CSIRO-Mk3.0 and UKMO-HadCM3 were obtained from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset and the British Atmospheric Data Centre. (Model output: MC1 [MAPSS-CENTURY, ver. 1], R.P. Neilson, U.S. Forest Service MAPSS Group [<http://www.fs.fed.us/pnw/mdr/maps/index.shtml>]; <http://www.fs.fed.us/ccrc/video/skamanian-scale.shtml>]; Maps: R. Drapek, USFS)

## 5.4 Future Plant Species Distributions

Projections of future changes in Oregon's forest, grassland, and shrubland vegetation, such as those presented in Figure 5.3, describe vegetation changes in terms of general vegetation types. In many cases, however, we are interested in how climate change may affect particular plant species in Oregon, such as species that are of particular conservation or economic concern. Rehfeldt et al. (2006) used statistical models to estimate the responses of western U.S. tree species to future climate changes. Their modeled projections indicate that future climate changes could increase the abundance of montane forest and grassland communities at the expense of subalpine, alpine tundra, and arid woodland communities. They also project extensive shifts in the spatial distributions of individual species, especially along elevation gradients. These results generally agree with the vegetation changes projected by the MC1 dynamic general vegetation model described above (Figure 5.3b and 5.3c), although MC1 simulates increased woody vegetation east of the Cascade Range. Statistical model simulations must be interpreted with some caution. Many statistical model projections are based on simple climate-species correlation models that do not incorporate a number of important processes that will affect future species distributions, such as the physiologic responses of plants to elevated atmospheric CO<sub>2</sub> concentration, range limitations from interactions with other species, and the ability for some species to persist for thousands of years, asexually, under climates unfavorable for seedling establishment (Neilson and Wullstein, 1983; Nogués-Bravo, 2009).

Process-based vegetation models are also used to simulate species distributions. Neilson et al. (2005a), using MC1, simulated the potential shifts in distribution for sagebrush (*Artemisia* spp.) in southeastern Oregon under projected future climate changes. In a different study, Busing et al. (2007), using a dynamic vegetation model accounting for individual tree interactions, simulated relatively small changes in forest composition and basal area for major tree species in the South Santiam River watershed under projected future climate changes for 2050. Their projections also indicated that some tree species, such as western hemlock (*Tsuga heterophylla*) and Pacific silver fir (*Abies amabilis*), could shift their distributions upward in elevation during this time (Busing et al. 2007).

Model projections of how species distributions may change in the future are a fundamental part of understanding potential ecosystem responses to climate change. Nonetheless, detecting and quantifying the *actual* changes in species distributions as they occur (e.g., Lenoir et al., 2008; Kelly and Goulden, 2008) is also a fundamental part of understanding ecosystem responses to climate change and the conditions to which humans and other species must adapt. Statistical modeling and mapping of individual species distributions based on field inventories is an essential component in both validating model projections of future species distribution changes as well as detecting and quantifying the actual rate and amount of change that occurs for individual species. An effective and reliable system of adaptation to the effects of climate change must be based on information and analysis conducted from large-scale, field-based monitoring systems that accurately quantify and delineate the actual status and trends of species distributions. These vegetation mapping efforts, such as the work described in Box 1, rest on the premise that vegetation patterns can be predicted from mapped environmental data (Franklin, 1995), using various hypotheses as to how environmental factors control the distribution of species and communities (Guisan and Zimmerman, 2000). In a number of

modeling studies, climatic gradients that include precipitation and temperature have been found to explain the distribution, composition and structure of forest vegetation in Oregon and the western U.S. using modeling approaches ranging from statistical to process-based models (Ohmann and Spies, 1998; Ohmann and Gregory, 2002; Rehfeldt et al., 2006; Coops et al., 2009). However, more experimental and observational information is still needed regarding how species are able to maintain their current distributions (at all spatial scales from micro-habitat to its full distribution) under modern climate, or to extend their range under a changing climate (e.g., Neilson and Wullstein, 1983).

## 5.5 Disturbance Regimes

Climate change can affect both the frequency and severity of disturbances that play a vital role in the natural dynamics of Oregon's vegetation. Events such as wildfires, insect outbreaks, diseases, droughts, windstorms and landslides profoundly influence ecosystem dynamics in terms of ecosystem structure, composition, and functioning (e.g., Perry and Amaranthus, 1997; Franklin et al., 2002; Campbell et al., 2004; Law et al., 2004; Wilson, 2004; Busing et al., 2007; Spies, 2009; Meigs et al., 2009). One of the most important disturbance agents for Oregon's vegetation is wildfire. An average of 317,300 acres burned per year over the last five years and 648,000 acres burned in 2007 (NIFC, 2010). The area of disturbance from insect pests and diseases is generally of the same order of magnitude as that of wildfires in western U.S. forests (Hicke et al., 2006). Mountain pine beetle (*Dendroctonus ponderosae*) is the most important insect pest in Oregon, affecting 348,400 acres per year on average from 2004 to 2008 (Nelson et al., 2009). A number of important disturbance agents are strongly climate sensitive (Dale et al., 2001) and interact dynamically (see Box 2). Consequently, changes in disturbance regimes are expected to constitute the most profound climate change impacts in forest ecosystems of the Pacific Northwest (Franklin et al., 1991; Littell et al., 2009b). The following sections focus on wildfire, insects and diseases, drought, invasive species, climate extremes, and the interactions of disturbances.

### 5.5.1 Wildfire

The frequency and extent of wildfires is strongly related to climatic factors. Analyses of fire history reveal a significant correlation of fire activity with decadal-scale (Pacific Decadal Oscillation), episodic (El Niño/Southern Oscillation) and interannual natural climate variation, with larger areas burned during warm and dry phases/years (Hessl et al. 2004; Pierce et al., 2004; Gedalof et al., 2005; Trouet et al., 2006; Kitzberger et al., 2007; Heyerdahl et al. 2008). A recent study found that both the frequency of large wildfires and the duration of the fire season increased sharply in the mid 1980s in the western U.S., an increase that could largely be explained by changed climatic drivers (Westerling et al., 2006). Critical climate-sensitive processes, however, differ by ecoregion and vegetation type. In mesic forest types (i.e., predominately west of the crest of the Cascade Range), dry and warm summers exert the strongest climatic influence on forest area burned, depleting fuel moisture and creating favorable conditions for fire spread (Littell et al., 2009a). In contrast, in drier forest types in eastern Oregon the main climatic influence on wildfire activity is via facilitation of vegetation growth in winter(s) prior to the fire (i.e., fuel availability is an important limiting factor for fires) (Littell et al., 2009a). These complex climate-vegetation interactions are important for assessing the potential impacts of climate change on wildfire activity, and they are replicated in the

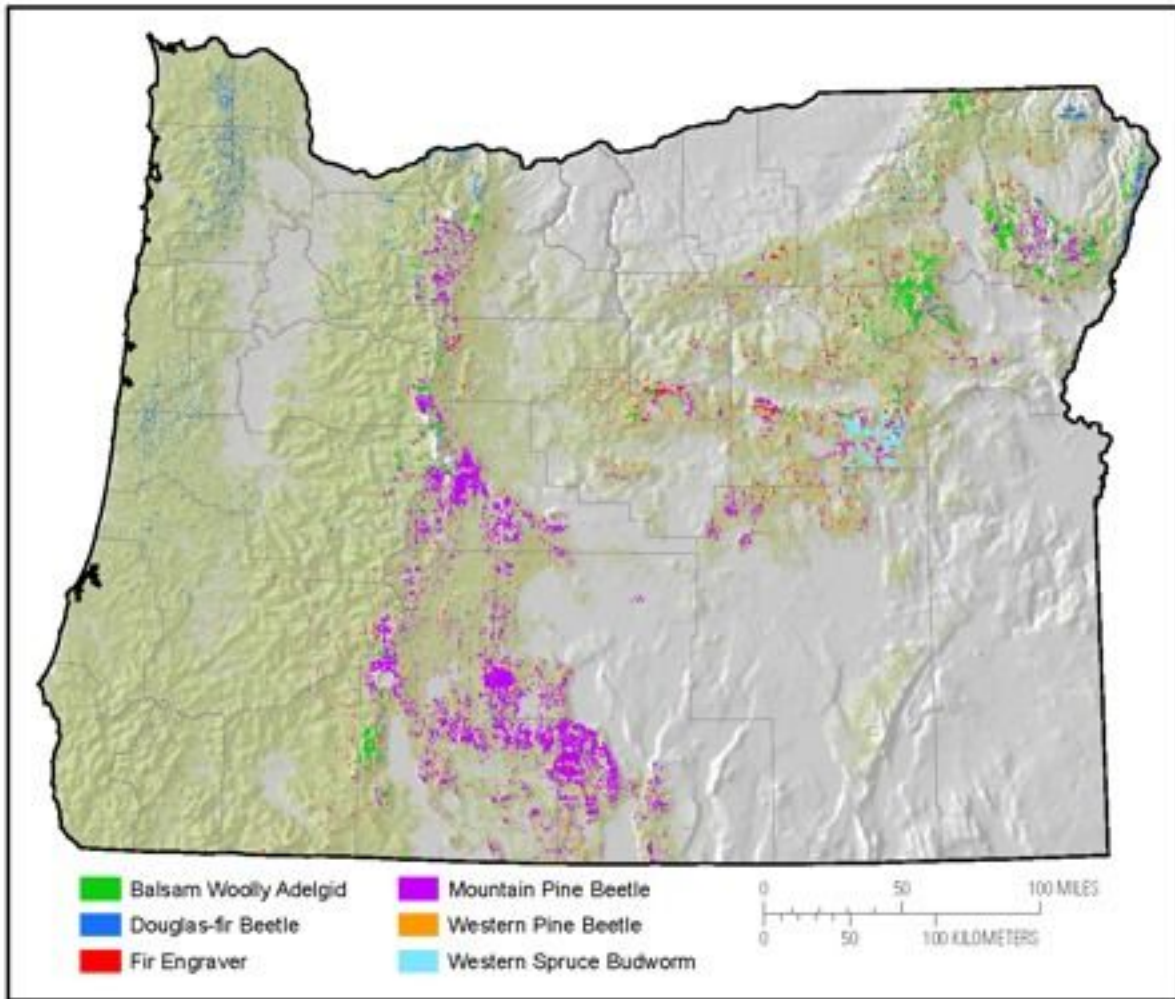
process-based fire simulations produced by vegetation models, such as MC1 (Millar et al., 2006; Rogers, 2009).

Despite the different seasonal climate conditions influencing fire occurrence for different forest types, an increase in fire activity is expected for *all* major forest types in Oregon and the western U.S. under projected climate changes (Figures 5.3f and 5.3g; Bachelet et al., 2001; Whitlock et al., 2003; Keeton et al., 2007). A 78% increase in forest area burned by the middle of the 21<sup>st</sup>-century is estimated for the Pacific Northwest (Spracklen et al., 2009b). Increases of up to 6-fold in area burned are estimated for regions in the Pacific Northwest by the end of the century (McKenzie et al., 2004; Littell et al., 2009b). However, estimates of projected future changes in area burned vary significantly depending on the climate scenario and estimation method used. As Mote et al. (Chapter 1) note, estimates of future precipitation changes for the PNW vary, with some projections indicating wetter than present conditions and other projections indicating drier than present conditions. Whether the future climate is wetter or drier will significantly affect potential changes in area burned by fire, as will increases in interannual to interdecadal climate variability.

The actual occurrence of future fires, however, is not only driven by favorable climate conditions but also requires a source of ignition (usually lightning or human ignition sources) and a mechanism for rapid fire spread (strong winds and topography). These factors are strongly influenced by local conditions and, to date, are not fully represented in many climate change projections. However, growing evidence points towards increasing lightning activity over the western U.S. under climate change (Price and Rind, 1994; Del Genio et al., 2007).

### 5.5.2 Insect pests and diseases

The forest area in Oregon affected by mountain pine beetle has been increasing for the last eight years (Nelson et al., 2009; Figures 5.4 and 5.5). Increasing winter temperatures enhance winter survival probability of the bark beetle, particularly in high elevation areas (Regniere and Bentz, 2007; Bentz, 2008). In addition, host susceptibility may increase under climate change as a result of increased drought stress. The highest vulnerability occurs during extremely high temperature and extended drought (Littell, 2009b), weakening the ability of trees to repel beetle parasitism (see Raffa et al., 2008). However, in order to overwhelm a tree's defense system, the mountain pine beetle depends on a synchronous emergence of a large number of adult beetles at an appropriate time of the year (a phenomenon referred to as "adaptive seasonality"). Rising temperatures will cause this adaptive seasonality to decrease in low elevation forests, which in some model simulations results in a distinct overall projected decrease in the area attacked by mountain pine beetle (Williams and Liebhold, 2002; Hicke et al., 2006; Littell et al., 2009b). High elevation forests, however, are likely to experience an increase in adaptive seasonality and hence of mountain pine beetle attacks in the coming decades, increasing the pressure on high elevation pine species such as whitebark pine (*Pinus albicaulis*). Later in the 21<sup>st</sup> century, adaptive seasonality is expected to also decline in high elevation forests, if warming continues as projected (Hicke et al., 2006).



**Figure 4.** Oregon forest area affected by insects in 2009 (Oregon Department of Forestry, 2010). Data: USFS Region 6 Forest Insect and Disease Aerial Detection Survey, version 11/2009. (Figure: R. T. Pelltier, USGS)

Climate change also affects forest diseases, increasing the ability of pathogens to survive through the winter and shortening regeneration times of bacteria and fungi. In the Oregon Coast Range, Swiss needle cast (caused by the fungus *Phaeocryptopus gaeumannii*), a foliage disease of Douglas-fir, was found to be highly sensitive to winter temperature with an average predicted increase of 9.2% in infected needles per 1°C increase in temperature (Manter et al., 2005). Another important disease that is strongly climate sensitive is sudden oak death (caused by the non-native pathogen *Phytophthora ramorum*), which has been spreading northward from California into southwestern Oregon forests since 2001. In addition to mild and wet conditions (Anacker et al., 2008), heavy precipitation events facilitate infection of new trees (Rizzo and Garbelotto, 2003). Infected trees are more susceptible to mortality during droughts, which can lead to large diebacks of infected trees during extended drought periods (Frankel, 2008). More extreme weather conditions projected for the future could thus facilitate sudden oak death in Oregon. In general, warming is likely to encourage northward expansion of more southern insects and diseases, while longer growing seasons may allow more insect generations per year.

### 5.5.3 Drought

Drought is a critical predisposing factor that leads to both wildfires and major insect outbreaks. However, it is also an important disturbance agent in itself and, while most vegetation types in Oregon are well adapted to the state's dry summers, projected future changes in the hydrological regime (Chapter 3) have the potential to cause large-scale tree mortality (Neilson, 1993; Bachelet et al., 2001; Bachelet et al., 2003; Mote et al., 2003; Whitlock et al., 2003; Lenihan et al., 2008). Projected increases in temperature will lengthen the growing season and increase evaporative demand, causing ecosystems to extract all available soil moisture before the end of the growing season. Recent increases in water deficit, for instance, are thought to be contributing to increased mortality rates in old-growth forests throughout the western U.S. (van Mantgem et al., 2009). A modeling study focusing on Ponderosa pine (*Pinus ponderosa* Doug. Ex Loud.), an important tree species in the dry forests of eastern Oregon, indicated that prolonged drought resembling the conditions of the 1920s and 1930s would surpass the species' physiological thresholds on 18-30% of its current area (Coops et al., 2005). Empirical data from the pine-woodland transition zone in southern Oregon corroborate the sensitivity of these ecosystems to drought, particularly on sandy and rocky soils (Knutson and Pyke, 2008). For the forests of neighboring Washington State, severe water-limitation was recently projected to rise by 32% in the 2020s and an additional 24% by the 2080s, compared to conditions of the 20<sup>th</sup> century (Littell et al., 2009b), although these projections do not include potential increases in CO<sub>2</sub>-induced water-use efficiency. Allen et al. (2010) provide a global overview of drought-related tree mortality.

#### **Case Study 2: Disturbance interactions in Oregon's forests**

The prevailing disturbance regime in Oregon's forests is, in many cases, the result of a disturbance complex of interacting agents. Drought, for instance, can directly stress a tree's physiology, but also increases the vulnerability of trees to insect attacks and increases the probability for fire (Figure 5.5). Well-documented positive relationships also exist between bark beetle outbreaks and fire: Trees weakened by fire have a higher vulnerability to insect attacks (Hood and Bentz, 2007; Breece et al., 2008; Youngblood et al., 2009). Similarly, insect outbreaks increase fuel loads and thus fire hazard and severity (Lundquist, 2007; Page and Jenkins, 2007; Jenkins et al., 2008). Considering these interactions, the impacts of climate change on the disturbance regime of Oregon's forests will likely exceed the effect on any single agent or factor (Franklin et al., 1991).

The interactions between disturbances and vegetation need to be taken into account when evaluating expected changes in disturbance regimes. With regard to the projected range changes for mountain pine beetle, for instance, the simultaneous changes in the insect's host species distribution also need to be considered. Simulation studies indicate that the climatically suitable habitat for the insect may shift at twice the rate of that of its host species, thus a net contraction of the mountain pine beetle outbreak range may occur (Williams and Liebhold, 2002). While climate-induced tree species migration is a relatively slow process, management measures influencing forest structure and composition have an immediate effect on disturbances (Hessburg et al., 2005; Ager et



al., 2007). In many cases management activities may be as important a driver of disturbance regimes as climate (Weisberg and Swanson, 2003; McCloskey et al., 2009). Fire suppression efforts over the past several decades resulted in smaller, low-severity fires despite indications of an increase in (mostly anthropogenic) ignitions (Weisberg and Swanson, 2003). The resulting increased stand density and decreased landscape heterogeneity, however, raise the likelihood of future large-scale, high severity wildfire events (Schoennagel et al., 2004; Keeton et al., 2007). In summary, the combined expectations regarding increases in water limitation, wildfire activity, high elevation adaptive mountain pine beetle seasonality, and insect host vulnerability, as well as their interactions, suggest that forest ecosystem functions and services of a large share of Oregon's forests may be affected by altered disturbance regimes as the region's climate changes.



**Figure 5.5** (Left) A stand burned by the B&B Complex Fires (2003, Mt. Jefferson Wilderness, Deschutes National Forest, Willamette National Forest) near Santiam Pass (Photo: R. Seidl, 2009). (Right) The effects of a mountain pine beetle outbreak around Little Three Creek Lake, Deschutes National Forest (Photo: E. Seidl, 2010).

#### 5.5.4 Invasive species

As climate changes, plant species that are not native to Oregon may be able to expand into the state, or expand their ranges if they already occur in the state. These invasive species may be

native to other parts of North America or they may be exotic species that have been introduced to North America from other places. When exotic species are introduced into suitable environments they can often expand rapidly, outcompeting native species. In the rangelands of eastern Oregon a number of exotic plant species, such as yellow starthistle (*Centaurea solstitialis*), are outcompeting native bunchgrasses that provide important forage for livestock on rangelands (Roché and Thill, 2001).

Invasive plant species also can alter fire regimes, particularly in relatively dry ecosystems such as occur in many parts of eastern Oregon. In these regions, the fuel cover provided by native vegetation is relatively sparse, limiting the ability of fires to spread across the landscape. Invasive species can increase the fuel load and fuel connectivity in these systems allowing fires to spread more easily. For example, cheatgrass (*Bromus tectorum*), an exotic annual grass in eastern Oregon, is highly flammable and can alter fire regimes by increasing the frequency of fires (Brooks et al., 2004). Statistical models indicate that cheatgrass could continue to expand in eastern Oregon under some future climate projections (Bradley, 2009). More information about invasive species in Oregon is available on the Oregon Invasive Species Council website (<http://www.oregon.gov/OISC/>).

#### **5.5.5 Climate extremes**

Many of the potential changes in disturbance described above will be driven by potential future changes in climate extremes. The western US is projected to experience increased heat wave severity under projected future climate change (Meehl and Tebaldi, 2004), which could lead to increased drought-related plant mortality (e.g., van Mantgem et al., 2009) and fire occurrence. Oregon could also experience more intense precipitation events. Leung et al. (2004) describe regional climate model simulations of future increases in winter extreme daily precipitation events for the Oregon Cascade Range. Tebaldi et al. (2006), using global climate model simulations, also reported increased precipitation intensity for parts of the Pacific Northwest. Changing climatic extremes could also affect many other types of disturbances, such as damage from wind and snow events, landslides, and flooding. Meehl et al. (2007), CCSP (2008a) and Chapter 1 provide additional information about potential future changes in extreme climate events.

## **5.6 Carbon in Oregon's Forests**

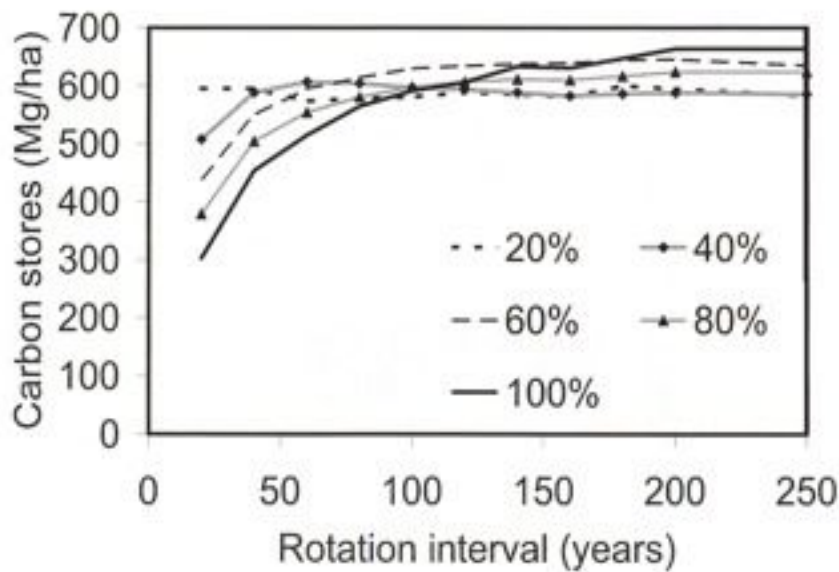
Oregon's forests have the potential to play a significant role in mitigating atmospheric CO<sub>2</sub> concentrations given the long-lived nature of many of the region's tree species and the dead material they form, such as the coarse woody debris (e.g., dead branches, fallen trees, etc.) found on the forest floor (Krankina and Harmon, 2006). Potential carbon stores in the Pacific Northwest are among the highest for forests in the world (Smithwick et al., 2002; Homann et al. 2005). The current carbon stores of these forests, however, are substantially below this potential (Smithwick et al., 2002; Hudiburg et al., 2009), which suggests a change in management could result in a major carbon sink within the region for many decades. Either an increase of the interval between harvests or a reduction in the amount of carbon removed each harvest would lead to an increase in average carbon stores in forests (Harmon et al., 2009). Indeed, changes in management of national forests under the Northwest Forest Plan (Mouer et al. 2005), which essentially increased the interval between harvests, have already led to a substantial increase in

carbon stores in the Pacific Northwest and have likely changed the carbon balance of Oregon's forests from adding carbon to the atmosphere to removing carbon from the atmosphere in less than a decade (Cohen et al., 1996; Turner et al., 2007; Hudiburg et al., 2009). While this trend helps mitigate atmospheric CO<sub>2</sub> emitted in Oregon, it also means that policy changes on national forests are unlikely to further increase forest carbon sinks. Some policies, such as thinning forests to increase climate adaptability or to alter fire behavior, would lead to decreases in forest carbon stores (Mitchell et al., 2009). To increase the uptake of carbon by Oregon's forests further it will be necessary to increase carbon stores on state and private lands. Increasing carbon stores would require increasing the interval between harvests and/or reducing harvest amounts, which may be unrealistic without having funds available to offset losses in traditional harvest-based revenues (Alig et al., 2002).

An alternative to increasing carbon stores within the forest is to harvest wood and store some of this carbon within wood products (Perez-Garcia et al., 2005). Under current manufacturing, use, and disposal practices this alternative is unlikely to increase the overall carbon store of the forest sector, which includes the forest and wood products derived from the forest (Harmon et al., 2009). Manufacturing, use, and disposal of harvested wood all entail significant carbon losses that are either as large as or larger than those in the forest itself (Krankina and Harmon, 2007). Wood products carbon offsets associated with biofuels and substitution of wood for more energy intensive building materials, such as steel and concrete, can theoretically increase the carbon "stores" of wood products beyond that stored in the forest itself (Perez-Garcia et al., 2005; Lippke et al. 2010). However, several issues need to be recognized regarding these offsets. First, most analyses have presented theoretical maximum product substitution offsets and ignored the effects of additionality (i.e., degree to which practices differ from business as usual or statutory requirements), permanence and replacement of existing wood products, and end-user preferences for building materials. If these factors are included, then substitution effects are substantially lower than the theoretical maximum and unlikely to surpass carbon stores in forests for many centuries if at all. Second, depending on the starting condition of the forest, both product substitution and forest-related biofuels can create carbon debts that delay carbon benefits. For example, biofuels harvested from existing forests could offset fossil fuel releases of carbon, but recent studies have indicated that carbon debts associated with the energy used during biofuel harvests, decreased carbon stores in forests, and differences in carbon to energy ratios could persist for decades to centuries, implying a significant temporal lag in net carbon uptake (Fargione et al., 2008; Searchinger et al., 2009). Third, being offsets, the effectiveness of both biofuel and product substitution will vary with the duration of the offset; the longer the delay in releasing fossil fuel carbon, the more effective offsets become: An offset with a 1 year delay would have little impact on atmospheric CO<sub>2</sub> concentrations, whereas an offset of hundreds of years would have a much greater impact. Unfortunately, the duration of offsets is not well understood at this point, but it is unlikely to be infinite as tacitly assumed in many current analyses. Finally, while offsets are often counted as carbon stores, they are difficult to directly inventory because they are not physically in an identifiable location, whereas carbon stored in forests can be more directly inventoried and quantified.

Increasing the store of carbon in Oregon's forests in the near term may increase carbon releases in the future. The degree to which this occurs will depend upon the degree, frequency, and severity of disturbance changes in the future (Smithwick et al., 2007). If disturbances increase in

frequency and/or severity, then carbon stores will decrease. For example, an increase in the frequency and severity of wildfire in Oregon will kill vegetation as well as combust live and dead plant matter, releasing carbon to the atmosphere (see Figure 5.3d-g). However, changes in disturbance frequency often need to be substantial before a major change in carbon stores occurs. In one analysis, a halving of average wildfire intervals from 200 to 100 years had relatively little impact on average carbon stores of forests in Yellowstone National Park (Kashian et al., 2006). The loss of carbon also depends on the degree that forests can reestablish after disturbances in the future. The effect of forest regeneration time is strongly influenced by the time interval between disturbances. However, unless disturbance intervals drop below 100 years, there appears to be little effect of regeneration rate on average carbon stores (Harmon and Marks, 2002). Still, if forests fail to regenerate, then substantial losses would occur as forests tree species generally store more carbon than grasslands or woody plants of lower stature. Regeneration failure of tree species is most likely on sites with low moisture and/or extreme temperatures. Some broadleaf tree species may be able to shift to asexual reproduction under these conditions, thus retaining some carbon sequestration capacity (e.g., Neilson and Wullstein, 1983).



**Figure 5.6** Average total system (ecosystem and forest products) carbon stores (Mg/ha) over a harvest rotation interval for different levels of removal (percent of live trees harvested) with an aggregated cutting pattern. An aggregated cutting pattern represents one contiguous harvest block. These data represent a system in which 75% of the harvested carbon is converted to long-term forest products with losses of 1% per year. (Figure from Harmon et al., 2009)

Many adaptation efforts are likely to decrease carbon stores in Oregon forests. Regenerating species or individuals of trees better adapted to future climate could release carbon if harvests are used to enhance regeneration, particularly if the time interval between harvests is shorter than current practices. This is because shortening the interval between harvests lowers the

average carbon store of the forest sector (Figure 5.6). Unfortunately, this constraint would likely slow efforts to adjust forests to future climates. Thinning to reduce water stress would also lower carbon stores in the short-term, but might assure more carbon is stored over the long-term if disturbance severity or frequency greatly increases or if forests disturbed in the future are unable to regenerate. It should be noted that due to the feedback between fire severity and fuel level, a period of more frequent, severe fires will not persist (more frequent removal of fuels means less fuel, which means lower severity fires). Removal of fuels to alter fire behavior and severity to reduce carbon emissions would, in most cases, lead to substantial losses of carbon stores as the amount of carbon needed to be removed to alter fire severity exceeds the amount released by fires at least 10-fold (Mitchell et al., 2009). Using removed fuels as a biofuels feedstock or for wood products narrows the carbon cost of fuel treatments, but it does not entirely eliminate the carbon debts created by these treatments. Assuming fuel removal continues to produce biofuels, it may take many decades to centuries to pay back the carbon debts incurred (Mitchell et al., 2009).

## 5.7 Genetic Changes

How plant species in Oregon respond to future climate change will be affected by the genetic variation in adaptive traits. Natural selection has resulted in current plant populations that are genetically adapted to their local climates, resulting in adaptive genetic variation within species that is structured across the landscape. As a result, the climatic tolerances of individual plant populations of a species are considerably narrower than the tolerances of the species as a whole. Populations are the primary biological unit of interest when evaluating adaptation to current and future environments.

When grown in a common environment, most forest tree species show geographic variation in such traits as growth rate, timing of bud flush or bud set, cold hardiness, germination rate, or biomass partitioning that correspond to gradients in temperature and moisture of source locations (Morgenstern, 1996; Howe et al., 2003; St.Clair et al., 2005; Savolainen et al., 2007). Maps of seed zones and seed transfer guidelines have been developed for forest trees in Oregon to manage this geographic genetic variation and ensure that planting stock used in reforestation is adapted to the environmental conditions where reforestation is occurring (Randall, 1996; Randall and Berrang, 2002; Johnson et al., 2004). More recently, seed zones in Oregon are being developed for native plants other than trees to ensure success in restoration projects (Erickson et al., 2004). These guidelines assume, however, that climates are static over long time periods, an assumption that we now know is unlikely. A study of Douglas-fir in western Oregon and Washington indicated that current practices of using local seed sources from within current seed zones for planting new stands would result in a high risk of poorly adapted Douglas-fir stands by the end of the century (St.Clair and Howe, 2007). The Douglas-fir populations expected to be adapted to future climates were located 500 to 1000 m lower in elevation and 2 to 5 degrees latitude (~200 km to ~540 km) further south.

With rapidly changing environments, plant populations face three possibilities (Aitken et al., 2008): (1) migration to new habitats in which they are adapted; (2) adaptation via natural

selection as climate changes; and (3) extinction. The persistence of plant populations by migration will depend upon the rate of migration via seed dispersal and establishment of new stands and upon the rate of gene flow via pollination from distant stands. Most studies of migration rates based on the establishment of new stands rely upon paleobotanical studies of range shifts over the last 25,000 years. Although estimates of historical horizontal migration rates vary widely from 10 km per century to exceptional examples of 150 km per century, all estimates are well below the 300 to 500 km per century that may be required to keep pace with current climate projections for the next century (Davis and Shaw, 2001; Aitken et al., 2008). Range shifts in mountainous areas may occur more quickly since locations of adapted populations could be relatively close, and, indeed, evidence of elevational range shifts associated with climate warming in the last century is being found (Millar et al., 2004; Lenoir et al., 2008). With respect to the potential for pollen flow to move adaptive genetic variation into populations, little is known for most species in native stands. Although pollen may be carried by wind over long distances, differences in the time of flowering between stands in different environments may limit the effectiveness of pollen from distant stands for promoting gene flow (Silen, 1963; White et al., 2007). Further research is needed to study effective pollen flow in native stands, particularly in highly heterogeneous environments such as the mountainous areas of Oregon.

Plant population persistence through adaptation via natural selection will depend upon a variety of factors, many for which we have insufficient knowledge from native populations to allow accurate predictions of the potential for evolution. Responses to natural selection within populations depend upon phenotypic variation (variation that is observable), genetic variation and the heritability of traits important for survival and reproduction, as well as the intensity of selection (Falconer and Mackay, 1996). High reproduction rates and large population sizes may allow for higher intensities of selection without population sizes being greatly reduced. Small populations may lead to loss of genetic variation through inbreeding and random processes called genetic drift.

Gene flow from adjacent populations may be an important contributor to genetic variation within populations of a species. The effectiveness of gene flow for contributing genetic variation important for adapting to a changing environment will depend on where the population is located within the species' geographic range. Populations of a species that are on the periphery of the species' range may have lower genetic variation as a result of their smaller population sizes and they may experience reduced gene flow as a result of their more isolated position on the edge of the species' range (Lesica and Allendorf, 1995). Any gene flow from populations adapted to warmer climate conditions into peripheral populations adapted to cooler climate conditions (e.g., at higher elevations) could result in the introduction of genetic variation into these populations that could be favorable for adapting to future climate changes. Similarly, peripheral populations at the warmer edges of a species' range that receive gene flow primarily from populations adapted to cooler climates could become increasingly maladapted to warmer climates (Davis and Shaw, 2001; Aitken et al., 2008). Such might be the case for species such as Douglas-fir, western redcedar, or Sitka spruce in southwest Oregon, which might see their southern ranges move north as environments become warmer and drier.

Finally, adaptation via natural selection requires generation turnover. Populations of long-lived species, such as Douglas-fir populations in Oregon, may persist for centuries before much of the existing population is replaced, during which time they may increasingly diverge from a population that is best adapted to the new environment. Generation turnover in short-lived species, on the other hand, allows for the opportunity to better keep pace with a changing environment given sufficient genetic variation and high intensities of selection (Lenoir et al., 2008).

The third possibility is that local populations may become extinct. Following from the previous discussion, populations that may be most vulnerable to climate change include small, fragmented and disjunct populations, particularly those at the low elevation and southern latitude edges of a species' range. Although they may persist for a while, long-lived species may be at a greater threat from climate change than short-lived species. Rare species and populations already threatened by other factors such as habitat loss, fire, disease, and insects may be at an even greater risk of loss given the added impact of climate change.

Fortunately, there are a number of adaptive management options that may be used to improve the ability of plant populations to respond to future climate change. The selection and adaptation of plant populations in new environments may be facilitated by managing the genetic diversity inherent among and within plant populations by:

- reducing landscape fragmentation and maintaining corridors for migration and gene flow;
- planting species and populations in new locations in which they may be expected to be adapted in the future (a process referred to as assisted migration);
- establishing "genetic outposts," genetically divergent planted stands that may facilitate gene flow for adaptive variation into adjacent native stands;
- using breeding programs to enhance adaptive traits such as drought hardiness, cold hardiness (for reasons of increased climatic variability and starting to move populations upslope), and pest resistance or tolerance;
- increasing genetic diversity within stands and across landscapes by planting mixtures of populations, and allowing for natural and human selection within diverse stands by planting at higher densities with the possibility of thinning;
- conserving genetic diversity by maintaining adaptive potential and reducing disturbance probability and intensity in native stands (*in situ* conservation) and by collection and storage of the most vulnerable populations (*ex situ* conservation).

## 5.8 Uncertainties in Projections of Future Vegetation Change

There are a number of uncertainties that are associated with our understanding of how Oregon's vegetation may respond to potential future climate changes. Climate model simulations, such as those discussed in Chapter 1, provide estimates of future climate changes but they cannot predict with perfect accuracy how Oregon's climate will change in the future. There is relatively good agreement among climate model simulations that air temperatures in Oregon will increase in the future. It is more difficult for the current generation of climate models to accurately simulate present and future precipitation changes, although the models

continue to be refined and improved. As climate model simulations become more accurate, simulations of future vegetation changes will improve as well. Giorgi (2005), Meehl et al. (2007), CCSP (2008b), and Wiens and Bachelet (2010) describe some of the uncertainties associated with future climates simulations and their use.

Models that simulate potential vegetation responses to climate change also have limitations that affect their ability to accurately simulate vegetation. Many models use complex hydrological, ecological, and physiological processes in order to simulate the effects of climate change on vegetation structure, composition, and function. These models require detailed information on the physiological and ecological responses of individual plant species to climate change. Some plant species in Oregon, particularly those with economic value such as Douglas-fir, have received significant research attention. For many other plant species, however, relatively little is known about how they may respond to future climate changes.

In some mechanistic vegetation models, species can be aggregated into plant functional types with similar physiological and ecological properties, thus considerably simplifying the data requirements for running the models. However, information is also lost by such aggregation and, as a result, ecosystem resilience may be underestimated. Novel future climate regimes may produce no-analog plant communities, thus rendering approaches where past plant functional types are extrapolated into the future more tenuous (Williams and Jackson, 2007; Hobbs et al., 2009). Species distribution models address potential changes at the level of individual species (e.g., McKenney et al., 2007). Some of their core assumptions, such as a species being in equilibrium with its environment, limited consideration of biotic interactions, and a simplified view of landscape level dispersal, also introduce uncertainties into their simulations of species distribution responses to climate change (Wiens et al., 2009). Recent efforts thus aim at increasingly incorporating process-based understanding into such models (Buckley et al., 2010; Franklin, 2010), since capturing fundamental ecological processes is widely seen as a key aspect of making these models more robust for simulating species responses to changing climate conditions.

This focus on improving model simulations is also being applied to understanding and projecting climate change impacts on disturbance regimes, where efforts to understand the complex interactions between climate, vegetation and disturbance agents (Dale et al., 2001; Turner, 2010) are increasingly fostering process-based models (Seidl et al. 2010). Models are essential tools to predict future impacts of climate change, but numerous empirical studies in Oregon and elsewhere are also instrumental in shaping our understanding of how plants will respond to future climate changes. The insights gained from these studies form the basis for improvements in vegetation simulations.

## **5.9 Summary and Conclusions**

Projected future climate changes will affect vegetation in Oregon. Evidence from both the paleoenvironmental record and more recent empirical studies clearly indicates that Oregon's vegetation has responded to past changes in climate. The ranges of plant species have shifted in latitude, longitude, and elevation in response to past climate changes and the distributions of different species have overlapped through time. More recently, earlier dates of first bloom for



some plant species (Cayan et al., 2001) and increased tree mortality in some locations in Oregon (van Mantgem et al., 2009) have been correlated with climate changes that have occurred over the last century. Past vegetation responses to climate change also have been affected by climate-driven changes in the frequency and magnitude of disturbance regimes, such as wildfire and droughts.

Vegetation modeling studies using estimates of future changes in climate and atmospheric CO<sub>2</sub> concentrations indicate that areas of subalpine forest and alpine tundra at high elevations in Oregon and shrubland areas in eastern Oregon will contract under projected future climate changes. Species that currently occur at lower elevations may expand upward in elevation over time. Plant species will respond individually to future climate change, and genetic variations within species will affect the ability of plant populations to adapt to changing climate conditions. Future climate change will also alter disturbance regimes in Oregon, such as fire, drought, and insect and disease outbreaks, as well as interactions between native species and invasive species in the region.

There are still many uncertainties associated with projections of future climate changes and the effects of these changes on vegetation. As research on climate change continues, data and models will improve, allowing for a better understanding of potential future climate changes and their effects. Finally, it has to be noted that this chapter provides only a brief overview of some of the potential effects of climate change on Oregon's vegetation. The references cited in the text will provide the reader with additional sources of information.

### **Acknowledgments**

We thank Steve Hostetler, Allen Solomon, and an anonymous reviewer for their comments on the manuscript. Ray Drapek (US Forest Service), Andrew Herstrom (Oregon Dept. of Forestry), and Richard Pelltier (US Geological Survey) provided assistance with data and figures. R. Seidl received funding from a European Commission Marie Curie International Outgoing Fellowship (grant agreement 237085). S.L. Shafer was supported by the U.S. Geological Survey Global Change Program. We acknowledge the modeling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the WCRP's Working Group on Coupled Modelling (WGCM) for their roles in making available the WCRP CMIP3 multi-model dataset. Support of this dataset is provided by the Office of Science, U.S. Department of Energy. We also are grateful to the UK Meteorological Office and the British Atmospheric Data Centre for providing access to their climate data.

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## 6. Impacts of climate change on Oregon's coasts and estuaries

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### Summary and Knowledge Gaps

Earth's changing climate is expected to have significant physical impacts along the coast and estuarine shorelands of Oregon, ranging from increased erosion and inundation of low lying areas, to wetland loss and increased estuarine salinity. The environmental changes associated with climate change include rising sea levels, increased occurrences of severe storms, rising air and water temperatures, and ocean acidification. The combination of these processes and their climate controls are important to beach and property erosion, flood probabilities, and estuarine water quality, with the expectation of significant changes projected for the 21st century.

Coastal change and flood hazards along the Oregon coast are caused by a number of ocean processes, each of which has significant climate controls such that the severity and frequency of the hazards in the future can be expected to increase. There is near certainty that the rate of sea-level rise will increase in the future as a result of global warming, with the potential of greater than a 1.0 meter increase in sea level by 2100. Evaluating the consequences of intensified and more frequent hazards is complicated by Oregon's tectonic setting, with there being significantly different rates of land uplift along the coast. Taken together, the variable rate of uplift plus the present-day rate of sea level rise, some stretches of the coast are submerging as the sea level rise is greater than the tectonic uplift, whereas other areas are emerging where the reverse is true. The prospects are that with accelerated rates of sea level rise, the entire coast will eventually be submerging and experience significantly greater erosion and flood impacts than at present day.

Another long-term trend is increasing storm intensities and the heights of the waves they generate. In addition, the periodic occurrence of major El Niños in the future will compound the impacts of increasing sea levels and waves, resulting in severe episodes of coastal erosion and flooding, as experienced during the El Niño winters of 1982-83 and 1997-98. At present it is not known whether or not El Niño intensity and frequency will increase under a changing climate. With these multiple processes and their climate controls having important roles in causing erosion and flooding along the Oregon coast, it is challenging to collectively analyze them with the goal of providing meaningful assessments of future coastal hazards during the next several decades.

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Coastal infrastructure will come under increased risk to damage and inundation under a changing climate with impacted sectors including transportation and navigation, coastal engineering structures (seawalls, riprap, jetties etc.) and flood control and prevention structures, water supply and waste/storm water systems, and recreation, travel and hospitality.

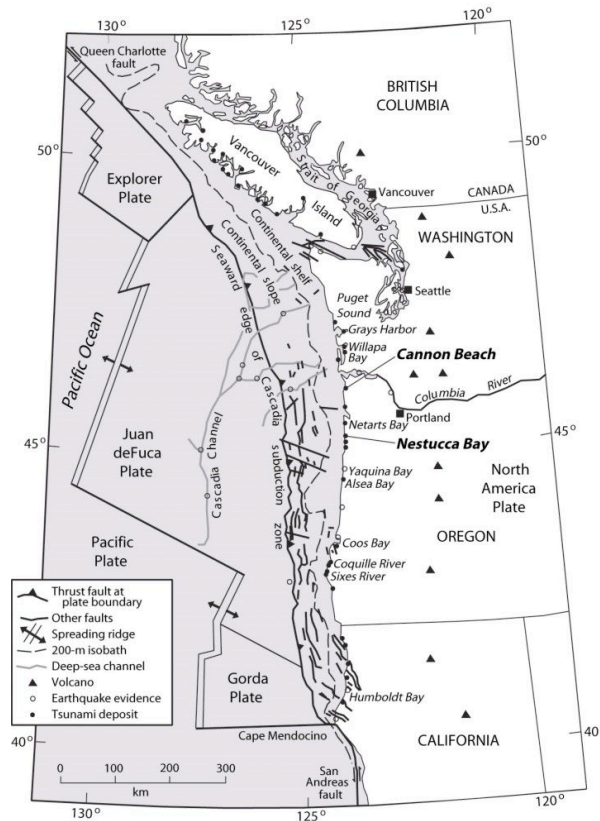
It is likely that regional coastal climate change will result in changes in the intensity and timing of coastal upwelling, shifts in temperatures and dissolved oxygen concentrations, and alteration of the carbonate chemistry (ocean acidification) of nearshore waters. The combination of these meteorological and nearshore ocean changes will exert stress on the communities of near-coastal and estuarine organisms. The range of community responses to the climate change stressors may include elevational shifts in the distribution of submerged aquatic vegetation, disruption of shell formation for calcifying organisms, alteration of the phenology of phytoplankton blooms, shoreward migration of tidal marshes, and increased colonization by non-indigenous aquatic species.

Unfortunately, significant knowledge gaps remain, impairing our ability to accurately assess the impacts of climate change along our coast and estuarine shorelands. For example, the uncertainty of future global sea level rise is significant with credible projections ranging from less than 0.5 m to as much as 2.0 m by 2100. At present we do not conclusively understand the climate controls on increasing storm intensities and wave heights and therefore have a very limited ability to project future trends in coastal storm impacts. The magnitude and frequency of major El Niños has significant implications for the state of Oregon; however, at this time we are unable to assess whether or not these will increase in the future due to climate change. Further, the long-term time-series data necessary to definitively identify perturbations of estuarine communities that can be attributed to anthropogenic climate change are lacking and therefore our understanding of anticipated shifts remain largely speculative.



## 6.1 Introduction

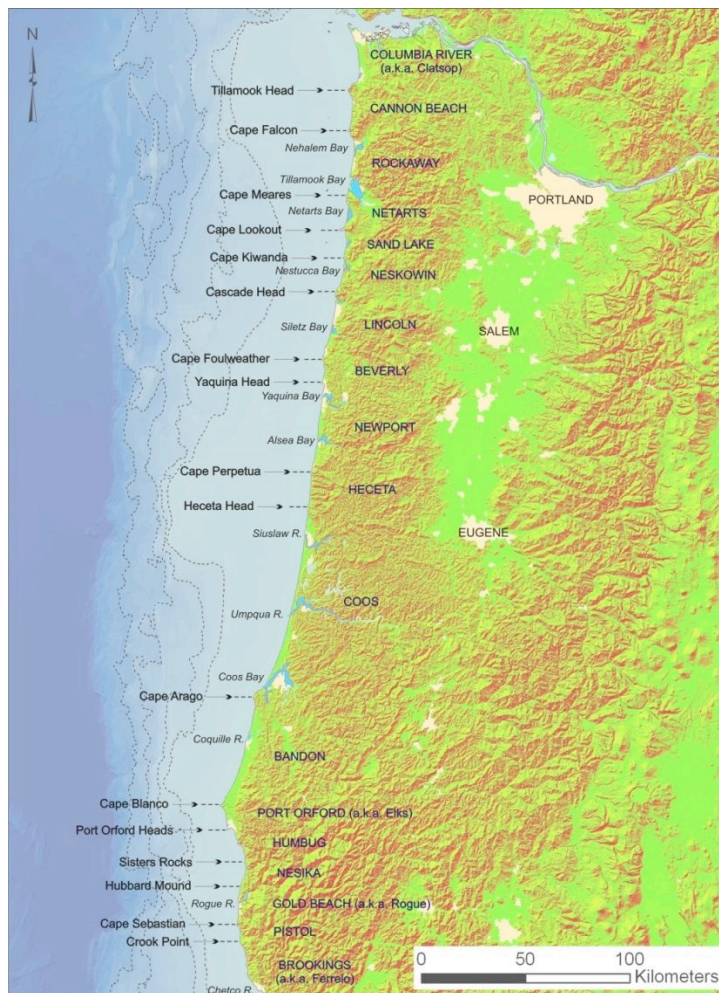
The Oregon coast is approximately 500 kilometers long, extending from the mouth of the Columbia River in the north to the Klamath Mountains and the California border to the south. The rugged character of this picturesque coast results directly from its geologic setting, involving the collision of Earth's tectonic plates off its shore, with the subduction of the oceanic plates beneath the continent (Figure 6.1). There are 17 large rocky headlands (Figure 6.2), with the coast otherwise consisting primarily of a series of littoral cells, stretches of beach that are confined between bounding promontories. Each stretch of shore is in effect a pocket beach, although they range widely in their along-coast lengths, geometry, and varying capacity of their beaches to act as buffers between storm waves and the backing sand dunes or sea cliffs along which infrastructure is located. In addition there are 43 estuaries and tidal creeks along the Oregon coast (11 of which have jettied entrances), but the majority of them are relatively small (< 10 km<sup>2</sup>; Lee and Brown, 2009). The geomorphology of the estuaries is diverse, including river-dominated drowned river mouths, tidal dominated drowned river-mouths, bar-built coastal lagoons, and numerous tidal creeks.



**Figure 6.1** The tectonic setting of the Pacific Northwest, with the collision and subduction of the ocean plates beneath the continental North American plate (Satake et al., 2003).

While the tectonic setting of the Oregon coast has fundamentally determined the geological framework of its headlands, beaches and estuaries, it is the dynamics of ocean and estuarine

processes that determine the evolution of this coast. Many of these processes are controlled by climate and Earth's changing climate is expected to have significant physical impacts along the coast and estuarine shorelands of Oregon, ranging from increased erosion and inundation of low lying areas, to wetland loss and increased estuarine salinity. The environmental changes associated with climate change include rising sea levels, increased occurrences of severe storms, rising air and water temperatures, and ocean acidification. The combination of these processes and their climate controls are important to beach and property erosion, flood probabilities, and estuarine water quality, with the expectation that these impacts along the Oregon coast will significantly increase throughout the 21st century.



**Figure 6.2.** The 17 major headlands (bold font with arrows), major estuaries (light font), and littoral cell names (capital letters) of the Oregon coast.

Due to the significance of existing coastal problems and the potential for future increases in these problems, there has been increased focus by coastal scientists and engineers directed toward documenting the impacts of climate change along our coasts. In this chapter we summarize our present understanding of the climate controls on coastal and estuarine processes that are important to Oregon. While this review represents a progress report in that much of this

research is still underway, these investigations have advanced to the degree that we can document the basic changes in important environmental variables (e.g., sea levels, wave heights, shoreline position), supporting preliminary assessments of the expected magnitudes of future problems along the Oregon coast and the extent to which they potentially could increase due to Earth's changing climate.

In the following sections we attempt to summarize the most recent literature documenting historical changes as well as what may be expected to occur in response to climate change. Where little information is available we draw preliminary conclusions about the potential for specific impacts. When possible we highlight what research is needed to bridge knowledge gaps to improve our ability to identify climate change impacts more precisely, ultimately allowing for future projections.

## 6.2 Sea Level Rise Trends

Recent assessments of climate change have documented that globally the average level of the sea rose throughout the 20th century, with the total increase having been on the order of 15 to 20 centimeters, with an average sea level rise (SLR) rate of about 1.5 to 2.0 mm/year. More precisely, a recent analysis by Holgate (2007) yielded a global average rate of 1.74 mm/year ( $\pm 0.16$  mm/year) during the 20th century. These assessments were based on records derived from tide gauges around the world, which measure the hour-to-hour changes in the water levels caused by tides, but when averaged for the entire year yield a value for the mean sea level for that year. Over the decades such analyses for each year document any progressive changes in the sea level.

A number of U.S. tide gauges have been in operation for more than a century such as those in San Francisco Bay and Seattle, while several in Europe provide records of changing sea levels that date back to about 1700 (Woodworth, 1999). Analyses based on those very long records demonstrate acceleration in SLR during the 19th century (e.g., Gornitz and Solow, 1991). This increase in the rate of SLR since the late 19th century is consistent with geological records (e.g., Donnelly et al., 2004) and correlates with direct measurements of increasing atmospheric and ocean-water temperatures (causing ocean water to expand and increase its volume), and with observations of the melting of mountain glaciers and ice sheets (directly contributing water to the ocean), the primary factors important in causing a rise in sea level. By combining tide gauge analysis with satellite altimetry data, Church and White (2006) documented for the first time another statistically significant acceleration of the global SLR rate, this time in the 20th century, a confirmation of the climate change model simulations reported by the International Panel on Climate Change (IPCC).

Since the early 1990s, satellite altimetry has been used to measure sea level with approximately global coverage. This represents a significant advance over analyses of tide gage data, which are limited to continental coastlines and islands. Between 1993 and 2007 satellite altimetry data reveal a rate of global mean SLR of  $3.3 \pm 0.4$  mm/year (Cazenave and Llovel, 2010). The global coverage of satellites has also exposed significant regional variability, with some areas experiencing as much as 3 times greater than the global rate during this 15 year period (e.g., the

western Pacific). The combination of altimetry, measurements of the mass of ice sheets and glaciers (via changes in the Earth's gravity field, gravimetry), and estimates of thermal expansion due to ocean warming allow for the development of a quantitative sea level budget during the period of 1993 to 2007. During that 15 year period it is estimated that approximately  $1.0 \pm 0.3$  mm/year of the SLR rate was due to thermal expansion,  $1.1 \pm 0.25$  mm/year was due to the melting of glaciers, and  $0.7 \pm 0.2$  mm/year was due to the melting of ice sheets ( $0.4 \pm 0.15$  mm/year for Greenland and  $0.3 \pm 0.15$  mm/year for West Antarctica). This sea level budget sums to  $2.85 \pm 0.35$  mm/year and is approximately equal to the  $3.3 \pm 0.4$  mm/year altimetry estimate considering the uncertainty in each of the measurements (Cazenave and Llovel, 2010).

Reports by the IPCC have projected that sea levels can be expected to rise at still higher rates during the rest of the 21st century in response to global warming that will increase ocean-water temperatures as well as accelerate rates of glacial melting (Bindoff et al., 2007). According to the recent IPCC projections (the fourth assessment report), the total increase in the average global sea level by the end of the 21st century will be significantly greater than the 15 to 20 centimeter rise during the 20th century. Projections range from 0.18 to 0.59 m of sea level rise by 2100.

It has been suggested, however, that even the more extreme IPCC projections might be on the low side since they did not account for the "wet processes" of glacial disintegration that are now evident for the Greenland and Antarctic Ice Sheets (Hansen, 2007). IPCC authors (e.g., Meehl et al., 2007) did suggest an additional 0.1 to 0.2 m of rise by 2100 based on future ice melt, acknowledging that the model projections could not account for the increased contributions due to ice melt because of the lack of scientifically based approaches at the time. In a recent attempt to constrain the range of possible sea level rise by 2100 with realistic physics of glacial melting, Pfeffer et al. (2008) suggested a maximum potential rise of 2.0 m by the end of the century, while reporting that estimates of ~0.8 m were probably more likely. Several other researchers have recently published semi-empirical projections of SLR, an approach that avoids modeling the complex glacier dynamics that the physics-based climate models are presently unable to accurately address. For example, Rahmstorf (2007) derived a semi-empirical relationship that connects global sea-level rise to global mean surface temperature and suggested that a projected sea-level rise in 2100 could be as much as 1.4 meters above the 1990 level. More recent semi-empirical estimates by several groups (e.g., Vermeer and Rahmstorf, 2009; Jevrejeva et al., 2010; Grinsted et al., 2009) suggest that the rise in sea level by 2100 may range between 0.59 to 2.15 meters. Limitations of these semi-empirical approaches include not being able to account for changes in nonlinear ice flows that are predicted to take place in the future (Rahmstorf, 2010). Therefore, these estimates might also be under predicting the amount of SLR that could occur by the end of the 21st century.

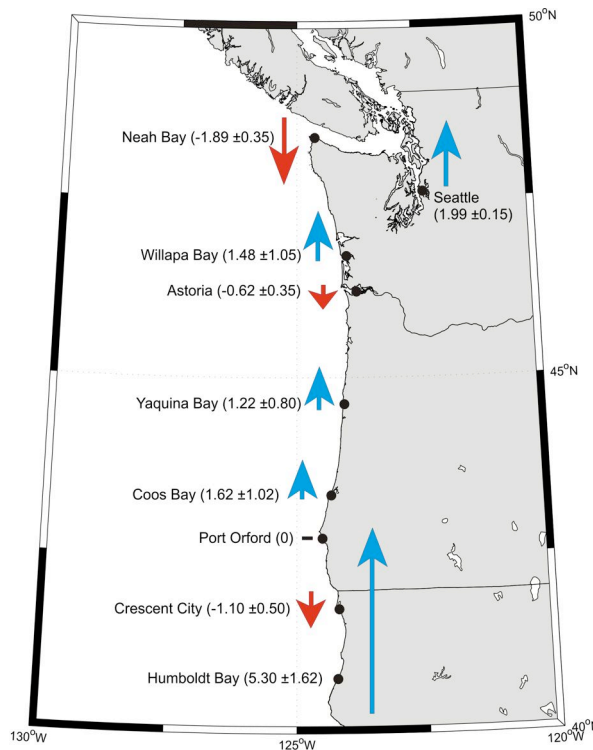
There clearly is a wide range of possible sea level rise scenarios for the 21st century, an indication of the significant uncertainty in our ability to make such predictions. Nonetheless, virtually all approaches predict a substantial increase in future sea level.

### **6.2.1 Relative Sea Level Rise in the U.S. Pacific Northwest**

Studies of global SLR have, for the most part, sought to quantify spatially averaged changes in sea surface height due to the direct addition of water mass to the oceans as well as from thermal

expansion due to warming of the oceans. Superimposed upon the global signal are processes that cause regional redistribution of ocean volume, (e.g., regional variability in thermal expansion (Cazenave and Llovel, 2010)). The effects of these regional perturbations can be fairly large relative to the total water level change observed during the 20th century. While global SLR during the 20<sup>th</sup> century is estimated to have been approximately 1.7 mm/yr, Burgette et al. (2009), using several approaches, estimate that the regional rate of SLR has been approximately 2.3 mm/yr in the Pacific Northwest (PNW).

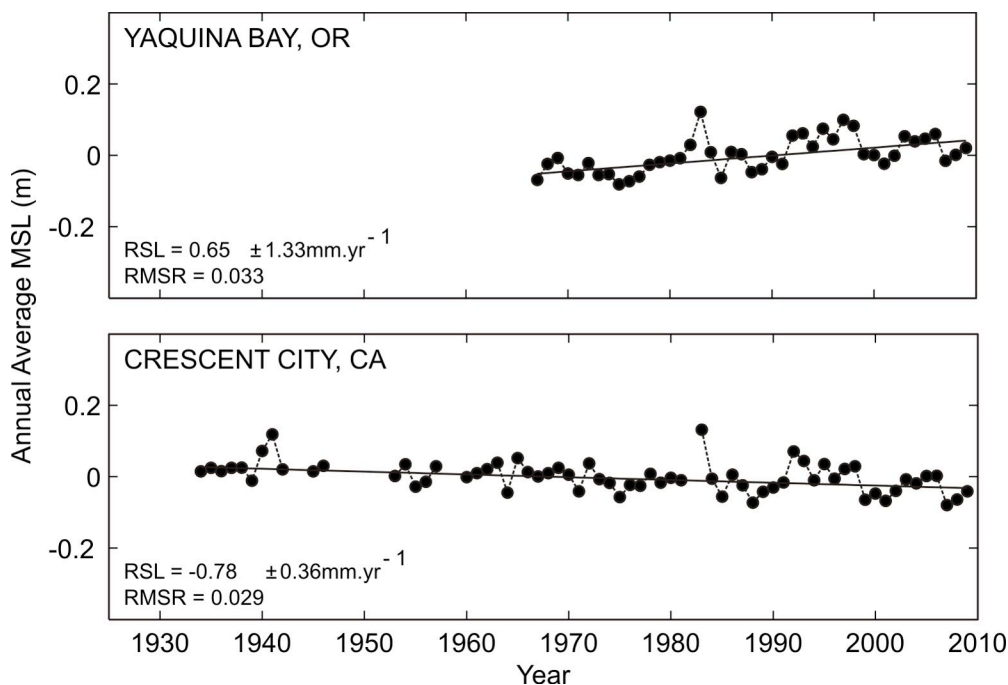
Komar et al. (in press) recently analyzed nine NOAA (NOS) tide gauges along the U.S. PNW coast (Figure 6.3) to document interdecadal trends and enhanced water levels that occur during strong El Niños. Hourly and monthly measured water level data were obtained from the NOAA's National Ocean Service, Center for Operational Oceanographic Products and Services<sup>8</sup> and analyzed using statistical approaches consistent with those of Holgate (2007) and Zervas (2009). The longest records along the U.S. PNW coast are those from Neah Bay, WA (75.4 years), Astoria, OR on the Columbia River (84.9 years), and the tide gauge at Crescent City, CA (77 years) near the Oregon-California border. The records from the other tide gauges range in lengths from 30 to 40 years, so the resulting analyses of their rates of changing sea levels are typically more uncertain.



**Figure 6.3** Analysis of NOAA tide gauges to assess changing sea levels along the coast of the PNW. Colored arrows represent the rates of change in relative sea levels (mm/yr), along with their uncertainty, generated using summer data only (see Section 6.2.2 for details). (After Komar et al., in press).

Examples of the analyses of the changing sea levels measured by two of the tide gauges are shown in the graphs of Figure 6.4, results for the Crescent City and Yaquina Bay tide gauges.

Each data point on the graph represents a mean sea level for that year, calculated by having averaged the hourly tide measurements over the entire year. It is evident that the trends of changing sea levels over the decades have been different at these two sites. The regression line through the Crescent City annual mean sea levels slopes downward at a rate of  $-0.78 \text{ mm/year}$  ( $\pm 0.36 \text{ mm/year}$ ), signifying that the measured sea levels have been dropping at that site on the coast of northern California, whereas the curve for Yaquina Bay on the mid-Oregon coast shows that the measured sea level has been rising at a rate of  $0.65 \text{ mm/year}$  ( $\pm 1.33 \text{ mm/yr}$ )<sup>9</sup>. While the Yaquina Bay annual average rate of rise is not significantly different from zero, due to the large amount of uncertainty associated with the calculated slope, there is a significant difference in the overall pattern of response between the two sites. This difference is caused by the tectonic induced changes in land elevations at these PNW coastal sites. In recognition that the rate measured by a tide gauge combines changes in both absolute (regional) sea levels and land elevations, the measured result is termed the relative sea level (RSL) change rate. In the case of Crescent City where there is a net drop in the RSL, the conclusion is that the land must be rising faster than the regional rise in mean sea level during the 20<sup>th</sup> century ( $2.3 \text{ mm/year}$ ). In contrast, the RSL rise measured by the Yaquina Bay tide gauge implies that at this mid-Oregon coastal site the extent of land-elevation change has been significantly less than has occurred at Crescent City.



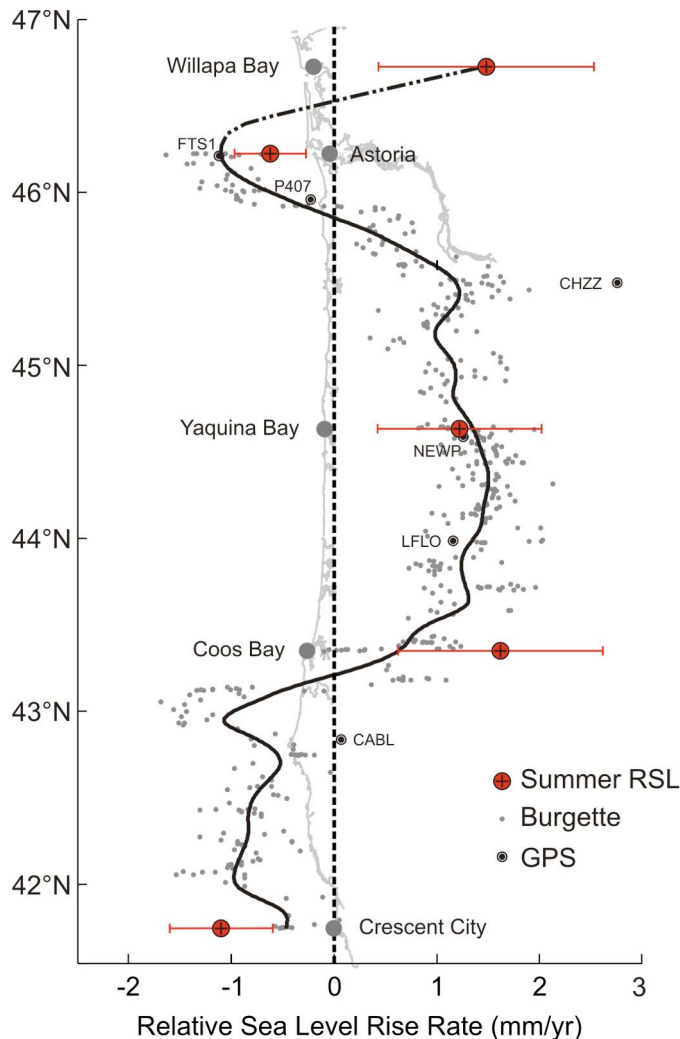
**Figure 6.4.** Analyses of the changing annual-average relative sea level (RSL) rise rates based on the tide-gauge records from Crescent City, California, and Yaquina Bay on the central Oregon coast. RMSR is the root mean square difference between the linear trend and the data. (After Komar et al., in press).

The land-elevation changes that have affected the measured sea levels at Crescent City and Yaquina Bay are due to the active tectonics of the PNW coast, involving the collision of Earth's tectonic plates, with the subduction of the oceanic plates beneath the continent (Figure 6.1). This plate subduction accounts for the greatest hazards faced along this coast, the potential for a massive subduction earthquake and tsunami like that which occurred on 26 January 1700

(Atwater et al., 2005). This tectonic setting is also altering the land elevations along the coast, in particular accounting for the stretches of shore that are rising at faster rates than the present-day rise in sea level. The magnitudes and directions in the rates of changing RSL determined from the PNW tide gauges are graphed as vectors in Figure 6.3, a red vector denoting that the tectonic uplift of the coast has been faster than the global rise in sea level, the measurements by the tide gauge being a drop in the RSL; the blue vectors represent results where there has been a trend of rising RSLs. There is seen to be significant variations in the RSLs along the coast, reflecting the tectonic control on the rates of land elevation changes.

Geophysicists have been able to directly assess the changes in land elevations based on models and periodic resurveys of established bench marks used by surveyors and their results are in reasonably good agreement with those derived from the tide-gauge records (e.g., Burgette et al., 2009; Mazzoti et al., 2008; Verdonck et al., 2007, Mitchell et al., 1994). The along coast patterns in RSL are developed in greater detail in Figure 6.5, where the alongshore varying RSL changes measured by the tide gauges are compared with both the direct measurements of the changes in land elevations derived from resurveys of benchmarks and land elevations measured at GPS sites along the coast (Komar et al., in press). To make the comparisons in Figure 6.5, it was necessary to subtract the rates of land elevation changes derived from the benchmarks and GPS measurements from the magnitude of the regional rise in sea level, 2.3 mm/year, as determined by Burgette et al. (2009), yielding the alongshore patterns in RSL rates graphed in Figure 6.5.

The different rates of land elevation changes along the coast and the resulting variable trends in the RSL rates evident in Figure 6.5 represent a primary control on the corresponding along-coast variations in property erosion and flooding impacts. It is apparent from the geomorphology of the coast and locations of communities which have experienced erosion, that the stretches of shore that are tectonically rising faster than the global rise in sea level (such as Crescent City) have been relatively immune from those hazards, while the areas that are not rising rapidly (such as in Tillamook County, Oregon) are those that have experienced the greatest impacts from erosion and flooding. The application of SLR estimates in decision making will depend on location, time frame, and risk tolerance. For decisions with long timelines and low risk tolerance, such as coastal development and public infrastructure, users should consider low-probability high-impact estimates that take into account, among other things, the potential for higher rates of SLR driven by recent observations of rapid ice loss in Greenland and Antarctica, which though observed were not factored into the IPCC's latest global SLR estimates. Combining the IPCC high emissions scenario with 1) higher estimates of ice loss from Greenland and Antarctica, 2) seasonal changes in atmospheric circulation in the Pacific, and 3) vertical land deformation, a low-probability high-impact estimate of local SLR for the areas of the coast experiencing little vertical land motions is 55 cm (22") by 2050 and 128 cm (50") by 2100. However, by the mid 21st century the projected increase in rates of SLR are expected to exceed the rates of uplift of the land all along the Oregon coast, resulting in erosion even where at present there has been little or no erosion impacts. The scenario as to when this enhanced erosion and flooding begins at a specific coastal site, and the magnitude of that enhancement, depends however on the contributions by other oceanic processes and their climate controls, particularly the increase in storm intensities and the heights of their generated waves (Ruggiero, 2008).



**Figure 6.5** Alongshore varying rates of relative sea level (RSL) rise as determined by three methods. 1) Tide-gauge records with trends based on averages of the summer only monthly-mean water levels (red circles with pluses, error bars represent the 95% confidence interval on the trends). 2) Subtracting the Burgette et al. (2009) benchmark survey estimates of uplift rates from the regional mean SLR rate (2.3 mm/yr) (small gray dots). 3) Subtracting the uplift rates estimated from GPS sites along the coast from the regional mean sea level rate (small filled black circles). [From Komar et al. (in press)].

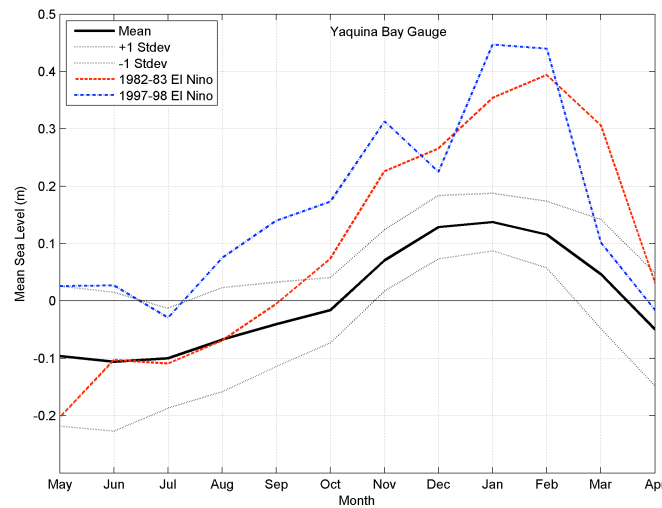
### 6.2.2 El Niño Induced Water Levels

While the interdecadal trends of changing sea levels and their future increasing rates pose a threat to the Oregon coast, it is the year-to-year variations that produce the extreme water-level elevations that cause episodes of erosion and flooding. This variability is evident in the curves of Figure 6.4 for the annual mean sea levels measured by the Crescent City and Yaquina Bay tide gauges, the peaks having been caused mainly by El Niños, the most conspicuous having been those for the 1982-83 and 1997-98 major El Niño climate events. A strong El Niño typically raises the monthly-mean water levels by 10s of centimeters, and therefore during extreme El Niños winter monthly mean water levels can exceed the magnitude of the projected global rise in sea level expected during the next few decades. The resulting impacts from erosion and flooding



along the Oregon coast have led to significant damage and losses of coastal properties (Komar 1997, 1998; Allan et al., 2003; Allan and Hart 2008; Allan et al. 2009).

The full effects of El Niños on the mean water levels during the winter are seen in Figure 6.6. The figure shows monthly means based on analyses of the tide-gauge record from Yaquina Bay. The records from other gauges along the PNW coast are closely similar in their magnitudes and the timing of the seasonal variations. The curve in this diagram for the long-term (1967-2009) average cycle shows that the highest monthly-mean water levels always occur during the winter months of December through February, the lowest being in the summer, with the normal difference between the two seasons being on the order of 0.25 m. This occurrence of the highest water levels during the winter is unusual in that on most coasts the highest levels occur in the summer when the water is warmest, resulting from solar radiation and the heating and thermal expansion of the water. However, along the coast of the PNW the development of upwelling during the summer (Chapter 1) brings cold dense water up to the surface; the water is therefore coldest in the summer and warmest during the winter. This unusual cycle of water temperatures along the PNW coast, together with the changing directions and magnitudes of the ocean's currents, produce the seasonal changes in monthly-mean water levels seen in Figure 6.6. This represents an important factor in occurrences of coastal erosion and flooding since the highest water levels occur at the same time as the strongest storms and their extreme waves.



**Figure 6.6** Seasonal cycles in the monthly mean water levels derived from analyses of the Yaquina Bay tide-gauge data, including the long-term averages and the cycles for the 1982-83 and 1997-98 El Niño years. (After Allan and Komar, 2002).

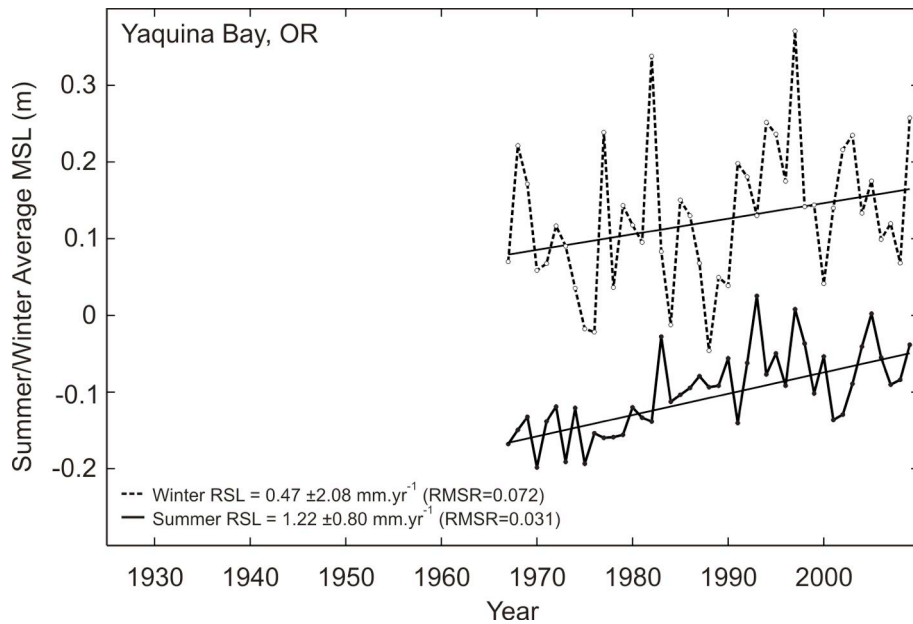
Also included in Figure 6.6 are the extreme seasonal cycles that occurred during the strong 1982-83 and 1997-98 El Niños. It is seen from their cycles that the monthly-mean water levels in the winter were some 50 centimeters higher than during the previous summer, approximately double the normal seasonal cycle. During the months of November through March the monthly-mean water levels of these strong El Niños were on average about 30 centimeters higher than occur during the normal long-term average cycle. The effect was much like there having been a 10- to 30-centimeter rise in sea level over a span of about 6 months; the average rate of rise would have been equivalent to 600 mm/year, about 300 times the rate of the global rise in sea level

spanning the 20th century. Fortunately, when each of these El Niños came to an end their elevated water levels returned to normal, but during those several months of high water levels considerable erosion, and occasional flooding, occurred along the Oregon coast.

The implications of this magnitude of increased water levels during El Niños to erosion and flooding is obvious, since it would have raised the levels of all tides by that amount, the low tides as well as high tides. This was particularly evident during the strongest El Niños in that many of the beaches were “flooded out” at all stages of the tides, there having been almost no dry beach throughout the winter. And at times of high tides, the elevated water levels were able to reach the shore-front properties, the toe of sea cliffs or foredunes backing the beach, resulting in significantly more erosion than occurs during normal (non-El Niño) winters.

It is apparent that episodes of extreme water levels during major El Niños need to be accounted for in evaluating coastal hazards and their climate controls. Some researchers have suggested that global warming may affect the frequency and intensities of El Niños (e.g., Trenberth and Hoar, 1997), however, at present there is no consensus about whether their activity will be enhanced or decrease in the future with a warmer Earth. The analysis in Figure 6.7 is much the same as presented in Figure 6.4 to examine the trends in the annual mean sea levels, but here the monthly-mean water levels for the winter and summer are separately analyzed, the objective being that by limiting the analysis to the winter months the result will emphasize the extreme water levels during El Niños (Komar et al., in press). To make the results particularly meaningful to hazard assessments, “winter” is defined as the combined average tide levels measured over a 3-month period around the peak of the seasonal maximum in water levels, typically the months of December through February. Similarly, “summer” represents the average tide level measured over a 3-month period around the seasonal minimum, typically the months between May through July when levels also tend to be least variable.

The contrast between the “winter” and “summer” seasons is evident in Figure 6.7, there being more variability in the winter record, with the peaks for the major El Niños being most prominent. In order to provide meaningful assessments of the contributions by El Niños to the measured water levels during the winter, it is necessary to detrend the data to remove the effects of the land elevation changes and the regional rise in sea level (Allan and Komar, 2006; Komar et al., in press). The resulting detrended “residual” winter water levels for each year of the Yaquina Bay record (not shown) have been correlated with the corresponding annual values of the Multivariate ENSO Index (MEI), which climatologists have developed to provide a measure of the ENSO events ranging from La Niñas to El Niños. The results document a well-defined increase in the residual



**Figure 6.7.** Mean sea levels for the “winter” and “summer” based on the Yaquina Bay tide gauge. Relative sea level (RSL) rise rates are given along with the uncertainty at the 95% confidence interval. The root mean square residual (RMSR) difference between the linear fit and the data are also given. [From Komar et al. (in press)]

water levels with increasing Multivariate ENSO Index, confirming that the highest elevated water levels occur during the strongest El Niños, while La Niños tend to depress water levels. Closely similar correlations were found for the records based on the other PNW tide gauges, confirming the existence of a fairly uniform along coast response of the elevated winter water levels to occurrences of El Niños.

Figure 6.7 illustrates that the data and linear regression for the summer months are systematically displaced about 0.25 m below the results for the winter, this difference reflecting the seasonal change in mean water levels earlier seen in Figure 6.6. Of significance, the variability caused by El Niños has been almost entirely removed in this graph for the summer months, reducing the scatter so that the long-term trend is better defined. The result is that the analysis based on the summer data only provides a better assessment of the decadal trend in RSL than the annual averages and therefore, only the summer-average derived trends have been included in Figures 6.3 and 6.5.

This series of analyses of the records derived from the tide gauges along the PNW coast have documented their interdecadal trends of increasing or decreasing RSLs, with the direction of change being dependent on the tectonic control on the rate of uplift of the land (Komar et al., in press). Superimposed on the resulting trend in the RSLs are the additive extremes of elevated winter water levels during major El Niños. As rates of global sea level rise accelerate during the 21<sup>st</sup> century, it can be expected that the “winter” average water levels together with El Niño-induced extremes will progressively shift to higher elevations. This pattern of increasing sea-level extremes will result in greater impacts from erosion and flooding along the Oregon coast.

## 6.3 Changes to Storm Climatology

The Oregon coast is well known for the severity of its winter storms and the heights of the waves they generate. During storms, the deep-water significant wave heights are regularly greater than 10 meters (about 1 storm of this size per year), the “significant wave height” being defined as the average of the highest one-third of the measured wave heights within a (typically) 20-minute period. Being something of an average, there are larger individual waves generated by the storm, with the maximum height being approximately a factor 1.7 greater than the significant wave height; therefore, for a storm with a 10-meter significant wave height, individual waves having heights up to ~17 meters can be expected. The most extreme storm in recent years in terms of the heights of the waves measured by offshore buoys occurred in early March 1999, when the significant wave heights reached 14 to 15 meters (Allan and Komar, 2002). With that 1.7 factor, the highest individual waves during that storm would have been ~25 meters, the height of a 10-story building. Being capable of generating such extreme waves, Oregon’s winter storms have been the dominant factor responsible for episodes of erosion and flooding along this coast (Ruggiero, 2008).

The first buoys designed to measure waves off of Oregon’s coast were deployed by NOAA in the mid-1970s, providing hourly measurements of wave heights and periods. Of concern, the heights of these waves have been increasing over the decades (Allan and Komar 2000, 2006; Ruggiero et al., 2010), a result of changing extratropical storm characteristics.

### 6.3.1 Extratropical Storm Intensity, Frequency and Tracks

Allan and Komar (2000, 2006) analyzed averages of winter significant wave heights and documented that, since the 1970s when wave buoys became operational, wave heights had increased off the shores of Washington and Oregon. Lower rates of increase were observed off the northern and central California coasts, while waves off southern California were found to have experienced little net change. Analyses by climatologists of North Pacific extra-tropical storms have concluded that their intensities (wind velocities and atmospheric pressures) have increased since the late 1940s (Graham and Diaz, 2001), implying that the trends of increasing wave heights likely began in the mid-20th century, earlier than could be documented with the direct measurements of the waves by buoys. Graham and Diaz (2001) suggested that the intensification of North Pacific winter storms has resulted from increasing upper-level winds; a finding that had been observed earlier by Ward and Hoskins (1996). Graham and Diaz (2001) further hypothesized that this increasing trend in upper-level winds might be the result of global warming, specifically the increased sea surface temperatures in the western tropical Pacific. An alternative hypothesis has suggested that “black carbon” aerosols (pollution) derived from industries in India and China could also be contributing to the increase in storm intensities (Zhang et al., 2007).

Additional research on trends in mid-latitude extra-tropical storms in the Eastern North Pacific has confirmed that there has been an increase in intensity, but a decrease in frequency, possibly since the storm tracks have shifted poleward during the latter half of the 20th century. McCabe et

al. (2001) showed a statistically significant decrease in the frequency of storms over the years 1959-1997. Geng and Sugi (2003) found that the decrease in annual numbers of storms is typically of the weak-medium strength variety, while the stronger storms have actually increased in frequency.

These documented changes in storm tracks are thought to be primarily due to changes in temperature and pressure gradients, which in turn are linked to changes in atmospheric temperature distributions due to increased greenhouse gas emissions. In other words, in the mid-latitudes of the Northern Hemisphere a decrease in the meridional temperature gradient (poles are warming faster than lower latitudes) has led to a decrease in mid-latitude storm frequency. Recognizing the trends in reanalysis data, Yin (2005) used the output of 15 coupled general circulation models to relate the poleward shift of the storm track to changes in baroclinicity in the 21st century. Though these studies were conclusive that the storm track shifts poleward in the Northern Hemisphere with warmer temperatures, uncertainties regarding natural variability and model limitations remain.

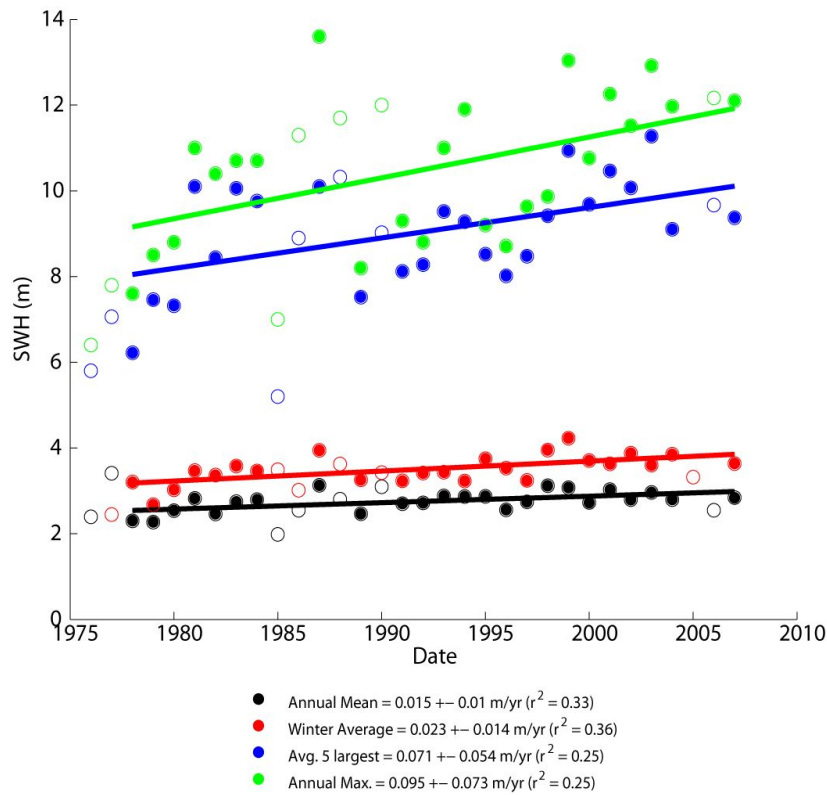
Recently, Favre and Gershunov (2006) analyzed wintertime cyclones (low pressure “storms”) and anticyclones (high pressure “calms”) over the Northeast Pacific for the period 1950 to 2001. They observed that while the strength of anticyclones had gradually diminished over the period and their frequency had become more variable, extratropical cyclones had intensified (consistent with the earlier work of Graham and Diaz (2001)) in a discrete shift with deeper more intense lows and further southerly trajectories occurring since the mid-1970s. This latter response produces a dipole of sea level pressure with an anomalously deep Aleutian Low and higher pressure in the Western Pacific inter-tropical zone, characteristic of the prevailing ENSO conditions and warm phase of the Pacific Decadal Oscillation that have dominated the North Pacific over the past three decades. However, the exact cause of these changes and the degree of intensity was not explained.

### **6.3.2 Increasing Wave Heights**

Of particular significance to Oregon’s coastal hazards is that the more extreme waves generated by the strongest storms are increasing at appreciably higher rates than are the “winter” averages (Allan and Komar, 2006; Ruggiero et al., 2010). This is shown in Figure 6.8, with the series of data plots and linear regressions ranging from the annual average measured significant wave heights, the winter averages, the average of the 5 largest measured significant wave heights that occurred each winter, and the annual maximum significant wave height representing the most severe storm each year. Apparent from this series in Figure 6.8 is that the more extreme the wave statistic analyzed, the steeper the slope of the linear regressions that represent the rates of increasing significant wave heights over the decades. While the averages of all significant wave heights measured during the winter have been increasing at a rate of 0.023 m/year, the maximum significant wave heights of the strongest storms have been increasing at the substantially higher rate of 0.095 m/year. As given by the regression line, this maximum has increased from about 9 meters in the latter 1970s to about 12 meters in 2005, the ~30-year span of measurements from the NOAA buoys.

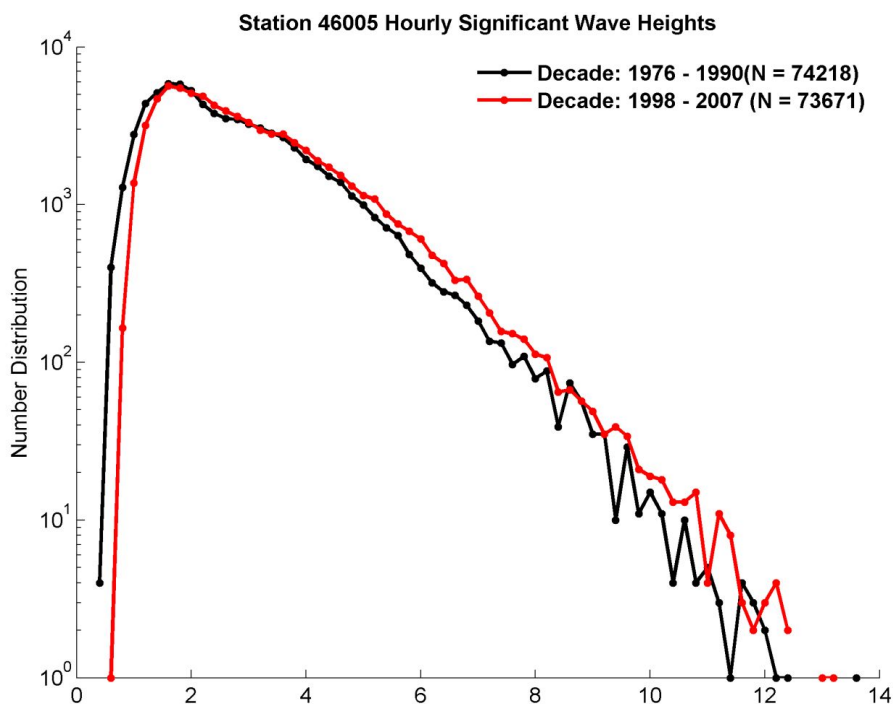
Another meaningful depiction of the changing wave climate is provided by histograms for the full range of measured significant wave heights (Komar and Allan, 2007). Figure 6.9 compares a pair of frequency counts based on wave data derived from the same NOAA buoy as analyzed in Figure 6.8, the separate curves comparing the ranges and numbers of significant wave heights measured during the 1976-1989 versus 1996-2006 “decades” (intervals during which nearly identical numbers of measurements were obtained). The shift to higher extreme measured significant wave heights is apparent in this pair of histograms. There is also a suggestion that the lowest measured significant wave heights, those that occur during the summer, have also experienced an increase over the decades (Ruggiero et al., 2010).

Ruggiero et al. (2010) pointed out that since the wave height climates are governed by the log-normal probability distribution, a modest increase in the annual mean wave height can result in a significant impact on the frequency and magnitude of extreme events. Therefore, measurements of significant wave heights off the U.S. PNW coast represent a clear example of a phenomenon that was suggested by Wigley (2009) in general terms; a gradual change in the mean climate of an environmental variable can result in significant increases in the frequency of extreme events.



**Figure 6.8** Decadal increases in annual mean, winter average, average of the five largest per year, and annual maxima SWHs measured by NDBC buoy #46005 off the PNW coast. The regression slopes and the uncertainty of the regression slopes are given along with the  $r^2$  values. Each of the regressions is statistically significant at the 95% confidence level. Open circles represent years that did not satisfy the criterion for inclusion in the regressions (after Ruggiero et al., 2010) and have not been included in the regressions.

Taken together the analyses in Figure 6.8 of the decadal trends in the average significant wave heights and in Figure 6.9 of the shift in the number distributions provide documentations of the increasing storm-generated waves measured by buoys off the coast of the PNW. To a degree they can provide guidance as to the magnitudes of increases in extreme-value projections, for example the 100-year events that are needed by coastal decision makers in coastal-hazard assessments and by coastal engineers in their designs of coastal structures. However, formal statistical analysis procedures have been developed that can be applied to time-varying changes in data populations, with many directed toward the environmental consequences of global warming (e.g., temperatures, rainfall, and river discharges). Such statistical procedures represent a significant advance over classical extreme-value theory, and have been applied in analyses of the decadal changes in the wave climate of the PNW. Ruggiero et al. (2010) showed that the 100-year wave height, for NDBC Buoy #46005, has been increasing at a rate of approximately 0.07 m/year, a result that is in good agreement with the linear regression for the highest measured significant wave heights (Figure 6.8). By having analyzed the extreme values using the more advanced procedures, the statistical significance and confidence in the results has been considerably improved (see Ruggiero et al., 2010, for details).



**Figure 6.9** Number distributions documenting changes in the ranges of measured significant wave heights off the coast of Washington (modified from Ruggiero et al., 2010).

The wave conditions along the U.S. west coast are also altered by the occurrence of strong El Niños. Most significantly, the coast of southern California is impacted by unusually high waves due to the altered tracks of the storms, so they cross the coast of central to southern California

during an El Niño, rather than following their more normal tracks that take them across the shores of the PNW. Although the storms are more distant from the PNW coast during an El Niño, their generated waves that reach the Oregon coast have an important role in the resulting erosion impacts. Most significant are the altered directions of the waves that arrive more from the southwest than normal. This dominance of the waves reaching the Oregon coast from the south to southwest produces a redistribution of the sand on its beaches, creating what is termed “hot spot” erosion that is characteristic of El Niño winters.

## **6.4 Climate Change Impacts on Coastal Hazards**

It is evident that coastal change and flood hazards along the Oregon coast are caused by a number of ocean processes, each of which has significant climate controls such that the severity of the problems in the future can be expected to increase. Important is the near certainty that the rate of sea-level rise will be greater in the future as a result of global warming. Evaluating the consequences to enhanced erosion and flooding is complicated by Oregon’s tectonic setting, with there being significantly different rates of uplift along the coast. Taken together, the variable uplift of the land plus the present-day rate of regional SLR, stretches of the coast are submerging whereas other areas are emerging. The prospects are that with the expected accelerated rates of SLR, the entire coast will at some point be submerging and experience significantly greater erosion and flooding impacts than at present day. Another long-term trend important to the future coastal change and flood hazards along the Oregon coast, possibly linked to global warming (Section 6.3.1), is the increasing intensity of major winter storms and the heights of the waves they generate. Application of simple coastal hazards models indicate that over the period of wave-buoy observations (~30 years) wave height (and period) increases have had a more significant role in the increased frequency of coastal flooding and erosion in the PNW than has the rise in sea level (Ruggiero et al., 2008). In addition to those progressive trends, the periodic occurrence of major El Niños in the future will compound the impacts of increasing sea levels and waves, resulting in the most severe episodes of Oregon coast erosion and flooding. With these multiple processes and their climate controls having important roles in causing erosion and flooding along the Oregon coast, it is challenging to collectively analyze them with the goal of providing meaningful assessments of future hazards during the next 25 to 100 years.

### **6.4.1 Observations of Coastal Change along the Oregon Coast**

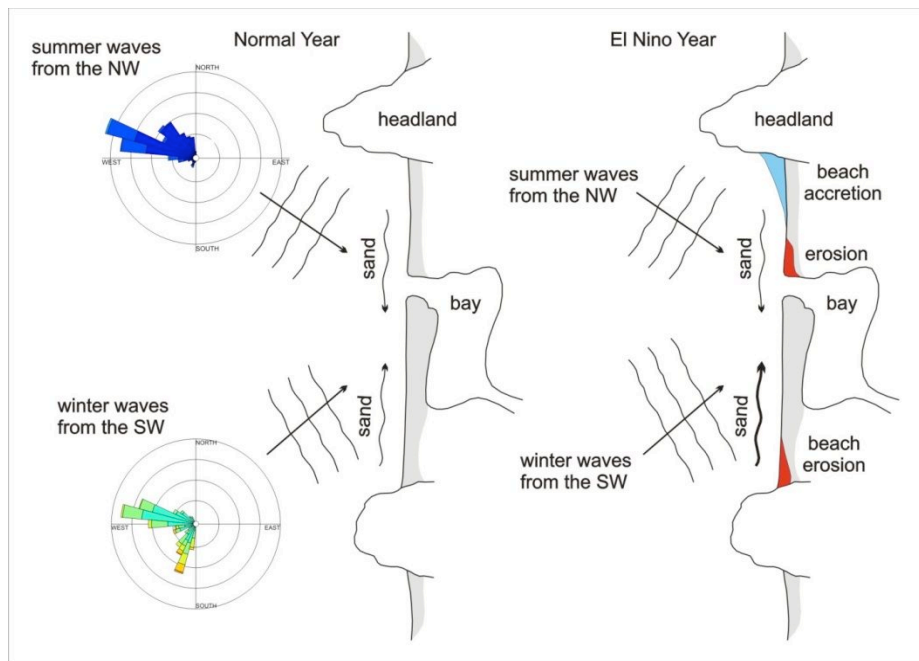
To understand the impacts of storms, particularly during major El Niños, and to improve our understanding coastal change due to climate change, staff from the Newport Coastal Field Office of the Oregon Department of Geology and Mineral Industries (DOGAMI), have developed the “Oregon Beach and Shoreline Mapping and Analysis Program (OBSMAP)<sup>10</sup>”. The OBSMAP program has two broad goals: first, to provide up-to-date information on the state of beaches and shorelines along the PNW coast, information that can be used by coastal managers, geotechnical consultants, and the public-at-large, and second to develop an improved understanding of the seasonal-interannual-decadal changes in Oregon beaches. Beach monitoring undertaken as part of the OBSMAP effort is based on repeated high-accuracy GPS surveys of selected beach profiles (e.g. Ruggiero et al., 2005; Allan and Hart, 2008). The OBSMAP monitoring network currently consists of 119 active beach monitoring sites that are funded through the Northwest Association



of Networked Observing Systems (NANOOS), and another 85 sites that have been observed on a case-by-case basis.

#### 6.4.1.1 El Niño induced coastal change

The occurrence of concentrated “hot spot” erosion during major El Niño events is due to the fact that the Oregon coast consists of a series of littoral cells, stretches of beach that are confined by bounding rocky headlands (Komar, 1997). The significance is that as diagrammed in Figure 6.10; during normal years there typically is a seasonal reversal in the longshore movement of the sand within each littoral cell, transported to the north during the winter by waves that arrive from the southwest, but during the summer with the waves arriving principally from the northwest an approximately equal volume of sand moves back to the south. The shoreline thereby maintains a nearly balanced equilibrium in the north-south oscillations of its sand during normal years. However, as also diagrammed in Figure 6.10, during an El Niño with a greater dominance of waves arriving from the southwest in the winter, a greater volume of sand is transported to the north within Oregon’s littoral cells. The consequence of this northward displacement of the beach sand within the cells is that the beaches at their south ends, to the north of the headlands, undergo massive erosion, becoming the primary zones of hot-spot erosion during El Niños (Komar, 1986, 1998; Peterson et al., 1990; Kaminsky et al., 1998; Revell et al., 2002; Allan et al., 2003; Allan et al., 2009). Erosion also tends to occur to the north of inlets into bays and the mouths of rivers, when they migrate to the north under the forces of the waves arriving from the southwest, or to the north of jetties that can act like mini-headlands.



**Figure 6.10** Sand movement along the beaches within Oregon’s littoral cells between rocky headlands due to the seasonal changes in wave directions, contrasting the equilibrium balance during normal years with that during a major El Niño when the waves transport greater volumes of sand to the north, resulting in zones of “hot-spot” erosion (after Komar et al., 2002).

The hot-spot zones of erosion during the major El Niños of 1982-83 and 1997-98 represent some of the most significant impacts to coastal properties in recent decades. That erosion was the

combination of the exceptionally high water levels experienced during the winter months, and the northward movement of the beach sand by the waves that reach the coast from the southwest, so that the property losses were greatest in the hot-spot areas. Examples of significant hot-spot erosion problems along the Oregon coast include the following.

- Neskowin, with the hot-spot area of maximum beach and foredune erosion having occurred immediately north of Cascade Head.
- The erosion and flooding impacts to Cape Lookout State Park at the south end of Netarts Spit, to the north of the Cape, during both the 1982-83 and 1997-98 El Niños.
- Impacts to The Capes development of condominiums that were constructed on a high sand bluff that was eroded by the northward migration of the inlet to Netarts Bay.
- Extensive erosion of the Bayshore development on Alsea Spit during both major El Niños, caused by the northward migration of the Bay's inlet.
- The erosion of the beach and foredunes in Port Orford north of The Heads, resulting in the loss of the community's sewage disposal facility, and leading subsequently to a breach through the dunes that carried water into Garrison Lake that was its source of fresh water.

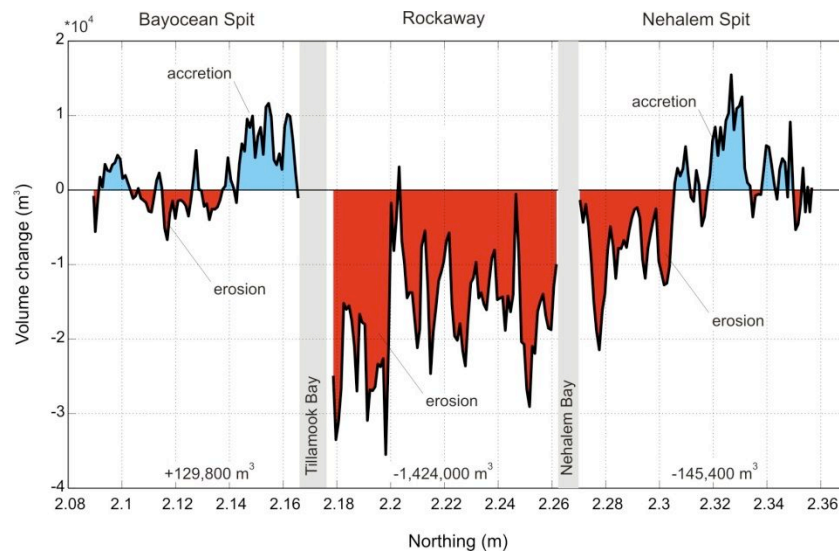
It is clear that the extreme processes and climate controls of El Niños need to be accounted for in hazard assessments along the Oregon coast, in addition to the climate controls on increasing sea levels and storm-generated wave heights. While it has been suggested that global warming may affect the frequency and intensities of El Niños (e.g., Trenberth and Hoar, 1997), at present scientists cannot definitively say whether their activity will be enhanced or decrease in the future with a warmer Earth (Collins et al., 2010).

#### *6.4.1.2 Interannual- to decadal-scale coastal change*

It is typical of the examples of erosion that began during one (or both) of the major El Niños that the erosion can continue for several years after the El Niño winter has ended. Furthermore, in the case of the 1997-98 El Niño it was followed by the winter of 1998-99 during which there was a series of unusually severe storms and extreme waves, including that in early March 1999 which generated the 14- to 15-meter significant wave heights, the highest in recent decades (Allan and Komar, 2002). These two years of consecutive impacts were characterized as having been a "one-two punch" that was responsible for extensive continued erosion. To-date many of the beaches on the northern Oregon coast, particularly in Tillamook County, have yet to fully recover from the cumulative effects of the 1997-98 El Niño and the more extreme 1998-99 winter (Allan and Hart, 2008). As a result, at the time of writing this report (summer/fall 2010) a number of beaches remain in a degraded state making them highly susceptible to potentially catastrophic future events that will inevitably take place during the next 'big' winter.

Erosion has become particularly acute along the Rockaway littoral cell (Figure 6.2) in Tillamook County, much of which can be attributed to the extreme storms that impacted this section of the coast during the 1997-1998 and 1998-1999 winters. Figure 6.11 was derived by analyzing topographic beach volume changes collected using airborne lidar (light detection and ranging)

data flown in 1997 and 2002. Subsequent monitoring of the beaches indicates that the shoreline has continued to experience ongoing erosion, with the Rockaway sub-cell having continued to lose sand over time, while Bayocean Spit and portions of the Nehalem Spit appear to be slowly gaining some of this sand; the net loss of sand from the cell is now estimated to be approximately two to two and a half million cubic meters of sand (Allan and Hart, 2008). Portions of the shore immediately north of Tillamook Bay have eroded by as much as 47 m, increasing the hazard potential to existing homes and infrastructure from ocean flooding and additional future shoreline retreat (Figure 6.12).



**Figure 6.11** Alongshore beach volume changes (in cubic meters) derived from an analysis of available lidar data for the period 1997–2002. Red shading indicates erosion, blue shading indicates accretion.

Findings from the OBSMAP beach monitoring program reinforce two important points concerning PNW beach and shoreline responses. First, high ocean waves exert a primary control on PNW beach and shoreline responses. Second, several littoral cells remain in a state of sediment deficit due to the volume of sand that has been removed from the beaches and dunes over the past decade. This is somewhat surprising since beaches typically begin to rebuild following major storms, and especially during the summer months when wave energy levels are significantly lower. However, analyses of the offshore wave climate as noted previously indicates that in fact wave energy levels and hence the wave heights have remained high over the past decade, and wave heights have been increasing since at least the mid 1970s (Allan and Komar, 2006). As a result, many Oregon beaches have continued to erode over the past decade, with signs of recovery having been confined to only a few discrete locations (e.g., the northern end of the littoral cells and sub-cells).



**Figure 6.12** Ongoing shoreline retreat over the past decade in the Rockaway cell and localized hotspot erosion effects have resulted in substantial sections of the shore having to be rip-rapped in order to safeguard property. SLR expected over the next century and enhanced storms will almost certainly increase the risk of failure of such structures and the potential loss of homes and important infrastructure backing the beach.(Photo courtesy of Mr. Don Best, 2009.)

#### *6.4.1.3 Long-term coastal change*

Relatively few studies have attempted to quantify the long-term (decadal to century) patterns of shoreline change on the Oregon coast. Of the studies that have documented long-term coastal change, most have primarily focused on bluff changes in varying geologic units on the central Oregon coast (e.g. Priest, 1999; Allan and Priest, 2001; Priest and Allan, 2004; Witter, Allan and Priest, 2007). Estimates of long-term erosion rates in these studies were typically determined by comparing changes along the bluff top or toe at specific locations where ground-control points could be identified using aerial photographs. Using this approach, Priest (1999) found mean erosion rates to be low, averaging  $\sim 0.19$  m/yr in northern Lincoln County, but could reach as much as 0.5 m/yr depending on the local geology. In contrast, Witter et al. (2007) identified erosion rates in south Lincoln county that were generally much lower ( $\sim 0.03$ -0.15 m/yr).

For dune-backed beaches, Allan et al. (2003) examined long-term changes at several sites on the Oregon coast, including most of Tillamook County and Port Orford on the southern Oregon coast. They concluded that the largest measurable net shoreline changes were those that resulted from jetty construction. Elsewhere, Allan et al. (2003) demonstrated that the Oregon coast is subject to large temporal and spatial variations in its shorelines, varying at any one site from extreme erosion to accretion. These changes are a response to the high-energy character of Oregon's coastal processes, to occurrences of extreme storms, and particularly to major El Niños. Therefore, Allan et al. (2003) concluded that historical shoreline change assessments based on aerial photographs and NOS "T" sheets were generally not appropriate for making projections of future shoreline positions.

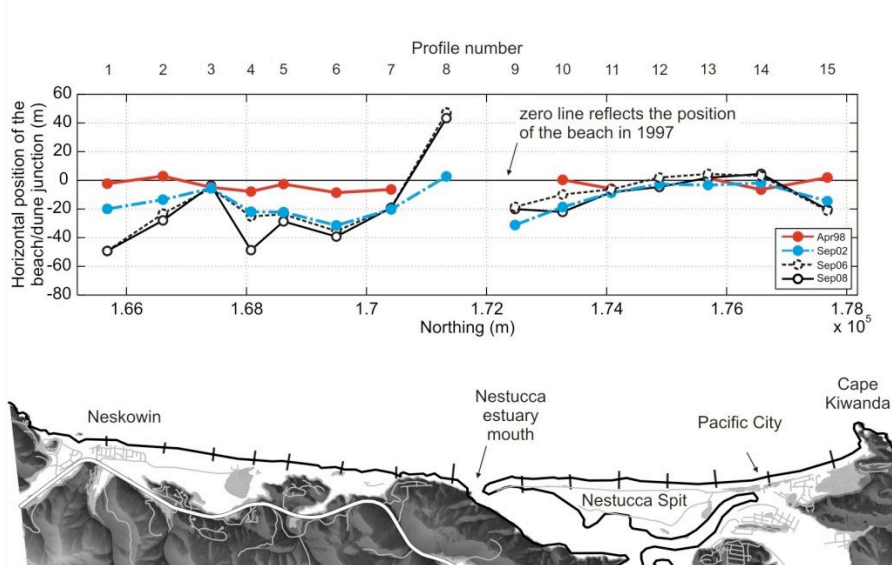
## 6.4.2 Projecting future hazards

Quantifying the impact of climate change on coasts is not straightforward because the response of these systems is a complex morphodynamic issue. In the absence of significant sediment sources and sinks, the Bruun Rule (Bruun, 1962) conceptually describes the retreat of unprotected coastlines due to SLR (via mass conservation). While the Bruun Rule is often pilloried for its simplicity, Stive et al. (2009) reviewed the various attempts to verify the approach against field and laboratory data over the last 4 decades and concluded that the basic concept of the Bruun Rule has been qualitatively confirmed. For many of the world's coastlines, where the nearshore beach slope is about 0.01 to 0.02, the Bruun Rule predicts a coastline retreat between 50xSLR and 100xSLR, values that are commonly used as a "rule-of-thumb". Unfortunately, the applicability of the Bruun Rule is usually compromised, particularly in the vicinity of tidal basins (Oregon has 43 estuaries.) Because of this, Stive et al. (2009) recommend that, at best, any predictions obtained via the Bruun Rule should be considered only as broadly indicative, order-of-magnitude estimates. Stive et al. (2009) go on to suggest that comprehensive bottom-up (small-scale, process-based) and top-down (large-scale, behavior-based) numerical modeling, validated by field data, is necessary to provide more scientifically robust and reliable predictions of coastline retreat due to future SLR. Unfortunately, this approach requires significant resources and is still under development, therefore it has yet to be applied to the Oregon coast.

One approach that is being followed to develop hazard zones along the Oregon coast (e.g., Allan and Priest, 2001; Baron et al., 2010) is the application of a series of simple models, with the first directed toward combining multiple processes to calculate the total water levels (TWL) at the shore and the frequency with which they can reach and impact shore-front properties, followed by simple models developed to evaluate the resulting property erosion (e.g., Komar et al., 1999). The first in the series of analyses is to calculate the 'nearshore processes climate' from the measured deep-water wave heights and periods. Next is the application of a simple TWL model (e.g., Ruggiero et al., 2001) which combines the varying levels of the tides with the runup levels of the storm waves to determine the TWLs achieved on beaches. Here the measured tides are used rather than the predicted astronomical tides, so as to include processes such as storm surge and the elevated winter water levels that would occur during a major El Niño. In making long-term projections, trends of increasing wave heights and future SLR are incorporated in a scenario-based approach. The TWL model provides a relatively simple tool to assess the increasing exposure of shore-front properties to erosion. However, the actual extent of the erosion depends on the nature of that property, whether it is a foredune, resistant sea cliff, or fronted by a shore protection structure. Simple "geometric" (similar to the Bruun Rule) and/or "process-based" models are available to evaluate the potential retreat of foredunes, which depends directly on the TWL (Komar et al., 1999). Models to predict the extent of sea-cliff erosion during a storm are more complex in that they depend on the resistance of the cliff to the impact forces of the waves (e.g., Collins and Sitar, 2008).

## Case Study of Neskowin, OR

Erosion has been particularly acute along portions of the Neskowin littoral cell in southern Tillamook County (see Figure 6.2 for location). This coastal change has been caused in part due to the effects of recent major El Niños as well as the progressive rise in sea level and wave heights over recent decades. Examination of lidar and beach monitoring data for the Neskowin cell documents coastal change between 1997 and 2008 (Figure 6.13). While the effects of the 1997–1998 El Niño winter storms were relatively moderate at high elevations on the beach (dune toe, Figure 6.13), erosion from the 1998–1999 winter was particularly acute adjacent to the village of Neskowin where the beach eroded by as much as 50 m. Similar to the Rockaway cell, the beach monitoring indicates that the southern end of the cell has continued to erode in subsequent years, with some storms having produced as much as 25 m of dune retreat during a single event (Allan and Hart, 2008).



**Figure 6.13** Positional changes in the beach/dune toe (elevation of 6 m) along the Neskowin Cell between 1997 and 2008 derived from lidar data and real-time kinematic differential Global Positioning System measured beach profile response. Circles and numbers correspond to the transect locations identified on the map (Allan et al., 2009).

Erosion and flooding along the beaches of Neskowin has today become a harbinger of the probable impacts of future climate change for other coastal communities along the Oregon coast. For example, the loss of significant fronting beach in this area that otherwise previously protected properties built along the shore has substantially increased the potential for catastrophic losses during a major storm. The best example of this scenario was a major storm that occurred on January 5<sup>th</sup> 2008 that came close to removing oceanfront homes in Neskowin. Because beach elevations had progressively been lowered over the course of the 2007/08 winter the combination of extreme waves during the January storm along with high ocean water levels enabled waves to break close to shore, scouring down the beach face and eventually undermining the toe of a riprap structure and causing part of the structure to fail (Figure 6.14). As a result, given that many beaches in Tillamook County have continued to see very little recovery in the intervening years (i.e., beaches today are narrower and have less sand volume compared with beaches in the mid 1990s), the community of Neskowin in particular remains at

high risk of being impacted by both coastal erosion and ocean flooding in the ensuing winter seasons and from future climate change.



**Figure 6.14.** Loss of beach at Neskowin has increased the potential for waves to damage coastal structures built to protect properties as well as increased the potential for flooding of homes built behind the structures.

The Neskowin Coastal Hazards Committee (NCHC) is a local community group that has emerged in response to increased coastal hazards along this stretch of the Oregon Coast. The group is chaired by a county commissioner and its mission is to recommend to state and county agencies and officials ways to maintain the fronting beach and protect the community through both short- and long-term strategies and to explore ways to plan for and adapt to the potential future climate induced changes in the Neskowin coastal area. Several state agencies and university researchers are collaborating with the NCHC to find solutions to Neskowin's erosion and flood hazard issues, and identify promising practices and policies that may be relevant to other coastal Oregon communities. The Department of Geology and Mineral Industries (DOGAMI) is responsible for hazards assessment and mapping and the department has been monitoring the Neskowin shoreline for years. Oregon State Parks (OSP) has jurisdiction and permitting authority for shore protection structures and is interested in communities being proactive about planning rather than having to deal with emergency permits during a crisis. The Department of Land Conservation and Development's (DLCD) Coastal Management Program supports local planning for hazards (Goal 7), coastal shorelines (Goal 17), and beaches and dunes (Goal 18). Neskowin's leadership in trying to address coastal erosion has been rewarded by a planning grant from DLCD to Tillamook County to conduct a "coastal hazards adaptation plan" for Neskowin and the county. Researchers from Oregon State University, the US Geological Survey (USGS), and Oregon Sea Grant are working on a separate but related project to evaluate the climate impacts of shoreline erosion, and assess the vulnerability of communities to those hazards. Findings from this work are informing the Neskowin Coastal Hazards Committee and the Tillamook County Coastal Hazards Adaptation Plan.

Early successes of the NCHC include the official formation of the group and recognition by Tillamook County, monthly meetings with formal agendas and minutes (Figure 6.15), drafting and sending a letter to community residents describing the nature of the hazards and why the group has formed, a formal assessment and map by Oregon State Parks evaluating the condition of the riprap along the entire community by individual tax lot, and the collection of research materials on beach protection strategies used by other states. Continued communication and interaction between local groups like this one and various state and federal agencies will be necessary for Oregon's coastal communities to plan for and adapt to coastal impacts due to climate change.



**Figure 6.15** Officials from DOGAMI and Oregon Sea Grant presenting scientific information about local coastal hazards to the NCHC in early 2010.

## 6.5 Climate Change Impacts on Estuaries

The Oregon shoreline is interrupted by 43 estuaries (major and minor) and tidal creeks (estuaries defined as coastal water bodies that had a National Wetland inventory estuarine polygon; Lee and Brown, 2009) that encompass a broad range of land-margin habitats located at the nexus of the land and the sea. The types of estuaries along the Oregon coast are diverse and include: (a) river-dominated drowned river mouths (i.e., Columbia, Umpqua, Coquille, Rogue, Chetco); (b) tidal dominated drowned river-mouths (i.e., Tillamook, Yaquina, Coos); (c) bar-built coastal lagoons (i.e., Netarts, Sand Lake); and (d) numerous tidal creeks (Rumrill, 2006; Lee and Brown, 2009). Physical and biochemical conditions are highly dynamic within the estuaries, and they exhibit considerable spatial and temporal variability that is generally reflective of the extent to which the tidal basins are driven by inputs from coastal watersheds versus nearshore oceanic waters (De Angelis and Gordon, 1985; Sigleo et al., 2005; Sigleo and Frick, 2007; Brown and Ozretich, 2009).



It is anticipated that warming of Oregon's temperate climate will contribute to fundamental changes along the coast including shifts in the timing and intensity of coastal storms (Section 6.3.1), changes in precipitation and the delivery of freshwater inputs (Chapter 1), sea-level rise (Section 6.2), and increased inundation of the shallow tidal basins. Regional coastal climate change may also result in changes in the intensity and timing of coastal upwelling, shifts in temperatures and dissolved oxygen concentrations (Chapter 1), and alteration of the carbonate chemistry of nearshore waters (Chapter 1). The combination of these meteorological and nearshore ocean changes will exert stress on the communities of estuarine organisms and alter water quality conditions in estuaries. The range of estuarine community responses to the climate change stressors may include changes in the abundance, distribution, growth, and reproduction of submerged aquatic vegetation (Short and Neckles, 1999; Kairis and Rybczyk, 2010; Shafer et al., 2008), disruption of shell formation for calcifying organisms (Miller et al., 2009), alteration of the phenology of phytoplankton blooms (Nixon et al., 2009), shoreward migration or loss of tidal marshes (FitzGerald, et al., 2008), and increased colonization by non-indigenous aquatic species (Stachowicz et al., 2002). It is important to note, however, that these changes are based on data from other regions and there is considerable uncertainty in these projections. In addition, long-term time-series data are lacking for Oregon systems to definitively identify perturbations of the estuarine communities and water quality that can be attributed to anthropogenic climate change.

### **6.5.1 Inundation of Estuarine Wetlands**

The estimated long-term rate of coastal wetland loss from all anthropogenic impacts is greater for the Pacific Coast than for any other area of the U.S. (US EPA, 2008) and an estimated 70-90% of tidal wetland habitat has been altered or lost in Oregon in the past 150 years (Brophy, 2005). Added to these historical impacts, sea level rise (SLR) will result in additional wetland loss with a concomitant loss of associated ecosystem services, such as habitat for juvenile salmon and waterfowl, flood control, maintenance of estuarine water quality, and carbon sequestration (Zedler and Kercher, 2005). While considerable research is needed to determine the precise relationships of these ecosystem services to specific wetland types, the first step is to project how SLR will affect the area and distribution of wetland types in Oregon. Susceptibility of these wetlands to SLR will vary among estuaries due to difference in RSL rise rate along the coast (Figure 6.5) as well as due to differences in the extent and type of wetlands within in each estuary (Lee and Brown, 2009).

Deciding how to begin modeling the vulnerability of estuarine wetlands to SLR in the Pacific Northwest is not clearly presented in the existing literature. However, in a recent review of SLR impact models, Mcleod et al. (2010) recommended the Sea Level Affecting Marshes Model (SLAMM) as an inexpensive yet detailed assessment of vulnerability of wetland habitats to sea-level rise. SLAMM models five of the primary processes involved in wetland conversion and shoreline modification during SLR including accretion, saturation, inundation, overwash, and erosion

(Park et al. 1989; [www.warrenpinnacle.com/prof/SLAMM](http://www.warrenpinnacle.com/prof/SLAMM)). SLAMM was initially developed for modeling intertidal marshes on the U.S. East coast, but since it is based on National Wetland Inventory (NWI; <http://www.fws.gov/wetlands/>) it offers a generalized tool for predicting SLR-induced change in freshwater, brackish, and estuarine tidal marsh ecosystems. For

example, SLAMM was applied at a regional scale to evaluate effects of SLR on 11 sites in Puget Sound and along the Pacific Coast from Washington to Tillamook Bay (Glick et al., 2007).

Among its advantages, SLAMM is scalable, GIS-based, and is capable of including the effects of surrounding land cover such as impervious surfaces and coastal armoring (e.g. dikes and seawalls). Additionally, SLAMM is an open-source program, and offers users flexibility in terms of model complexity and climate change scenario choices. Because of its generality and flexibility as a planning decision support tool, SLAMM has gained traction among coastal managers and has been used, for example, to evaluate SLR impacts on ecosystem services of Georgia marshes (Craft et al., 2009a). In addition, several Federal, State and non-government agencies are utilizing SLAMM to model potential effects on tidal wetlands in Pacific Northwest estuaries and aid decisions about their restoration. Model results are being used by the U.S. Fish and Wildlife Service in developing comprehensive conservation plans for many National Wildlife Refuges (NWR) including the Willapa Bay NWR, in Washington and, in Oregon, the Bandon Marsh (NWR), Nestucca Bay NWR, and Siletz Bay NWR in Oregon. The USGS is using SLAMM to model habitat responses to SLR in the Yaquina Bay Estuary based on 1m, 1.5m, and 2m SLR scenarios. A broader, watershed level SLAMM modeling effort for Oregon estuaries is being undertaken by Ducks Unlimited.

Available SLAMM predictions for Oregon wetland refuges indicate different types of impacts across different estuaries or estuarine segments. Current results indicate that Bandon Marsh NWR is predicted to lose between 19% and 92% of its swamp by 2100 depending on the SLR scenario utilized (Clough and Larson, 2010a). SLAMM simulations for Siletz Bay NWR indicate dry land losses will range from 12%-40% by 2100 depending on the SLR scenario (Clough and Larson, 2010b). In the Nestucca Bay NWR, SLAMM predicts that the non-diked portions are vulnerable to SLR and 7%-30% of the dry land is predicted to be lost (Clough and Larson, 2010c). Preliminary SLAMM results for the Yaquina Estuary based on 30 m digital elevation models (DEMs), recently updated NWI data, and a 1 meter SLR scenario by the year 2100, with no protection to developed areas, indicates a 74% reduction of tidal flat area, 94% reduction of irregularly flooded marsh, and a 85% increase in regularly flooded marsh from their initial areas (Reusser et al., unpublished results).

It is important to recognize the limitations of SLAMM, both because of general model limitations and because of data gaps for Oregon estuaries. There are limited published peer reviewed studies including the SLAMM methodology. Craft et al. (2009a) and the subsequent responses by Kirwan and Guntenspergen (2009) and Craft et al. (2009b) provide valuable insights into gauging the confidence of model simulations due to the uncertainty of input parameters, primarily base elevation and accretion rates. The use of lidar data in SLAMM has been shown to increase certainty of the base elevation parameter, however, precise elevation data collected with lidar are sparse for most of the upland area of the coastal watersheds in Oregon.

Another important data gap is the paucity of accretion rates specific to regularly flooded marsh, irregularly flooded marsh, and the tidal flats. For the Oregon modeling efforts mentioned above, the regional low marsh accretion rates measured in the Salmon River (Thom, 1992) were the best available data. Short-term (1-2 year) accretion rates are currently being measured in 7 Oregon estuaries in both low and high marsh habitat by the U.S. Environmental Protection Agency

(EPA), and will be available in the future for refinement of SLAMM simulations. Another data gap with regard to inundation of estuarine habitats is how marsh accretion rates will change if there are dramatic changes in rates of RSL rise. Some studies from other regions of the U.S. have suggested that marsh habitats can increase their accretion rates to keep pace with sea level rise if there is an adequate sediment supply; however, when the rate of RSL rise exceeds a certain threshold marsh communities will no longer be able to keep up with SLR and will be inundated (Mudd et al., 2009).

One general model limitation is in how salinity changes are modeled, in particular with the assumption of a salt-wedge estuary, which is likely to underestimate the extent of increased salinity experienced by emergent marshes in response to increased advection of sea water into estuaries. Another general model limitation is that SLAMM does not predict changes to submerged aquatic vegetation (SAV), an important habitat type for juvenile salmon and migratory waterfowl.

As with any model, researchers and managers should weigh the uncertainties in SLAMM predictions against their specific needs. We suggest that the current version of SLAMM is sufficient to address general questions about changes in emergent wetland in the Pacific Northwest, but not sufficient for higher resolution projections due both to regional data gaps and model assumptions. Through a joint research project, the U.S. EPA and USGS are working toward filling these gaps with new data collection for accretion rates, and are developing estuarine salinity models, and software enhancements to the SLAMM program. These regionalized input data and model improvements should allow us to more accurately model changes in critical wetland habitats in Oregon estuaries in the next few years.

### **6.5.2 Status of Climate Change Research on Estuarine Water Quality**

There have been relatively few studies on water quality conditions in Oregon estuaries, with most of the research focused on the Columbia, Coos, Yaquina, and Tillamook estuaries. There are even fewer long-term estuarine datasets to assess the effect of climate change on Oregon estuaries, with the exception of the Columbia River Estuary. High variability in water quality conditions combined with differences in sampling in historic datasets may make it difficult to assess climate change impacts in estuaries even when long-term datasets exist. Little or no research has been conducted on the effect of climate change in most Oregon estuaries, with the Columbia River Estuary being an exception.

Even when long-term datasets are available, it is often difficult to distinguish climate impacts from other anthropogenic modifications. Jay and Naik (2002) estimated that about 9% of the flow reduction in the Columbia River is related to climate change and 7% is associated with water withdrawals. Historical changes in estuarine currents, salinity and sediment transport remain poorly understood, and a combination of approaches including historical data analyses, numerical modeling, and new observations have been recommended to elucidate the effect of climate change on estuaries (Jay and Naik, 2002). Research is currently being conducted on the effect of climate change on the Columbia River Estuary by the Center for Coastal Margin Observation and Prediction (<http://www.stccmop.org/>). Numerical modeling is being

conducted, which simulates the effect of changes in SLR and river flow using climate scenarios provided by the Climate Impacts Group at the University of Washington. Response variables that are being used to assess the effect of climate change include estuarine salinity intrusion, plume volume, and plume area. Model simulations have found that the effects of climate change on the Columbia Estuary are spatially variable and that salinity intrusion length in the estuary is sensitive to climate drivers (personal communication with Dr. Antonio Baptista). In addition, model simulations suggest that there is high degree of non-linearity in estuarine responses to climate drivers. Since there has been little research on the effect of climate change for most Oregon estuaries, in this section we will review the key climate drivers influencing water quality parameters, and will speculate as to how climate change may influence estuarine water quality.

### **6.5.3 Factors that Influence Water Quality in Estuaries**

Water quality conditions in PNW estuaries are strongly influenced by both freshwater inflow and ocean conditions (Roegner and Shanks, 2001; Brown and Ozretich, 2009; Lee and Brown, 2009; Roegner, et al., 2010). As a result, there is the potential for climate change to influence estuarine water quality. During the wet season (November to April), water quality conditions in estuaries are dominated by freshwater inflows, while during the dry season (May to October), freshwater inflows to the estuaries decline and the estuaries become more marine-dominated. The dry season also roughly coincides with the upwelling season on the Oregon shelf (Chapter 1). Previous studies have demonstrated that water quality conditions within PNW estuaries during the summer are influenced by intrusions of oceanic water into the estuaries, affecting nutrients (Haertel et al., 1969; de Angelis and Gordon, 1985; Brown and Ozretich, 2009; Lee and Brown, 2009), phytoplankton (Roegner and Shanks, 2001; Roegner et al., 2002; Brown and Ozretich, 2009; Lee and Brown, 2009; Roegner et al., 2010), and dissolved oxygen levels (Pearson and Holt, 1960; Haertel et al., 1969; Brown and Power, in review). Water quality conditions in Oregon estuaries are also influenced by land use/cover and human activities in the watersheds. Climate change has the potential to influence water quality conditions in estuaries primarily through changes in precipitation in the watersheds, land cover in the watersheds, temperature (atmospheric, riverine, and oceanic), coastal upwelling, wind stress, and RSL rise. Changes in snow melt will primarily affect the Columbia River Estuary (Hamlet and Lettenmaier, 1999), because of the small amount of snow pack in the watersheds of the coast range.

Different types of estuaries will have differing responses to climate change drivers (Table 6.1). For example, a lagoonal estuary with limited freshwater inflows, such as Netarts estuary, will probably have relatively small changes in salinity; however, this system will be strongly influenced by conditions occurring on the inner shelf and any changes in upwelling related to climate change will likely influence water temperature, nutrients, dissolved oxygen, and pH levels in this type of estuary. Netarts Estuary may also be susceptible to coastal erosion on the barrier spit, which forms the estuary. In comparison a river-dominated estuary, such as the Columbia River Estuary, may experience changes in the salinity regime in response to SLR and changes in freshwater runoff and snow melt.

There are some indications that there has been an increase in upwelling favorable wind stress during the last 50 years (Chapter 1); However, global models for different emission scenarios predict there will little change in upwelling favorable wind stress in the PNW (Chapter 1). Since

coastal upwelling is a major driver in water quality in Oregon estuaries, and there are unknowns with regard to future changes in coastal upwelling, in the following sections, we include discussions of how water quality conditions may be influenced by changes in upwelling.

The most common causes of water quality impairments in Oregon estuaries are temperature, dissolved oxygen, and bacterial contamination (Oregon Department of Environmental Quality, Oregon's 2004/2006 Integrated Report Database, <http://www.deq.state.or.us/wq/assessment/rpt0406/search.asp>). Climate change has the potential to cause water quality impairments through various mechanisms that will be discussed in the following sections. We will review the possible effects of climate change on estuarine water temperature, salinity, dissolved oxygen, nutrients, chlorophyll a, bacterial contamination, and carbonate chemistry and the key climate drivers which influence these water quality variables.

**Table 6.1.** Hypothesized effects of climate alterations on estuaries.

Climate Alteration	Potential Effects
Sea level rise and extreme water levels.	Increased inundation of estuarine habitats including tidal flats, marshes, and SAV. Increased intrusion of oceanic water into estuaries. Extent of effect will vary with relative river flow, location in the estuary, and RSL rise rates in the vicinity of the estuary.
Increased winter precipitation and decreased summer precipitation	Increased winter–early spring flow of coastal rivers and creeks and reduced flow during summer. Extent of effect related to relative river flow, with a greater impact on river-dominated estuaries (e.g., Umpqua) and tidal coastal creeks (e.g., Yachats) than on tide-dominated estuaries (e.g., Yaquina, Coos), with smallest effect on bar-built estuaries (e.g., Netarts).
Increased snow melt	Change in seasonal pattern of river flow into the Columbia River; minor changes in other coastal estuaries and creeks.
Increased air temperature	Potentially high vulnerability of intertidal organisms because of the high proportion of intertidal area in Oregon estuaries that may be exposed to elevated temperatures. Air temperature also has the potential to influence water temperatures particularly in the upriver portions of estuaries.
Increased upwelling	Increased advection of high nutrient ocean water into the lower estuary during summer. Possible increase in the advection of low dissolved oxygen and low pH water into the lower estuary during the summer. Changes associated with upwelling may be more important in tide- versus river- dominated estuaries.
Increased storm activity	Potential breaching of barrier dunes at mouth of estuaries without jetties (e.g., Alsea, Siletz) and episodic input of sediment to estuaries. Estuaries with jetties may be less impacted (e.g., Yaquina, Coos, and Rogue).
Ocean acidification	Unknown effect on estuaries or how alterations may vary across estuary classes.

## 6.5.4 How Climate Change May Influence Estuarine Water Quality and Research Needs

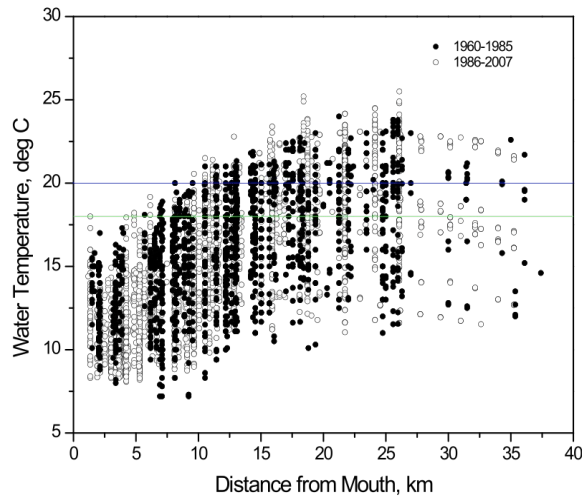
### 6.5.4.1 Temperature

Estuarine water temperature is an important factor influencing the rates of biological, chemical, and physical processes in estuaries as well as the distribution and well being of aquatic life. The effect of global climate change on estuarine water temperature will vary with estuary configuration, estuary type, and location in the estuary. The primary climate drivers which may influence estuarine water temperature are increases in the temperature of riverine inflow, air and

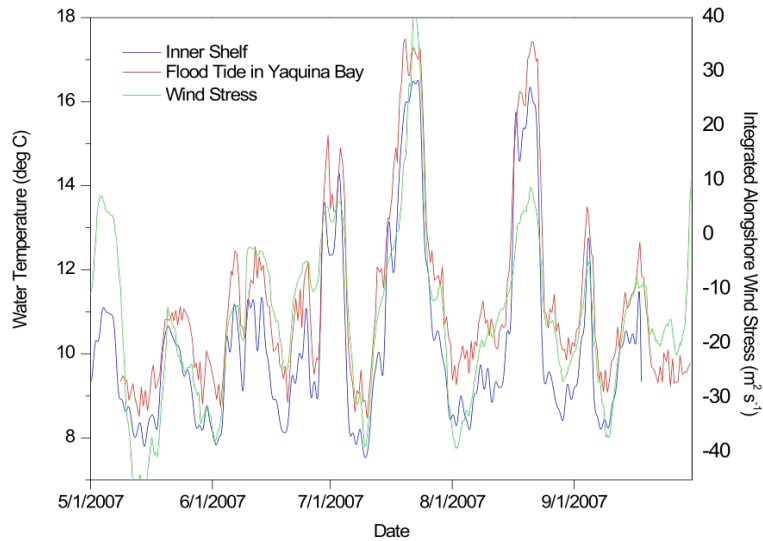
the ocean, SLR, changes in upwelling, and changes in river discharge. The Oregon water temperature criterion for ocean and bay water states that these waters may not be warmed by more the 0.3 °C above natural conditions (ambient levels) unless a greater increase would not reasonably be expected to adversely affect fish or other aquatic life (DEQ, 2008). More research is needed to determine if global climate change would result in elevation of estuarine water temperatures above this threshold.

In most Oregon estuaries during the dry season, there is a longitudinal gradient in water temperature (Brown et al., 2007; Roegner et al., 2010). Cooler temperatures typically occur near the estuary mouths and increase to a maximum in the tidal freshwater regions. Figure 6.16 shows the longitudinal water temperature gradient in the Yaquina Estuary. Both historic (1960-1985) and recent data from the Yaquina Estuary (1986-2007) are presented in Figure 6.16. These data do not suggest that there have been major changes in estuarine water temperature. However, formal analyses were not performed due to differences in sampling (e.g., depth and tidal stage) within the compiled datasets. In the upriver portion of the estuaries, instantaneous water temperatures at times exceed temperature criterion for the protection of migration and juvenile rearing of salmon and trout (Figure 6.16). The relatively cool temperatures near the mouth of the estuaries result from the intrusion of cold oceanic water into the estuaries.

Figure 6.17 shows an example of the coupling between inner shelf water temperature and flood-tide water temperature near the mouth of the Yaquina Estuary. Water temperatures in the lower portion of Oregon estuaries are temporally variable during the upwelling season and respond rapidly to changes in alongshore wind stress (Figure 6.17; Brown and Ozretich, 2009). Long-term measurements of ambient water temperature have also been collected by a series of dataloggers deployed within the South Slough estuary (a sub-system of the greater Coos Bay) since 1995 (Rumrill, 2006). Water temperatures inside Coos Bay are positively correlated with the Pacific Decadal Oscillation (PDO;  $r^2=0.55$ ), and water temperatures inside the estuary provide a general reflection of fluctuating regional cycles in the nearshore Pacific Ocean waters (Figure 6.18; O'Higgins and Rumrill, 2007).

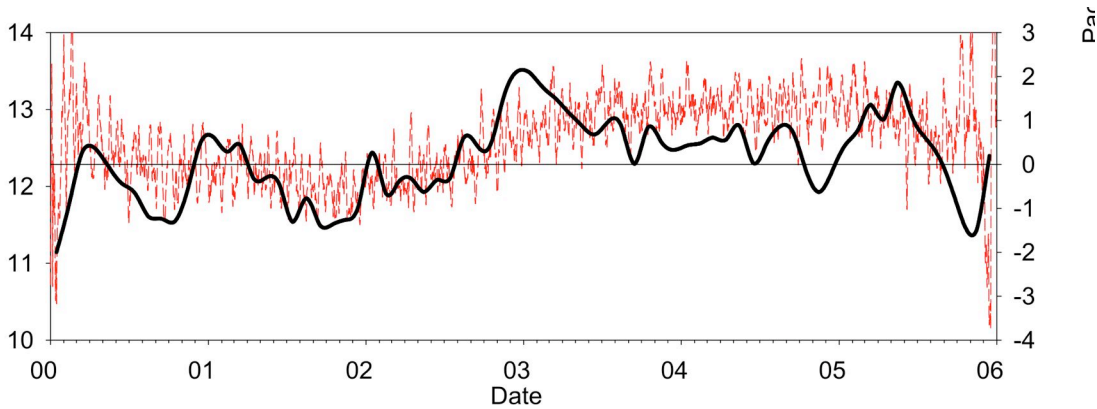


**Figure 6.16** Dry season (May - October) water temperature versus distance from the mouth for the Yaquina Estuary (Data source: Brown et al., 2007). The blue line shows the maximum temperature criterion recommended for protection of migrating salmon and trout, and the green line shows the criterion for protection of migrating and non-core juvenile rearing of salmon and trout (US EPA, 2003).



**Figure 6.17** Flood-tide water temperature in Yaquina Bay, inner-shelf water temperature, and alongshore wind stress. Water temperature in Yaquina Bay is significantly correlated with inner shelf water temperature ( $r = -0.97$ ,  $p < 0.001$ ) and alongshore integrated wind stress, an indicator of upwelling ( $r = 0.85$ ,  $p < 0.001$ ). Yaquina Bay data are from the US EPA and inner shelf data are from Station SR15, which is located 12 km south of Yaquina Bay at the 15-m depth contour (Data Source: <http://www.piscoweb.org>). Alongshore integrated wind stress (normalized by density of seawater) is calculated following the method of Austin and Barth (2002), using wind data from Station 46050 with a decay coefficient of 6 days.

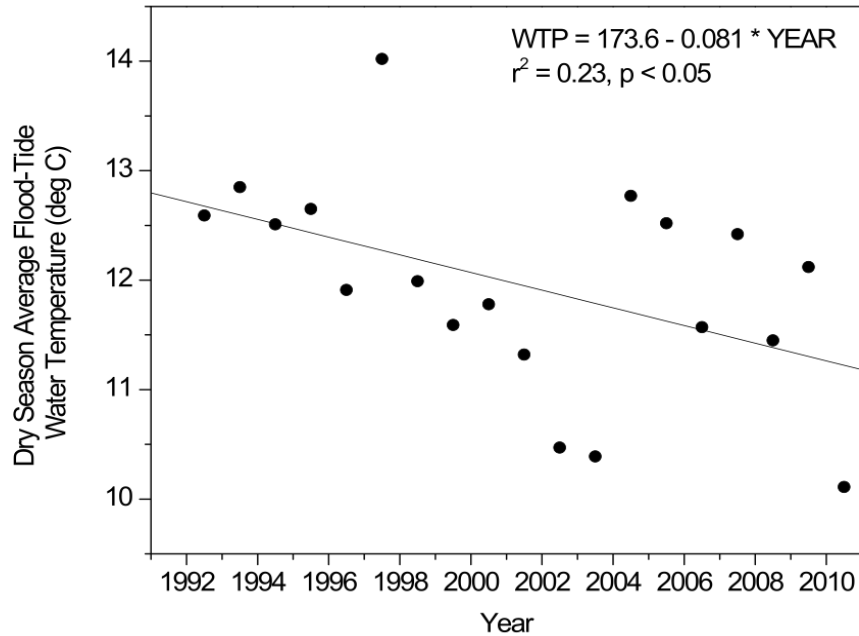




**Figure 6.18.** Time-series of estuarine water temperature within the South Slough estuary (red) and the Pacific Decadal Oscillation (PDO) index (black) over the period 2000-2006 ( $r^2 = 0.55$ ,  $p < 0.01$ ); from O'Higgins and Rumrill, 2007.

Most of the assessments of trends in upwelling in the California Current system have relied upon trends in wind stress or coastal upwelling index (Chapter 1) or model simulations of the effect of different emission scenarios (Chapter 1; Mote and Salathé, 2010; Wang et al., 2010; Mote and Mantua, 2002; Snyder et al., 2003). Due to the high variability in water temperature in the coastal ocean, and the lack of long-term high resolution datasets, it is difficult to assess whether there have been changes in nearshore coastal upwelling (Chapter 1). However, there are some relatively long-term estuarine water temperature datasets available. The close correspondence between estuarine flood-tide water temperatures and inner shelf water temperatures demonstrates that these estuarine datasets may be useful to assess long-term trends in upwelling.

Figure 6.19 shows average dry season flood-tide water temperature near the mouth of the Yaquina Estuary. The interannual patterns in average dry season flood-tide water temperature (using data from 1992-2010) are significantly correlated with cumulative alongshore wind stress ( $r = 0.58$ ,  $p < 0.01$ ; source for cumulative alongshore wind stress is <http://damp.coas.oregonstate.edu/windstress/>), and are an indicator of the amount of upwelling occurring during May through September on the inner shelf. During 1992-2010, there is a significant decreasing trend in dry season flood-tide water temperature at the Yaquina Estuary. Since cool water temperatures indicate upwelling activity, these data suggest that there has been a long-term increase in coastal upwelling during the last 19 years; however, it isn't clear if this is due to climate change or long-term basin-scale oscillations. More research is needed to compile additional data that may be available, and to explore relationships with climate indices.



**Figure 6.19** Dry season average flood-tide water temperature at the Yaquina Estuary as an indicator of coastal upwelling. Data Source: US EPA and NOAA South Beach tide gauge. Data compiled by Cheryl Brown, US EPA.

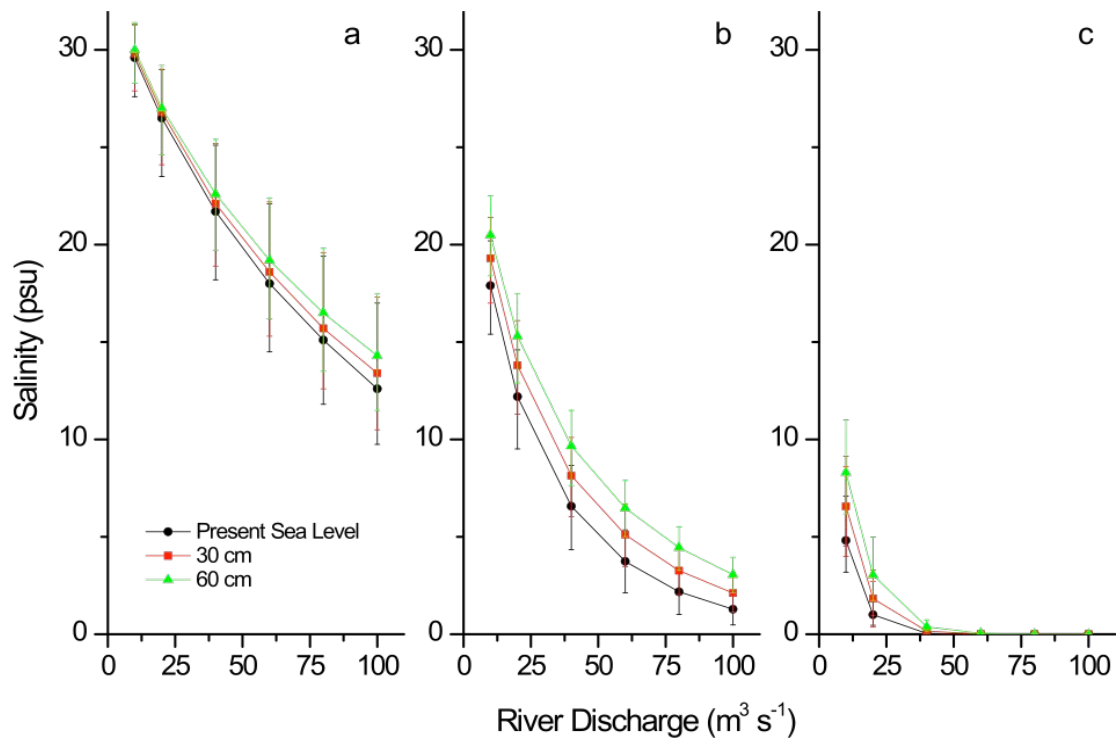
In the marine-dominated portion of Oregon estuaries, it may be difficult to separate variability associated with upwelling and downwelling dynamics and longer term cycles (such as Pacific Decadal Oscillation) from a climate change signal. Any increases in upwelling associated with climate change may obscure warming trends in the marine-dominated portion of the estuary at least during the summer. Water temperature in estuaries will be more sensitive to changes in upwelling, than to changes in ocean sea surface temperatures (SSTs) such as those projected by global climate change models (Chapter 1). As discussed in Chapter 1, the climate model projections for SSTs represent surface waters about 100 km offshore, rather than the nearshore which is influenced by upwelling of water from depths that are not as immediately influenced by climate change. An increase in sea level may result in increased intrusion of cool ocean water into the estuaries, further obscuring the climate change signal.

Climate change may result in an increase in water temperatures in the brackish region of the estuaries due to increases in water temperature of freshwater inputs to the estuary, increases in air temperature, and reductions in freshwater inflow during the summer. More research is needed to determine to what extent climate change may influence estuarine water temperatures. Since estuarine water temperatures are closely coupled to upwelling dynamics, improvement is needed in models which are used to predict changes in upwelling (Chapter 1). Since present water temperatures in the upriver portions of estuaries often exceed temperature criterion for protection of salmon and trout, there is the potential for climate change to result in an increase in temperature impairments, and thus to potentially affect the distribution and survival of cold water species.

#### 6.5.4.2 Salinity

Salinity is an important factor influencing the distributions of organisms in estuaries as well as an important factor determining the water density in estuaries. Studies in other regions have demonstrated that climate change has the potential to influence estuarine salinity (Gibson and Najjar, 2000; Hilton et al., 2008). Estuarine salinity may be influenced by climate change primarily through changes in precipitation and snow melt in the watershed (resulting in changes in freshwater inflows) and increased intrusion of seawater associated with rising sea levels. In Oregon estuaries, salinity levels increase during the dry season due to reduced freshwater inflows. Rising sea level is expected to have more of an impact on estuarine salinities during the dry season, than during the wet season. The effect of climate change on estuarine salinity will vary with location inside the estuary and the magnitude of the RSL rise rate in the vicinity of the estuary (see Figures 6.3 and 6.5). For example, salinity intrusion due to sea level rise may be more important for Yaquina and Coos estuaries than for the Columbia River estuary, due to differences in land movements. In addition, whether an estuary is river- or tide-dominated may influence the extent of variations in salinity associated with climate change.

As discussed previously in Section 6.5.2, the Center for Coastal Margin Observation and Prediction is conducting modeling on the effect of climate change on salinity in the Columbia River Estuary. Model simulations are showing that salinity intrusion in the Columbia River Estuary is sensitive to climate drivers. The US EPA is presently conducting research on the effect of sea level rise on salinities in the Yaquina, Netarts, Coquille, and Coos estuaries. Figure 6.20 shows simulation results of the effect of sea level rise at three locations in the Yaquina Estuary for different steady river discharges. These simulations show the non-linearity in salinity response to rising sea level. Near the mouth of the estuary (Figure 6.20a), sea level rises of 30–60 cm will result in changes in salinity of less than 2 psu. At this location, there will be little change in peak salinities with rising sea level, while median and 25<sup>th</sup> percentile salinities will increase with increasing river discharge. At the mid-estuary location (Figure 6.20b), an elevation



**Figure 6.20** Simulated effect of sea level rise on salinity in the Yaquina Estuary for different steady river discharge conditions at three locations (a-c). Simulations were performed for present sea level and sea level rise of 30 and 60 cm. The symbol indicates the median simulated salinity and the lower and upper error bars show the 25<sup>th</sup> and 75<sup>th</sup> percentiles. Panels a-c show model results for locations that are 10, 19, and 26 kms, respectively, from the mouth of the estuary. Source: Cheryl Brown (US EPA).

of sea level of 60 cm will increase salinities by about 2 -3 psu across a broad range of river discharge levels. In the oligohaline portion of the estuary (Figure 6.20c), salinity increases associated with a 60 cm rise in sea level are only present at low discharge rates. These simulations show how the interaction of changes in river discharge and sea level associated with climate change produce non-linear patterns in the response of estuarine salinity, which vary with location inside the estuary. Future work by the US EPA will link estuarine models to down-scaled climate scenarios to examine the effect of RSL rise on estuarine salinity for systems ranging from lagoonal system (e.g., Netarts) to a river-dominated (Coquille) system.

#### 6.5.4.3 Dissolved oxygen

Dissolved oxygen levels within estuaries result from the interaction of numerous physical and biological factors, including stratification and mixing, water column and benthic oxygen demands, and photosynthesis. Dissolved oxygen levels in estuaries have the potential to be influenced by climate change through numerous climate drivers including temperature (of river, air, and ocean), riverflow, and ocean conditions.

Dissolved oxygen (DO) is an important water quality metric because of its effects on the well-being of resident and transitory estuarine organisms. Hypoxia is commonly defined as occurring when the DO levels fall below 2  $\text{mg l}^{-1}$ ; however, biological stress for organisms has been documented at DO levels between 2 and 5  $\text{mg l}^{-1}$  (U.S. EPA, 2000; Diaz and Rosenberg, 1995).

The existing State of Oregon dissolved oxygen criterion for estuaries ( $6.5 \text{ mg l}^{-1}$ ) is based on a review of physiological requirements of biota, and is high compared to DO criteria for other estuaries (U.S. EPA, 2003). A review of the DO criterion found that  $6.5 \text{ mg l}^{-1}$  may be difficult to achieve in Oregon estuaries during the summer due to natural conditions (DEQ, 1995).

In Oregon estuaries, typically low dissolved oxygen conditions have been observed near the upper end of salt water intrusion (DEQ, 1995), such as in the sloughs of Tillamook Estuary. In the Yaquina Estuary, there has been a shift in the location of low dissolved oxygen conditions. Historically, low dissolved oxygen levels occurred in the upper portion of the Yaquina Estuary (20 km from the mouth; Brown et al., 2007), which coincided with the location of the point source discharges and a region of extensive log rafting. Recently, there have been occurrences of severe hypoxia on the inner continental shelf of Oregon (Chapter 1; Grantham et al., 2004; Chan et al., 2008), which influence dissolved oxygen levels in Oregon estuaries. For example, low dissolved oxygen conditions have been periodically imported from the inner shelf into the Yaquina Estuary (Brown et al., 2007), as well as into Umpqua, Tillamook, Coos, and Siletz estuaries (Brown and Power, in review). This low dissolved oxygen water has a distinctive thermal signature and dissolved oxygen levels in the Yaquina Estuary are correlated with alongshore wind stress. Recent time-series data (2001-2007) demonstrate that the water advected into the Yaquina Estuary from the coastal ocean has dissolved oxygen levels  $<5$  and  $<6.5 \text{ mg l}^{-1}$  about 13% and 38% of the time, respectively (Brown and Power, in review). Research has also demonstrated that dissolved oxygen levels in South Slough Estuary are related to ocean conditions. O'Higgins and Rumrill (2007) found a negative correlation between dissolved oxygen levels inside the South Slough and the PDO (O'Higgins and Rumrill, 2007).

Any changes in frequency or intensity of upwelling may cause changes in the occurrence of low oxygen conditions in the marine-dominated portion of estuaries, particularly for tide-dominated estuaries. A rise in sea level may cause oceanic low dissolved oxygen water to penetrate further into the estuaries. In the more upriver parts of the estuaries, dissolved oxygen levels may also be influenced by climate change through increased stratification, reduced flushing, as well as temperature effects. In estuaries, dissolved oxygen levels typically decrease with increasing temperature due to both reduced solubility of oxygen in water and to increased respiration and decomposition rates. In a comparison of water quality conditions in four west coast estuaries (including Coos Estuary), the number of hours of oxygen stress (dissolved oxygen levels  $< 5 \text{ mg l}^{-1}$ ) per day increased linearly with mean annual water temperature (O'Higgins and Rumrill, 2007). Through various mechanisms, climate change has the potential to influence dissolved oxygen levels in estuaries; although to what extent this may happen is unknown at this time.

#### *6.5.4.4 Nutrients*

Oregon estuaries receive nutrients from watershed point and non-point sources as well as from the coastal ocean (Haertel et al., 1969; de Angelis and Gordon, 1985; Sigleo et al., 2005; Sigleo and Frick, 2007; O'Higgins and Rumrill, 2007; Brown and Ozretich, 2009; Lee and Brown, 2009). There is considerable interannual variability in coastal upwelling and in nutrient concentrations on the shelf (Corwith and Wheeler, 2002; Wheeler et al., 2003), as well as in the input of oceanic nutrients to coastal estuaries (Brown and Ozretich, 2009). In addition, previous studies have suggested that the presence of red alder trees in the watersheds is a significant source of nitrogen

to many Oregon estuaries (Wigington et al., 1998; Compton et al., 2003; Naymik et al., 2005; Brown and Ozretich, 2009; Lee and Brown, 2009).

Climate change has the potential to influence nutrient levels in Oregon estuaries through various mechanisms. If there are changes in upwelling, the nutrient input (primarily as nitrate and phosphate) from the coastal ocean may change. Sea level rise may cause oceanic nutrients to propagate further into the estuary. Previous studies have shown that dissolved inorganic nitrogen loading to Oregon estuaries is related to river discharge (Sigleo and Frick, 2007; Brown and Ozretich, 2009); therefore, changes in precipitation and resulting riverflow may influence nutrient loading. Nutrient utilization inside estuaries will be influenced by changes in estuarine stratification, flushing and residence times, and the timing and magnitude of nutrient delivery. Previous studies have suggested that there is little utilization of nutrients inside Oregon estuaries during the wet season due to high flushing rates and low solar irradiance (Haertel et al., 1969; Colbert and McManus, 2003; Brown et al., 2007; O'Higgins & Rumrill, 2007). Therefore, estuaries may be more susceptible to changes in nutrient loading and physical effects during the dry season. More research is needed on the effect of climate change on nutrient loading from both oceanic and watershed sources and nutrient utilization inside Oregon estuaries. Research is also needed on how the distribution of red alder may change in response to climate drivers in the watersheds of Oregon estuaries.

#### 6.5.4.5 *Chlorophyll a*

Previous studies have demonstrated that chlorophyll a is advected into estuaries along the Oregon and Washington coasts from the coastal ocean during the dry season (Roegner and Shanks, 2001; Roegner et al., 2002; Brown and Ozretich, 2009; Roegner et al., 2010). Although the import of chlorophyll a from the coastal ocean to estuaries is related to coastal upwelling, there is a lag between upwelling on the coast and import of phytoplankton to estuaries (Brown and Ozretich, 2009). Ohana-Richardson (2007) further investigated statistical relationships between cell concentrations of the diatom *Pseudo-nitzschia* in South Slough estuary and estuarine water temperatures, and he found that the diatom concentrations were elevated during cold water periods ( $r^2=0.65$ ,  $p<0.05$ ). Conversely, diatom cell concentrations decreased during periods of estuary warming. The advection of phytoplankton from the coastal ocean into estuaries appears to be more important for tide-dominated than river-dominated estuaries (Lee and Brown, 2009).

A rise in sea level may result in chlorophyll a of oceanic origin reaching further into Oregon estuaries, particularly for tide-dominated systems. As discussed in Section 7.4.1, more research is needed on the effect of global climate change on coastal phytoplankton levels, and the subsequent import of these blooms into the estuaries. In the Yaquina Estuary, there are high chlorophyll a levels in both the high salinity and tidal fresh portions of the estuary (Brown et al., 2007). In the Columbia River Estuary, the main source of chlorophyll a in the spring is riverine sources, and in the summer when river discharge decline oceanic sources increase in importance (Roegner et al., 2010). Newton and Horner (2003) demonstrated that high productivity phytoplankton blooms were imported from the coastal ocean and that these blooms consisted of species of oceanic origin, while moderate blooms which included species of oceanic and estuarine origin also occurred within the estuary. Climate change can also influence chlorophyll a levels in estuaries through changes in nutrient loading, timing in nutrient delivery, and utilization inside the estuary. During the wet season, chlorophyll a levels in Oregon estuaries are

low due to high flushing rates (Roegner et al., 2010) and low solar irradiance, while during the dry season chlorophyll a levels increase (Haertel et al., 1969; Karentz and McIntire, 1977; Colbert and McManus, 2003; Brown et al., 2007; O'Higgins & Rumrill, 2007). Chlorophyll a levels in estuaries will be more sensitive to changes in river inflow during the dry season. Reductions in river discharge during the dry season may result in an increase in chlorophyll a levels in the estuary due to increased residence time of nutrients in the estuary.

#### 6.5.4.6 Bacterial contamination

Climate change has the potential to influence bacterial contamination in estuaries. In some Oregon estuaries, such as Tillamook Estuary, agricultural lands are currently protected from inundation by dikes and levees. However, increases in RSL rise rate and storms may result in increased flooding and inundation of agricultural lands, which may cause an increase in runoff from these lands. As an example, in the Tillamook Estuary high concentrations of fecal coliform levels (indicator of fecal contamination) occurred in the fall and were preceded by dry conditions and high intensity rainfall (Sullivan et al., 2005). Climate projections for the PNW suggest that there may be decreases in summer precipitation and increases in winter precipitation (see Section 2.3.3 in Chapter 1). With this projected change in precipitation pattern, it is possible that there may be higher fecal coliform levels during the fall and early winter if there are sources in the watershed.

In addition, the upwelled waters that are brought to the surface along the Oregon coast (cold, hypoxic, nutrient-rich) are highly conducive to outbreaks of the pathogenic bacterium *Vibrio tubiashii* (Elston et al., 2008), which are lethal to oyster larvae and early juveniles. During 1998, 2006, and 2007, there were losses of oyster larvae and juveniles along the Pacific coast of North America, which was attributed to an outbreak of *V. tubiashii* (Elston et al., 2008). It is believed that these vibrio outbreaks were related to seeding of vibrios and nutrients in the nearshore region associated with coastal upwelling, combined with subsequent elevated water temperatures, which resulted in a rapid increase in vibrio populations (Elston et al., 2008). Thus, changes in upwelling associated with climate change combined with warmer nearshore and estuarine water temperatures may result in an increase in outbreaks of *V. tubiashii*.

#### 6.5.4.7 Carbonate Chemistry

Long-term observational records and empirical studies provide strong evidence that global increases in atmospheric carbon dioxide (CO<sub>2</sub>) concentrations have contributed to widespread changes in the carbonate chemistry of ocean waters (Feely et al., 2004; Fabry et al., 2008; Dore et al., 2009). Elevated atmospheric CO<sub>2</sub> values are directly coupled with increased pCO<sub>2</sub> values in the ocean, and the shift in equilibrium results in increased carbonic acid (H<sub>2</sub>CO<sub>3</sub>) and decreased pH values. Long-term decreases in pH values (ocean acidification) have the potential to pose a major environmental problem, and ocean acidification has emerged as a pressing regional, national, and international issue that has important physiological and ecological implications for marine organisms throughout the world. The biochemical process that contributes to ocean acidification is driven by availability of hydrogen ions (H<sup>+</sup>), and shifts in pH values are of particular concern for species such as coral reefs, pteropods, coccolithophores, echinoderms, mollusks, and the larval stages of marine invertebrates that have calcium carbonate skeletons (i.e., calcite, aragonite; Orr et al., 2005; Kurihara, 2008). In the eastern Pacific Ocean, it is

estimated that pH values have decreased by 0.08 units over the past 200 years (Orr, et al., 2005) and will continue to decrease at an annual rate of  $-0.0019 + 0.0002$  pH units per year (Dore et al., 2009).

Recent oceanographic measurements demonstrate that acidified seawater is currently upwelling close to the Pacific continental shelf of Oregon and northern California (Feely et al., 2008). The acidified waters are presumed to move by advective transport directly into Oregon estuaries. This acidified water may have adverse impacts on the larvae of native Olympia oysters (*Ostrea lurida*) and non-native Pacific oysters (*Crassostrea gigas*) that inhabit the intertidal zone of Netarts Bay (Langdon and Hales, pers. comm.). Like the larvae of several other groups of marine invertebrates that incorporate calcite or aragonite into their tissues (Orr et al., 2005; Kurihara, 2008), oyster larvae are sensitive to acidified marine waters which contribute to dissolution of their thin calcified shells (Miller et al., 2009).

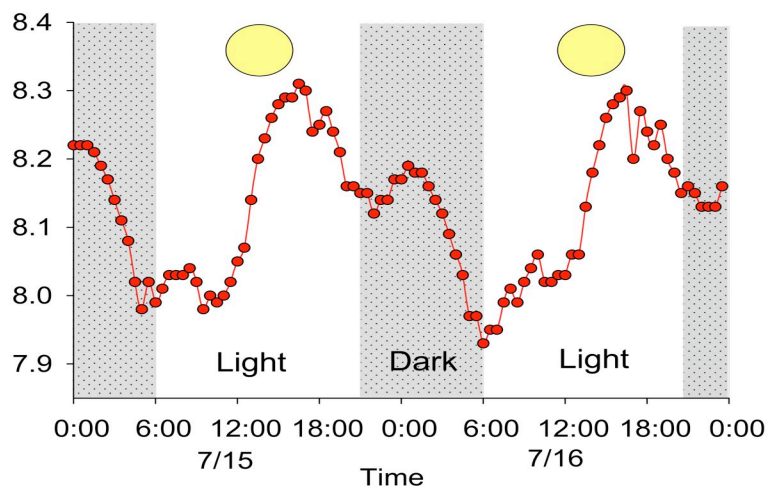
The presumption that ocean acidification and intensified upwelling is uniformly problematic for shellfish populations in all Oregon estuaries may not be valid, however, because it is not clear how the pH and total alkalinity of estuarine waters are related or influenced by the carbonate chemistry of nearshore ocean waters. For example, water conditions in Coos Bay and the South Slough oscillate seasonally between being driven by watershed inputs during the wet season and ocean inputs during the dry season. It is likely that pH variability and aragonite saturation state in many of Oregon's estuaries differ substantially from the aragonite state in the nearshore ocean, and that ecological conditions for the sensitive early life-history stages of oysters (i.e., pediveliger larvae and settled post-larvae) and other calcifying organisms are only indirectly coupled to the undersaturated carbonate waters further offshore. The carbonate chemistry of Oregon's estuarine waters will be modified on a site-specific basis depending on the extent of watershed influence and biochemical processes that occur within each individual estuary. Furthermore, it is also likely that pH variability differs even more substantially from the ocean waters within the mesohaline and polyhaline regions of the estuary which are influenced by the watershed drainage basin and are critical for larval settlement, recruitment, and early growth of native oysters and other shellfish.

To address the issue of shifting carbonate chemistry within the Coos Bay/South Slough estuary, time-series measurements were examined for water column parameters recorded by a YSI-6600 EDS multi-parameter datalogger equipped with a YSI 605091 pH/ORP sealed gel probe (resolution 0.01 pH unit; accuracy  $\pm 0.2$  pH unit; Figure 6.23). The datalogger was deployed within the primary tidal channel of the South Slough estuary (Charleston) where it operated continuously over the period of 2002-2009. Estuary pH values typically ranged between 7.7 and 8.3 throughout each day within South Slough, and we observed a strong tidal signal as well as a diurnal cycle with lowest pH values in mid-morning and highest pH values in mid-afternoon. The daily pH cycle appears to be driven by photosynthesis and respiration of phytoplankton, macroalgae, and submerged aquatic vegetation within the estuary (Figure 6.21). Preliminary analysis reveals that there has been a long-term shift in estuary pH values from a median value of 7.9 in 2002 to a median value of 8.1 in 2009 (Figure 6.22). The intermediary years (2003-2008) exhibited intermediate pH values and the time-series trend is strongly directional (Figure 6.23).

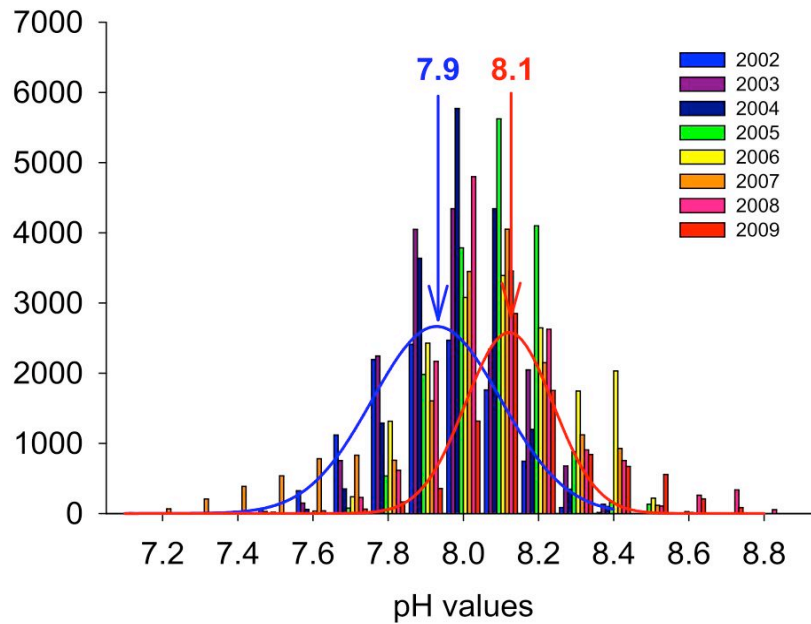


Although the apparent shift toward increased alkalinity falls within the reported accuracy of the pH probe, the directional trend is supported by over 200,000 data points and suggests that increased alkalinity may be real rather than an artifact. The long-term trend toward increased alkalinity of the marine-dominated South Slough estuary is unexpected, and provides evidence that the relationship between ocean acidification and pH values in the estuary is not straightforward. Unlike Netarts Bay, larval settlement and recruitment was consistently good for Olympia oysters (*Ostrea lurida*) in Coos Bay over the past 5-6 years, particularly within the mesohaline region of Coos Bay where estuarine water column conditions are only indirectly coupled to upwelling of the nearshore ocean waters (Groth and Rumrill, 2009). Datasets similar to those from Coos Bay are available in the Yaquina Estuary (US EPA). These data show that flood-tide pH during the dry season in the marine-dominated portion of the estuary are closely coupled to the inner shelf and alongshore wind stress.

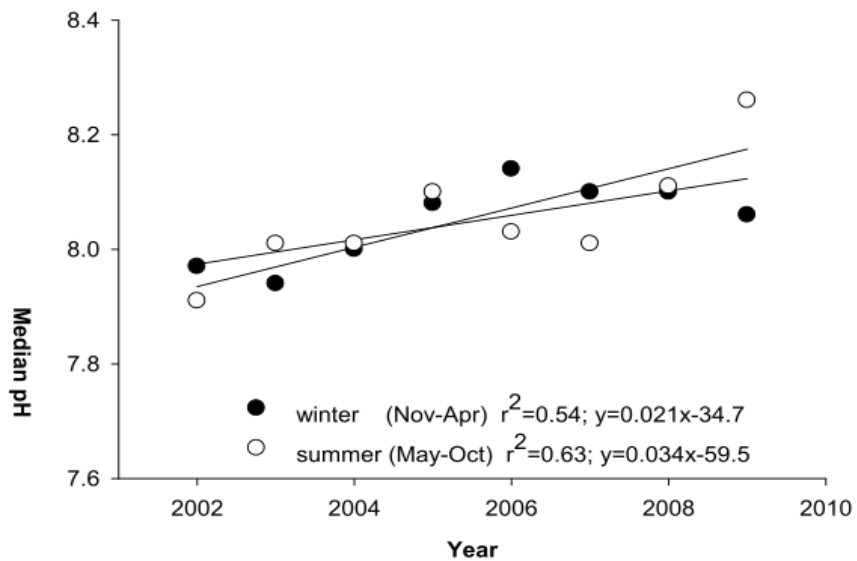
Very little is known about the inherent variability in  $p\text{CO}_2$  concentrations in the nearshore marine waters of the Pacific northwest coast (Wootton et al., 2008), and the relationships between ocean acidification and pH values are poorly understood for the different types of Oregon estuaries. Although substantial data records from water quality monitoring stations, municipal outfall discharge sites, mariculture operations (and other sources) exist to characterize temporal variability and fluctuations in pH values in Oregon estuaries, the datasets are typically generated by different types of instruments, vary significantly in resolution and accuracy, and have not been assembled and synthesized into a coherent characterization of pH dynamics. Despite these limitations, the existing datasets have tremendous spatial and temporal coverage, and may be useful to address the potential implications of regional climate change and ocean acidification in Oregon estuaries. Long-term datasets that span periods of multiple decades are required to fully analyze inherent temporal and spatial variability in Oregon's estuarine water parameters, and to identify possible directional changes in pH values as a prospective response variable that can contribute to increased understanding of climate-induced changes in ocean carbonate chemistry.



**Figure 6.21** Diel cycle of daily changes in pH values measured within the South Slough estuary (Coos Bay, OR) over the period of 15-16 July, 2008, data from South Slough National Estuarine Research Reserve / System-Wide Monitoring Program.



**Figure 6.22** Annual frequency distributions for pH values (2002-09) at the Charleston SWMP station, South Slough estuary (Coos Bay, OR). Annual median values are shown for 2002 (blue) and 2009 (red); datasets from South Slough National Estuarine Research Reserve / System-Wide Monitoring Program.



**Figure 6.23.** Median seasonal pH values at the Charleston SWMP Station (South Slough estuary (Coos Bay, OR)) for Winter (Nov-Apr) and Summer (May-Oct). Datasets from South Slough National Estuarine Research Reserve / System-Wide Monitoring Program.

## 6.6 Climate Change Impacts on Coastal Infrastructure

Climate change may negatively impact Oregon's coastal infrastructure, including both public and private property such as coastal highways, bridges, sewage treatment facilities, airports, oceanfront homes, hotels, industrial sites, and dairy operations around estuaries. As climate conditions change some infrastructure systems may be less effective or may fail altogether, which could alter the function, value, or viability of improvements these systems protect or serve. Public officials and private landowners need to understand how climate change may affect their property and be prepared to make decisions about how to respond and adapt. The sectors described in the following sections may be significantly impacted by climate change (DLCD, 2009).

### 6.6.1 Transportation and Navigation

Coastal roads, highways, and rail lines are at risk from the effects of increased winter precipitation, increased coastal erosion, and flooding. Over the long term, roads, highways, and railroads will be affected by SLR and increased tidal elevations along the ocean shore, estuaries, and coastal rivers. Airport runways such as those in North Bend and Astoria are located on filled estuarine wetlands and may be at risk of inundation from storm surge and high tides and, over time by SLR. In Oregon there are 11 jettied navigation entrances (including the mouths of the Columbia River, Tillamook Bay, Depoe Bay, Yaquina Bay, Siuslaw River, Umpqua River, Coos Bay, Coquille River Port Orford, Rogue River, and Chetco River) with over 30 miles of rubble mound structures maintained by the Portland District of the US Army Corps of Engineers. Port facilities, jetties and groins will be subject to damage from larger storm waves. Watershed flooding may increase sediment loads into estuaries and thus increase the need for dredging of navigational channels. Increased tidal height will affect docks and bulkheads.

#### *6.6.2 Shore protection and flood control structures*

In some coastal counties significant portions of outer coast shorelines have been armored against erosion from ocean waves, primarily in front of properties developed before 1977. Extensive areas in Oregon's estuaries are protected from tidal inundation by dikes, levees, and other structures often to create and protect agricultural lands. Increases in erosion and inundation due to rising sea level and increasing wave heights may threaten the integrity of these coastal structures.

#### *6.6.3 Water supply, wastewater treatment, and stormwater systems*

While rainfall in winter is projected to increase, storing water across longer, drier summers may be a problem for some coastal communities where storage systems are already at or over capacity during summer. Reduced precipitation in summer months, especially in conjunction with warmer winter temperatures, may reduce the water available for municipal supply systems. In addition, wastewater treatment facilities are usually located at the lowest elevation in a watershed, which places those facilities at risk from rising sea level and tidal elevation. The capacity of local stormwater management systems may be exceeded as the magnitude or frequency of rainfall events increases, especially as tidal elevations rise leading to localized flooding, accelerated deterioration, and possible system failure. Systems at or near capacity

today may be unable to handle future storm loads, which could have a significant effect on location of future development.

#### *6.6.4 Recreation, travel and hospitality*

The Oregon coast has long been an attractive destination for tourists and for those who enjoy its recreational opportunities and resources. Businesses in these sectors may benefit from the effects of climate change on the Oregon coast. Longer, drier summers may benefit Oregon's coastal recreation industries by extending the recreation season and expanding options. However, parks and recreational facilities along the ocean shore and around estuaries are likely to be affected from increased winter storms, ocean flooding, and over time, sea level rise. Coastal forest trails and campgrounds may experience frequent damage from high winds and flooding.

#### *6.6.5 Growth and development*

Climate conditions, even though changed from historic patterns, may be relatively attractive compared to other parts of the country and therefore may attract "climate-refugees" seeking more optimum climate conditions. Coastal communities could thus experience increased in-migration, particularly retired persons, which would increase demand for residential and commercial development and demands on public facilities.

## **Acknowledgements**

Authors Ruggiero, Komar, and Allan gratefully acknowledge the support of the Sectoral Applications Research Program (SARP) of the U.S. Department of Commerce's National Oceanic and Atmospheric Administration (NOAA) under NOAA Grant# NA08OAR4310693. Lead author Ruggiero was also supported by NOAA's National Sea Grant College Program under NOAA Grant #NA06OAR4170010. Deborah Reusser was funded by the USGS National Climate Change and Wildlife Science Center. This document has been reviewed in accordance with U.S. Environmental Protection Agency and the U.S. Geological Survey (USGS) policies and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation of use.

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# 7. Oregon's Fish and Wildlife in a Changing Climate

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## Summary and Knowledge Gaps

Oregon's fish and wildlife include animals on land, fish and other species in rivers and lakes, and various kinds of sea life in estuaries and coastal ocean. Of great cultural and economic value, this immense biodiversity—some of which is already threatened or endangered—inhabits complex and dynamic ecosystems we have only begun to understand, let alone examine in terms of climate change. However, it is clear that the abundance and distribution of species are shifting already and will shift more rapidly as habitats on land, in freshwater, and in sea are altered due to increasing temperatures and related environmental changes. Some patterns are already evident.

- Insects from south of Oregon, including pests, are moving into the state, and the timing of development of native species is advancing as spring conditions arrive sooner.
- Frogs are reproducing earlier in the year compared to past decades and emergent infectious diseases affecting frogs and their relatives are increasing in severity.
- Land birds are shifting their distributions northward and migrating earlier.
- Small mammals in eastern Oregon are contracting their ranges on mountaintops.
- In our fresh waters, climate-related habitat loss has increased in severity for salmon and other cool-water fishes.
- In the ocean, harmful algal blooms have increased substantially in the past 15 years, and recurring "dead zones" have appeared in recent years.
- The species composition of copepods (food for many marine fishes) has shifted substantially in recent years.
- Highly predatory Humboldt squid have recently shifted their distribution into Oregon waters from tropical and subtropical regions.

Of increasing concern are predicted changes in fish and wildlife populations during the coming decades as climate change accelerates. In general, these changes include continued northward shifts in species distributions, including species invading from the

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south, upward shifts of mountain species, and declines in the abundance of affected species. Species may be negatively affected directly by physiological stress caused by changes in temperature, water availability, and other environmental shifts, and/or indirectly by habitat degradation and negative interactions with species that benefit from climate change (diseases, parasites, predators, and competitors). Because there is a broad range of possibilities regarding the degree of forthcoming climate change, especially regarding the response of complex biological systems, the severity of predicted responses is unknown, even though the direction of such changes is more certain. Predictions of economic and cultural relevance in Oregon include:

- Increasing frequency and severity of insect pest outbreaks, including new invasive species (see Case Study 7A).
- Extinction of native frog species.
- High vulnerability of nine coastal bird species.
- Continuing range contraction of mammals on mountain tops and in deserts, with possible extinction of rare species.
- Declines in aquatic insects that feed freshwater fishes.
- Continuing decline of salmon and other cool-water fishes as warm-water species, especially invasives, thrive.
- Increasing severity of harmful algal blooms and "dead zones" in the ocean.
- Worsening ocean acidification that threatens shellfish and other sea life.
- Decline of some ocean fisheries, with perhaps emergence of new fisheries.
- Population declines of diving seabirds (e.g., murre and puffins).
- Shifts in migratory patterns of marine mammals and possible increases in diseases.

Knowledge gaps in understanding the responses of Oregon's fish and wildlife to climate change are due to lack of basic ecological understanding of smaller organisms, such as insects and many ocean species. Needed are broad-scale surveys of the biodiversity, geographical ranges, and population sizes of indicator species in all major land, freshwater, and ocean habitats. For these key species (including present and potential invasives) knowledge of ecological interactions (predation, competition, and mutualism) is essential for predicting indirect effects of a changing climate. To increase the accuracy of predictions, such ecological data must be integrated with climate models to produce region-by-region scenarios for future shifts in fish and wildlife communities.

Climate change and its effects on Oregon's fish and wildlife can be moderated by natural resource policies that foster ecological resilience (see Case Study 7B). Given that relatively intact ecosystems are known to be resistant to major changes, an effective resilience tool is to protect refuge habitats on land, in freshwater, and in the sea in networks of reserves where native species can occur and migrate in natural abundances, ages, and sizes. Resilience is also fostered by allowing natural cycles and disturbances to run their course, rather than attempting to rigidly control a changing biosphere.

## 7.1 Introduction

Oregon is blessed with a rich diversity of fish and wildlife that inhabits a broad variety of habitats on land, in freshwater, and in the sea. This biodiversity -- the genetic variation within species, the number of species, and the range of ecosystems -- provides innumerable benefits to Oregonians, including fisheries, hunting, outdoor sports and recreation, and scientific research. There are also numerous, less tangible, yet extremely valuable ecosystem goods and services provided by these species, such as pollination of crops by insects and transport of ocean nutrients to stream habitats by migrating salmon.

The habitats occupied by Oregon's fish and wildlife, and the effects of climate change on those habitats, are covered in chapters 1 (ocean), 3 (freshwater), and 5 (forests and rangelands). This chapter reviews what is known, predicted, and unknown about the effects of climate change on Oregon's living natural heritage, focusing in turn on the land, freshwater, and the sea. Focused perspectives (Case Study boxes) on invasive species and ecological resilience also are provided.

## 7.2 Land Animals

Oregon is rich in species of land animals. Many of these species occur only in very specialized habitats and are expected to respond to changes in the distributions of those habitats as climate changes. Species that occur in alpine areas or depend on aquatic habitats in eastern Oregon may be especially sensitive to climate change. Currently, we know relatively little about the precise habitat requirements for most species. We lack sufficient details on the current distributions and population sizes of nearly all species, even of birds, which are comparatively well-studied because of great interest by amateur birdwatchers. The lack of detailed data reduces our ability to predict responses to climate change. In the following summaries, we provide an overview of the current diversity of each animal group in Oregon, what is currently known about responses of each group to climate change in our state, what information from neighboring regions or states may be applicable to Oregon, and important gaps in knowledge that must be filled in the coming years.

### 7.2.1 Insects and Relatives

Insects and their relatives (collectively known as arthropods) are joint-legged invertebrates that function in numerous critical ecological roles (Miller, 1993). Most abundant across the coastal, valley, mountain, and range habitats of Oregon are insects, spiders, and mites. Lists of species are very incomplete but reasonable estimates indicate that more than 14,000 species of arthropod live in Oregon (Danks, 1995; Miller, unpublished). Insects, spiders, mites, centipedes, and millipedes serve integral roles in soil chemistry, plant growth, food and timber production, human health, and the structure and function of habitats and ecosystems. Importantly, arthropods are virtually everywhere. Many species are uniquely beneficial as pollinators and decomposers, or notorious as pests of crops and carriers of diseases that infect plants and

animals. However, the majority of arthropods are relatively innocuous in the context of human concerns and public awareness. Nonetheless, these species are vital to the well-being of our environment and they are highly sensitive to climate dynamics (Forister et al., 2010).

The recognition of endangered and threatened species of arthropods, nationally and within Oregon, is relatively limited. In the context of all plant and animal species, the arthropods are extremely under-represented on federal and state lists of species of concern. Among the arthropods, butterflies dominate federal threatened and endangered species lists. In Oregon, two species of butterfly have been designated as federally threatened and endangered: the Oregon Silverspot, *Speyeria zerene hippolyta* (Figure 7.1) and the Fender's Blue, *Icaricia icarioides fenderi* (Miller and Hammond, 2007). These species, and others (Forister et al., 2010), are on the verge of extinction primarily due to habitat loss. However, the dynamics of rapid climate change creates an additional dimension to the environmental challenges that affect those species already recognized as teetering on the brink of extinction.



**Figure 7.1** The Oregon Silverspot, *Speyeria zerene hippolyta*, a federally listed endangered species. View of the underside of the wings showing why the butterfly was given the common name of 'silverspot.'

Regardless of any official assessment, the status of a population or species may be strongly altered by climate change. Most critical are changes in temperature because all arthropods exhibit a very strong relationship between temperature and developmental rate—the time it takes to grow from a fertilized egg to an adult (Miller, 2004a,b). Also, climate in general influences the geographical range of each species—where that species is found on the globe. Thus, the critical issue with arthropods and climate change is a potential shift in seasonal timing (phenology) of critical life-history events, such as egg deposition, growth rates of immature stages, and timing of maturation of adults. The timing of these events is related to the seasonal cycles of plants and animals that provide food and shelter for arthropods. Most arthropods exhibit one generation per year. Thus, the sequence of development through life-history stages (egg, larva, pupa, adult) is intimately timed to occur in synchrony with other biological events. For example, a bee pollinator must develop from egg to adult so that the adult bee emerges from the pupal stage precisely when the flower it pollinates has nectar and pollen. In certain cases, the timing of multiple biological events must occur within days of one another for survival of one or more species.

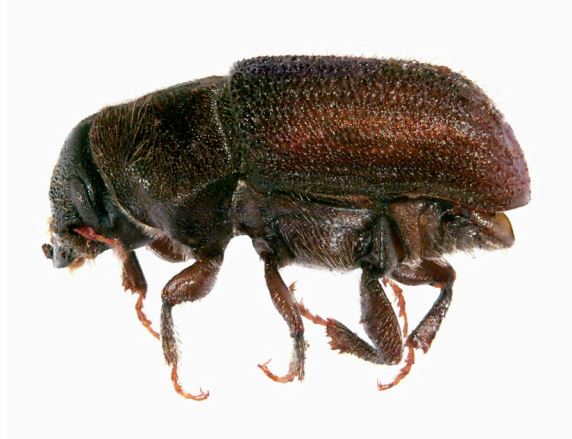
The problem lies in the fact that each species has its own genetically-based, temperature-dependent, biological clock that dictates its phenology expressed under the temperature regime of its habitat. A change in the temperature regime will result in a change in the synchrony/asynchrony of the life cycles of interacting species. Therefore, a trend in changing climate (e.g., rising temperatures) will have the following possible consequences for arthropods and other species: (1) dying-out locally or regionally, (2) moving to a place where suitable conditions do exist (assuming such a place is available), or (3) adapting and remaining in the same area. The faster the rate of climate change, the more likely that scenarios (1) and (2) will occur and the less likely that scenario (3) will occur.

All three consequences listed above have been documented by scientific studies. Although examples within Oregon are few, the impacts are dramatic. In Oregon, during 2004–2008, Miller (in preparation) documented the phenology of moth flight at the H. J. Andrews Experimental Forest located at an elevation of 1,000 to 4,500 feet on the western slope of the Cascade Mountains about 35 miles east of Eugene. This study revealed that a rise of 2°C (3.6°F) will hasten the annual, and typically well defined, flight period in moths by more than 18 days. A shift of 18 days in the overall flight period is not a trivial issue in the survival of moth species. The seasonal timing of flight (a period of only 10–25 days for most species) is a critical time because this is the only chance females have to deposit eggs, an event followed by caterpillars feeding on suitable foliage. If moth flight times shift due to climate change, then likewise a certain degree of change is also occurring in plant growth. A shift in the seasonal timing of foliage maturation (bud break to leaf toughening) and moth flight creates a situation of asynchrony. Asynchrony between two or more species that depend on one another will result in negative consequences in the population dynamics and community composition for the moths and the plants. The implication is that all 5,000+ species of arthropods known to occur in the H.J. Andrews Forest (Parsons et al., 1991), let alone the 14,000+ species in Oregon, are temperature-dependent in their developmental sequence. The timing of the life history of each of these species will be affected one way or another by a warming climate, with the potential of compounding negative effects on those non-temperature-dependent species, such as insect-eating birds, bats, and mammals, that otherwise require arthropods for some type of ecological service, such as food.

This latter concern is illustrated by the interaction that exists between insects and migratory birds. These birds come to Oregon and rear their young, depending on insects to feed their nestlings. The birds migrate to the Cascade Mountains from South America based on day-length cues that are very consistent. However, the availability of the insect diet they require is not consistent through time because it is highly influenced by climate. As mentioned above, a 2°C (3.6°F) shift in warmer average temperatures has the potential of altering the availability of a required food resource by more than 18 days. If this food (e.g., a caterpillar) has developed into a later life stage (i.e., a butterfly) that is not a prey by the time the migratory birds arrive, then the bird populations are likely to be negatively affected due to a lack of food for their young.

Additional examples of how arthropods have been affected by climate change may be found in neighboring regions. For instance, subtropical mosquito species (often carriers of devastating diseases) are shifting their geographic distributions toward temperate regions like Oregon

(Epstein et al., 2008; Shope, 1992). In California, Forister et al. (2010) documented a geographical shift in butterfly assemblages across a valley-mountain transect in California. In British Columbia, Kurz et al. (2008) modeled the effect of shifting an entire forest from a minor carbon sink to a major carbon emitter due to an on-going massive outbreak of the mountain pine bark beetle (*Dendroctonus ponderosae*) that was initiated by climate warming. The mountain pine bark beetle (Fig. 7.2) is currently causing severe damage to forests in eastern Oregon (see Chapter 5).



**Figure 7.2** The mountain pine bark beetle (*Dendroctonus ponderosae*) has caused severe damage to forests in eastern Oregon.

Another present-day concern in the Pacific Northwest (Oregon, Washington, and northern California) involves a new exotic insect pest of small fruits, *Drosophila suzukii*. This fly has entered the region explosively with potentially dire economic impacts on small fruit production (Bolda et al., 2010). Climate models (Damus, 2009) that predict the potential geographical range and population dynamics of *D. suzukii* are proving to be critical for designing and applying a regional management plan. One of the most valuable aspects of the climate models is that they can predict the geographic distribution and phenology of the fly based on real and projected temperature data. Two implications derived from the climate models are that, as average temperatures increase, there will be a subsequent increase in the geographic range of the fly and the number of generations per year. The ramifications of these predictions suggest the possibility that costs for fruit production will increase and greater losses in agricultural production will occur.

#### 7.2.1.1 Research needs

The relevance of addressing arthropods as species vital to the study of climate change is clearly justified by examples from agriculture and human health. However, the approaches necessary to conduct a rigorously documented study that addresses arthropods and climate change must be established in a very precise manner to obtain high-resolution data suitable for statistical analysis. In addition to a network of field-based climate stations, research activities must include models based on an assessment of temperature-dependent requirements for arthropod development through the entire life cycle (egg to adult) for groups of species of special interest.

Two components that are essential to a well-planned comprehensive study of arthropods and climate change are (1) landscape-scale monitoring of species assemblages involving permanent sites subjected to repeated intra-annual sampling efforts at a frequency of 7–10 day intervals, and (2) expertise in identification of various species groups. The scope of the project at a landscape scale is a critical issue because the expected shift in species ranges may occur across 100s to 1,000s of miles. Therefore, a monitoring plan should encompass transects, founded on elevation or latitude, that represent gradients of climate conditions across a broad geographical region. Also, reliance on a single species as a model organism is not advisable. A species complex, involving dozens to hundreds of species, should be monitored. However, the identity of arthropods typically is not a simple matter, as accurate identification requires expertise that is acquired through specialization in systematics, and such taxonomists are few in number. To alleviate taxonomic problems with arthropods, new initiatives are presently underway. Recently, Miller and Luh (unpublished) developed an interactive website that can assist non-taxonomists with the rigors of identifying certain butterflies and moths (Lepidoptera) via the simple act of uploading an image, subjecting the image to an automated pixel-by-pixel analysis, and acquiring an accurate identification. Another team of scientists at Oregon State University is developing an automated identification system for aquatic insects (Larios et al., 2008). Both projects are in the pilot stage. These efforts have the potential to provide much needed taxonomic expertise to non-experts and thereby mitigate the demands of taxonomic specialization that thwart the inclusion of arthropods in large-scale ecological projects.

A final point reiterates the need to study multiple species rather than a single “iconic” species. A novel approach, yet to be conducted by any group of scientists, would be to integrate arthropods into climate studies in concert with other species, all of which are associated via ecological connections, such as food webs. Specifically, it would be valuable to design a project that includes a climate study involving numerous groups of plants, arthropods, and other animals that are ecologically linked, exhibiting a strong relationship of being inter-dependent, so the consequences of dying out, moving away, and adapting to a changed environment can be better understood and the new information used to address the goal of conserving biodiversity.

## 7.2.2 Amphibians and Reptiles

### 7.2.2.1 Amphibians

Oregon is considered a biodiversity hotspot for amphibians (frogs and salamanders) because of the relatively large number of species present within the state. There are an estimated 29 native amphibian species in Oregon: 17 salamanders and 12 frogs (Jones et al., 2005). The conservation status of these species varies considerably, with several currently experiencing range contractions while other species have healthy and robust populations. The Oregon Spotted Frog (*Rana pretiosa*) and the Oregon Slender Salamander (*Batrachoseps wrighti*) are the only two species in Oregon that are listed as vulnerable on the IUCN Red List, while the Siskiyou Mountains Salamander (*Plethodon stormi*) of southwest Oregon is listed as endangered (IUCN, 2003; Figure 7.3). Nine of Oregon’s amphibian species have been assessed as being nearly threatened (IUCN, 2003). The Oregon Department of Fisheries and Wildlife designated the conservation status of 4 amphibian species as critical in all or part of their Oregon range—the Oregon Spotted Frog (*Rana pretiosa*), the Foothill Yellow-legged Frog (*R. boylei*), the Columbia

Spotted Frog (*R. luteiventris*), and the Northern Leopard Frog (*R. pipiens*) —and 17 other species as vulnerable. These classifications indicate that critically sensitive species are in immediate danger of extinction within specific geographic regions, and vulnerable species could become critically imperiled due to current threats to specific geographic regions or populations (OAR 635-100-040).



**Figure 7.3** Three species of endangered and vulnerable Oregon amphibians: (a) Oregon Spotted Frog (photo by William Leonard), (b) Oregon Slender Salamander (photo by Gary Nafis), and (c) Foothill Yellow-Legged Frog (photo by David Paoletti).

Worldwide, amphibians are a group of serious conservation concern. Population extinctions and declines are already occurring on a global scale (IUCN, 2004), often due to additive and synergistic impacts from multiple environmental stressors, such as habitat loss and climate change (Alford et al., 2007; Root et al., 2003; Stuart et al., 2004; Wake and Vredenburg, 2008). Amphibians are strongly tied to specific habitats and can be indicators of environmental status (Feder and Berggen, 1992; Gibbons and Bennett, 1974; Blaustein et al., 1994; Olson et al., 2007). They are also cold-blooded (ectothermy), making them highly sensitive to shifts in temperature and moisture conditions (Blaustein et al., 2003; Pounds and Crump, 1994, Rome et al., 1992). Physiological constraints associated with an ectothermic life history and dependence on specific local conditions (microclimate) make amphibians particularly susceptible to changes in climate predicted to occur during this century (Blaustein et al., 1994; Carey and Alexander, 2003; Parmesan, 2006).

The majority of amphibian species in the Pacific Northwest have freshwater associations and require dispersal between aquatic and upland terrestrial habitats (Olson and Burnett, 2009). Many Oregon species breed in temporary (ephemeral) water bodies (i.e., wetlands, vernal pools, and intermittent headwater streams) and require adequate wet periods and water quality, as well as suitable temperatures. Changes in precipitation patterns and temperature regimes will affect wet periods, winter snow pack, and flooding events (Chapter 3). These changes will likely affect breeding success, survival, and dispersal, and alter breeding phenology (timing of seasonal reproduction) for many species native to Oregon (Blaustein et al., 2010; Corn, 2003). Environmental cues, such as temperature shifts and rain events, can trigger breeding in many amphibian species, and miscues can result in complete reproductive failure (Hartell, 2008). In addition, amphibians have species-specific temperature tolerances, and exceeding these thermal thresholds will reduce survival. For example, Pacific Giant Salamanders (*Dicamptodon tenebrosus*) and Tailed Frogs (*Ascaphus truei*) are normally found in rivers less than 13°C (55°F) in Oregon (Huff et al., 2005). However, embryonic and larval development rates are highly

correlated with temperature, and warmer temperatures may advantageously affect species in ephemeral habitats (Duellman and Trueb, 1986).

Earlier spring thaws and warmer ambient temperatures may affect breeding phenology for many Oregon species. Several studies have shown that various amphibian species are breeding earlier in response to a warming climate (Beebee, 1995; Chadwick et al., 2006; Reading, 1998). Blaustein et al. (2001) examined the breeding patterns of two Oregon frog species, the Western Toad (*Bufo boreas*) and the Cascades Frog (*Rana cascadae*), and found that three of five populations analyzed had strong associations between breeding time and temperature. Only one population, however, had a statistical trend towards earlier breeding times over the two decades examined (Blaustein et al., 2001). While this study concluded that climate change was not influencing breeding phenology for these two Oregon species, subsequent analysis of these data by Corn (2003) revealed that significant relationships existed between dates of breeding and snow accumulation. Corn concluded that breeding phenology of mountain species are driven more by snow pack than by air temperature, and that 20-year data sets are too short to reveal significant changes in life history (Corn, 2003).

Lawler et al. (2009, 2010) employed climate models to project species turnover and range shifts for amphibians and other faunal groups across the Western Hemisphere. This analysis found that amphibian species loss was greatest in range-restricted species inhabiting areas with significant precipitation decreases. These models found greater species gain and loss rates for amphibians relative to birds and mammals due to predicted range expansions and contractions (Lawler et al., 2009). Similarly, Olson and Suzuki (in review) predicted that amphibian species with small geographic ranges in the Cascade Mountains and the western Cascade foothill regions will be negatively affected by reduced precipitation and variable wet periods. Six amphibian species have ranges restricted to the Cascade Mountains and are therefore at risk from shifting climate conditions (Jones et al., 2005). Predicted increases in temperature, a reduction in total snow pack, and increased variability in precipitation patterns in the Cascade Mountains and in the foothills of the Cascades (Chapter 3) will likely reduce available breeding habitats and upland hibernation habitats (hibernacula) for these species.

Climate change will also affect ecological interactions among species of amphibian. Shifts in breeding phenologies may result in species sharing similar breeding habitats when they did not previously overlap (Blaustein et al., 2010). These shifts will result in new competitive interactions and predator/prey dynamics in these shared environments. Invasive American Bullfrogs (*Lithobates catesbeianus*) have invaded permanent and ephemeral breeding habitats in much of Oregon, and earlier breeding phenologies would increase their overlap with native amphibians substantially (Bury and Whelan, 1984). Vegetation structure and heterogeneity will also be affected by changes in temperature, precipitation, and wet periods (Stroh et al., 2008). These changes will affect larval and adult habitat use, reproductive success, and may influence egg-laying behavior for aquatic and terrestrial species (Williams et al., 2008). And because a changing climate influences the geographic distribution of potential competitors, predators, and prey, amphibians will encounter different biotic communities and experience subsequent changes in their population dynamics (Alford, 1989; Lawler and Morin, 1993).



Disease dynamics in amphibian assemblages are also predicted to change with climate. Amphibian species differ in susceptibility to many of the pathogens and parasites present in Oregon, thus the effects will be both species-specific and region-specific (Alford et al., 2007; Garcia et al., 2006; Kiesecker and Blaustein, 1995). The emergent amphibian disease chytridiomycosis has been implicated in the decline of amphibian populations worldwide, and the impacts of this disease may be compounded by climate change (Pounds et al., 2006; Alford et al., 2007; Bosch et al., 2007). The fungus causing chytridiomycosis (*Batrachochytrium dendrobatidis*) is present in Oregon and is transmitted via aquatic spores, so changes in freshwater wet periods may affect transmission rates and prevalence throughout the pathogen's range (Daszak et al., 1999; Lawler et al., 2010). Yellow-Legged Frogs (*Rana boylei*) in Northern California were found to have significantly higher infection rates from a parasitic copepod during two years when daily mean summer temperatures exceeded 20°C (68°F) (Kupferburg et al., 2009). Similarly, Kiesecker and Blaustein (1995) found that decreased wet periods and warmer water temperatures facilitated infection of frogs in the Oregon Cascades by the fungus *Saprolegnia*. Such studies suggest that climate change in Oregon will negatively affect amphibian species via disease both directly and indirectly.

#### 7.2.2.2 Reptiles

Reptiles are divided into several distinctive groups, the three occurring in Oregon being turtles, lizards, and snakes. Oregon is home to two native and two introduced species of turtle, as well as four native species of sea turtle. Oregon has twelve native species of lizard and fifteen species of snake (Storm and Leonard, 1995). The highest diversity of reptiles on Earth tends to occur in warm, tropical locations. The number of species declines with distance from the equator owing, at least in part, to declines in temperature and reduced length of summer as one moves away from the equator. Thus, given Oregon's northern location, the state has comparatively few species of reptiles. As of 2004, Oregon had seven reptile species (excluding sea turtles) that were of conservation concern, but none were federally endangered or threatened (Oregon Natural Heritage Information Center, 2004). The Painted Turtle (*Chrysemys picta*) and Northwestern Pond Turtle (*Emys marmorata marmorata*) are considered to be of conservation concern. The only lizard of concern is the Northern Sagebrush Lizard (*Sceloporus graciosus graciosus*). Four snakes are of concern: Western Rattlesnake (*Crotalus viridus*), Common Kingsnake (*Lampropeltis getula*), California Mountain Kingsnake (*Lampropeltis zonata*), and Ground Snake (*Sonora semiannulata*). All sea turtles are federally listed as endangered or threatened.

The possible influence of climate change on reptiles in Oregon has yet to be studied. Based on the biology of reptiles, one can make some predictions of possible outcomes, but these predictions must be evaluated with appropriate studies. Reptiles are cold-blooded (ectothermic), which means their activity varies with the temperature of their environment; they do not generate their own body heat as birds and mammals do. Reptiles become active when temperatures warm, so most of their activity occurs during warm periods and seasons. Typically this means that activities are limited to times and places where temperatures are, at a minimum, above freezing, but typically temperatures for reptile activity must be much warmer. This dependence on temperature indicates that climate change will affect the activities of reptiles, and perhaps their distribution and abundance (Tewksbury et al., 2008). One might expect that as climate warms, the numbers of places that reptiles can live could increase. Longer

periods within a year that are warm enough to allow certain species to establish populations might occur. Habitats that are presently too cold to support certain reptiles could warm enough to allow expansion of ranges into those habitats or sites (for example, moving up elevation in mountainous landscapes).

However, simply expecting all reptiles to expand their distributions or increase in numbers as the climate warms is not realistic (Tewksbury et al., 2008). Another key factor limiting the distribution and abundance of some reptiles is the ability to stay cool (Huey et al., 2009). Many reptiles regulate their body temperatures to keep the temperature within specific ranges (warm, but not too warm). A common strategy is to engage in behavioral thermoregulation: when temperatures are too hot, reptiles move to shady sites or underground and find cooler locations that allow them to maintain their body temperatures appropriately. In some cases, if the climate warms too much, the distribution of particular species may be more affected by availability of appropriate cover, such as shade from vegetation, than by temperature alone (Kearney et al., 2009). Therefore, it is possible that distributions and abundances of some reptiles may change as vegetation within habitats they select also changes (see Chapter 5). Given that few studies have directly evaluated how reptiles will respond to climate change, and little is known particularly about the Pacific Northwest and Oregon, additional studies are required to evaluate expectations of how climate change will affect reptiles.

### 7.2.3 Land Birds

Oregon is one of the most ecologically diverse states in the U.S. with all four of the world's major biomes represented: alpine/tundra, desert, grassland, and forest. Given the ubiquitous distribution of land birds throughout the state and these regions, there is immense avian diversity representing over half of all land birds known to occur in North America north of Mexico (810 species, Sibley, 2000): 360 bird species regularly occur in Oregon and an additional 135 are more occasional visitors (Marshall et al., 2003). Among land birds breeding in Oregon, three are federally listed under the U.S. Endangered Species Act: Northern Spotted Owl (*Strix occidentalis caurina*), Western Snowy Plover (*Charadrius alexandrinus nivosus*), and the Marbled Murrelet (*Brachyramphus marmoratus*). The U.S. Fish and Wildlife Service recently (March 2010) determined that ESA-listing of the Greater Sage-Grouse (*Centrocercus urophasianus*) was "warranted, but precluded by higher priority listing actions." They will develop a proposed rule to list the Greater Sage-Grouse as their priorities allow (Federal Register 2010). Federal species considered candidates for Endangered Species Act-listing include Yellow-Billed Cuckoos (*Coccyzus americanus*) and Streaked Horned Larks (*Eremophila alpestris strigata*). There are an addition 22 avian species of federal concern ([www.fws.gov/oregonfwo/species/Data/Default.asp#Birds](http://www.fws.gov/oregonfwo/species/Data/Default.asp#Birds)).

Birds provide recreational benefits to hunters, bird-watchers, and overall appreciators of nature. They contribute substantially to Oregon tourism, outdoor recreation, outdoor sporting good manufacturers, as well as private and federal habitat conservation efforts in the State. The ubiquitous distribution of birds throughout all habitats in Oregon lends them to be susceptible to the varying effects climate change may have on each biome. Further, most birds are migratory, hence they are also subjected to changing climates along their migratory pathways going north and south, as well as their wintering grounds (Both et al., 2009). As reported in the

most recent *State of the Birds* (NABCI, 2010): “Birds in every terrestrial and aquatic habitat will be affected by climate change, although individual species in each habitat are likely to respond differently.”

Avian response to climate change around the world has been manifested in several ways: the geographical distribution of species has shifted poleward and to higher altitudes; and the beginning of the breeding season and/or migration is shifting to earlier dates (Moller et al., 2004; Gienapp, 2008; Sheldon, 2010). Some birds that once were migratory (e.g., Canada Geese, *Branta canadensis*) have become permanent residents in one location throughout the year. Such change can have a domino effect on other species accustomed to occupying previously open habitats during certain times of year.

The 2010 *State of the Birds* evaluated vulnerability to climate change for every avian species in North America (NABCI, 2010). Among all Oregon birds, nine species were given the highest rating for vulnerability and all were coastal species. Two of these species were breeding Black Oystercatchers (*Haematopus bachmani*; Fig. 7.4) and Pigeon Guillemots (*Cepphus columba*), and seven were species that migrated through or wintered on the Oregon coast: Surfbird (*Aphriza virgata*), Wandering Tattler (*Tringa incana*), Yellow-Billed Loon (*Gavia adamsii*), Black Turnstone (*Arenaria melanocephala*), Western Sandpiper (*Calidris mauri*), Rock Sandpiper (*Calidris ptilocnemis*), and Short-Billed Dowitcher (*Limnodromus griseus*; also found in the Willamette Valley and Great Basin).



**Figure 7.4** Rising sea levels and ocean acidification threaten breeding and feeding habitats, respectively, for these Black Oystercatchers, one of nine bird species in Oregon given the highest rating for vulnerability to climate change by the North American Bird Conservation Initiative (NACBI, 2010). Photo by Brian Guzzetti.

Climate change has not been definitively studied for birds in Oregon, although observed general patterns in climate allow one to suggest changes that might occur among the varied habitats. Overall, predictions for Oregon and the Pacific Northwest are for warmer wetter winters and hotter drier summers (Karl et al. 2009; Chapter 1). On the Pacific Coast, rising sea levels are expected to inundate or fragment low-lying habitats such as the estuaries, rocky intertidal areas and sandy beaches (Chapter 6). Increasing frequency and severity of storms and increases in water temperature and acidity will affect the quality and quantity of coastal habitats and alter marine food webs (Chapter 6 and this chapter). Changes in nearshore sea surface

temperatures, though smaller than on land, are likely to substantially exceed interannual variability (Chapter 1). Coastal bird species are expected to shift their distributions northward, as warmer temperatures cause shifts in food resources and nesting opportunities (Browne and Dell, 2007). Lower seasonal flows of freshwater into Pacific coastal marshes will change water and soil salinity and affect the plants and invertebrates needed by foraging waterbirds. This will affect beach nesting and foraging for resident species such as Snowy Plovers and Black Oystercatchers. The *State of the Birds* (NABCI, 2010) found that most coastal birds show medium or high vulnerability to climate change. In addition to the most vulnerable species listed above, coastal species expected to be particularly impacted are diving ducks, such as Canvasbacks (*Aythya valisineria*) and Ruddy Ducks (*Oxyura jamaicensis*) because their existing habitats in the region have already been severely affected by human development (Glick, 2005; Brown and Dell, 2007). Other migratory birds such as the Western Sandpiper, Wandering Tattler, Whimbrel (*Numenius phaeopus*), Harlequin Duck (*Histrionicus histrionicus*), Red-Throated Loon (*Gavia stellata*) and many others will be vulnerable to these changes in their stopover and wintering habitats.

The Willamette Valley provides refuge for hundreds of thousands of Canada Geese, Dunlin (*Calidris alpina*), and other water birds in the winter (Taft and Haig 2003). The predicted warmer, wetter winters could enhance this wetland/savannah habitat. However, the more ephemeral wetlands are created by rain, the more they are drained for agricultural reasons (Taft et al., 2008). Thus, summer residents such as Oregon's state bird, the Western Meadowlark (*Sturnella neglecta*), may not fare as well as warmer temperatures dry up water resources and invertebrates. The largest urban areas in Oregon are located in the Willamette Valley, and common urban birds such as Vaux's Swift (*Chaetura vaux*) and Common Nighthawks (*Chordeiles minor*) are declining (NABCI, 2009). Ironically, resident urban birds appear to be holding their own, yet migrants such as the swifts and nighthawks are not.

Further inland, snowpack has decreased substantially and will continue to do so (Chapter 3). Impacts will probably be high for mountainous wetlands where temperature-sensitive birds will be unable to move upslope (NABCI, 2010). Wetlands that depend on snowmelt will diminish or disappear. This lack of water or declining water levels in permanent and ephemeral Cascade Mountain lakes may most affect nearby cavity-nesting ducks such as the mergansers, Common Goldeneye (*Bucephala clangula*), and Bufflehead (*B. albeola*). Other Pacific forest birds of similar concern include Marbled Murrelet, Spotted Owl, Olive-Sided Flycatcher (*Contopus cooperi*), Varied Thrush (*Ixoreus naevius*), Band-Tailed Pigeon (*Patagioenas fasciata*), Rufous Hummingbird (*Selasphorus rufus*), White-Headed Woodpecker (*Picoides albolarvatus*) and Chestnut-Backed Chickadee (*Poecile rufescens*) (NABCI, 2009).

Warmer, wetter winters and hotter drier summers may prove to be an additional challenge for the threatened Northern Spotted Owl in the Coast Range and Cascade Mountains (Johnson, 1994; Glenn, 2009; Carroll, 2010). Glenn (2009) and Carroll (2010) both found changing climate, particularly wetter winters, accounted for moderate to high amounts of variation in owl survival and population growth rates. McRae et al. (2008) similarly found that small changes in vital rates resulting from climate change or other stressors can have large consequences for population trajectories in Winter Wrens (*Troglodytes troglodytes*) in mature conifer forests in the

Cascades as well as Song Sparrows (*Melospiza melodia*), which prefer more open, shrubby Cascade habitats.

In the Great Basin, decreased summer precipitation will result in an increase in fuels from the growth of annual weeds leading to conditions for extensive and intensive fires. Many arid land birds (over 40%; NABCI, 2009) are at increased risk because of fire, drought and the potential for summertime temperatures greater than they can tolerate. Important wintering areas for many arid land birds may also become unsuitable due to increased drought (NABCI, 2010). Greater Sage-Grouse, other ground-nesting and sage-nesting birds are particularly vulnerable because of their high site fidelity. The climate-enhanced succession to juniper forest in the Great Basin will further exacerbate these habitat limitations.

Understanding the impact of climate change for the many water bird species using the chain of wetlands in Oregon's western Great Basin is complex. Most simply put, the higher salinity (salty) wetlands such as Lake Abert and Summer Lake in south-central Oregon provide superabundant invertebrate food resources for adults (Haig et al., 1998; Plissner et al., 2000). However, chicks need to live near freshwater because they do not possess a developed salt gland (Mahoney and Jehl, 1985; Barnes and Nudds, 1991; Hannam et al., 2003). Thus, the juxtaposition of the need for fresh and saline wetlands is exacerbated by changing climate patterns for the region. If summers are hotter, then freshwater sites will become more saline and less useful for raising young water birds. However if there is increased precipitation, then the decreased salinity at sites like Summer Lake and Abert Lake will decrease food availability for adult breeding birds and millions of water birds that pass through on migration. These changes will be felt most by the species most dependent on them. Most of North America's Snowy Plovers breed in the region. Most of North America's Eared Grebes (*Aechmophorus occidentalis*), Long-Billed Dowitchers (*Limnodromus scolopaceus*), and the all of the world's Wilson's Phalaropes (*Phalaropus tricolor*) use the region during migration. Most of the world's American Avocets (*Recurvirostra americana*) use the region for an extended post-breeding period—over 50% of this species breed in the Great Basin, and most of the world's White-Faced Ibis (*Plegadis chihi*) breed in the Great Basin (reviewed in Warnock et al. 1998). Western Grebe (*Aechmophorus occidentalis*), Clark's Grebe (*A. clarkii*) and Northern Pintail (*Anas acuta*) will also be vulnerable to changes in water level and distribution that affect breeding habitats (NABCI, 2010).

#### 7.2.3.1. Research needs

As the climate changes and Oregon birds respond to these perturbations, it is important to recall that most of Oregon's birds are migrants. Thus, we need to understand how their world is changing in each phase of their annual cycle and how carryover of changes in one phase of the annual cycle is affecting the next (Webster et al., 2002). In many cases, we do not know migrant pathways to winter sites or locations of these winter sites. Understanding this annual connectivity is key to conservation planning. Closer to home, we need to better document basic information on distribution, abundance, elevation, and habitats used by birds now and as they change in the future. Even the most common of Oregon's birds must be understood, as the scale of change we are undergoing is far greater than we could have imagined. Patterns in Oregon will likely follow those predicted for California (Stralberg et al., 2009), hence managers will need to consider the potential for changes in community composition and unanticipated

consequences of novel species assemblages. One way to track these changes would be to institute a system such as the California Avian Data Center ([data.prbo.org/cadc2](http://data.prbo.org/cadc2)) in which a species, habitat, region, etc. can be queried as to its projected distribution as a result of climate change over particular time frames. At the least, bird distribution information could be entered into eBird ([ebird.org](http://ebird.org)) or the USGS North American Bird Phenology Program ([www.pwrc.usgs.gov/bpp/index.cfm](http://www.pwrc.usgs.gov/bpp/index.cfm)), web-based datasets for amateurs and professionals interested in changing locations of bird species in real time.

In any case, the unprecedented events we are experiencing will require an unprecedented effort to understand the changes on Oregon's birds and provide for their future existence.

#### 7.2.4 Land mammals

Mammals in Oregon are a major source of economic activity through hunting, wildlife watching, and trapping. Mammals also influence habitat for fish, birds, and other species, help control agricultural pests, and are highly valued by the public as wilderness symbols and part of the state's biodiversity. Oregon has a diverse assemblage of land mammals representing most mammalian orders and families found in North America, including about 128 native species and at least 9 established non-native species (Verts and Carraway, 1998). Species found only in (i.e., endemic to) Oregon include two species of shrew (*Sorex bairdi* and *S. pacificus*) and the Camas pocket gopher (*Thomomys bulbivorus*). The red tree vole (*Arborimus longicaudus*) is endemic to Oregon and extreme northeastern California, and the gray vole (*Microtus canicaudus*) is endemic to Oregon and Clark County of Washington (Verts and Carraway, 1998). Oregon was recently recolonized by gray wolf (*Canis lupus*) and also colonized by moose (*Alces alces*) (Pat Matthews, Oregon Department of Fish and Wildlife, personal communication). Species listed under the Endangered Species Act (ESA) include the endangered Columbian subspecies of white-tailed deer (*Odocoileus virginianus leucurus*), gray wolves, and the threatened Canada lynx (*Lynx canadensis*) (Oregon Natural Heritage Information Center, 2004; Fig. 7.2.4.A), although lynx are not known to breed in Oregon (Verts and Carroway 1998). Recent candidate species for ESA listing include fisher (*Martes pennanti*), Washington ground squirrel (*Spermophilus washingtoni*), and American pika (*Ochotona princeps*). The state is also home to at least 18 U.S. Fish and Wildlife Service "species of concern," including pygmy rabbit (*Brachylagus idahoensis*), wolverine (*Gulo gulo*), 10 species of bat, 3 species of pocket gopher (*Thomomys* spp.), Preble's shrew (*Sorex preblei*), and two species of vole (*Arborimus* spp.) (United States Fish and Wildlife Service, 2010).

(a)



(b)



(c)



**Figure 7.5** Three large endangered mammals in Oregon. (a) The Columbian white-tailed deer is restricted to Douglas County and several islands in the Columbia River. (b) The gray wolf has recently recolonized Oregon, yet the impact of climate change on large predators in Oregon is unclear. (c) The Canada lynx is associated with persistent snow cover during winter months (photos courtesy of the American Society of Mammalogists).

The effects of expected climate change on Oregon's mammals have not been evaluated specifically, but several studies have examined past and future climate effects on small mammals in larger regions that include Oregon. For instance, Beever et al. (2003) recorded more apparent population extinctions of pika (*O. princeps*) in low elevation mountain ranges in the Great Basin deserts of western North America, including areas of eastern Oregon. This range contraction to higher elevations has occurred over the past 7,500 years as the climate has warmed and become more arid (Grayson, 2005), but warming is expected to accelerate much more rapidly during this century (Galbreath et al., 2009; Chapter 1). However, some low elevation populations of pika have persisted (Beever et al., 2008; Simpson, 2009), perhaps due to favorable small-scale habitats that provide shelter from higher temperatures. Studies of historical change in species distribution or abundance from the fossil record (Grayson, 2000; Blois and Hadly, 2009) demonstrate that periods of warming and drying occurred in the Great Basin within the last 10,000 years. These past climate shifts were associated with rapid loss or range contraction of species of small mammals adapted to wetter conditions, such as pocket gophers (*Thomomys* spp.), pygmy rabbit (*B. idahoensis*), and yellow-bellied marmot (*Marmota flaviventris*), as well as expansion of species adapted for arid habitats, such as kangaroo rats (*Dipodomys* spp.). Grayson (2000, 2006) predicted that increases in summer temperature would cause declines in species such as bushy-tailed woodrat (*Neotoma cinerea*), Great Basin pocket mouse (*Perognathus parvus*), and western harvest mouse (*Reithrodontomys megalotis*), but only if precipitation decreases (see Chapter 3). Any major shift in precipitation (drier or wetter) would be expected to influence communities of small mammals by favoring either dry or wet-adapted species (Grayson, 2000). Predicted extinction of many Great Basin mammal species, such as the western jumping mouse (*Zapus princeps*), Belding's ground squirrel (*Spermophilus beldingi*), and the whitetailed jackrabbit (*Lepus townsendii*) resulting from an anticipated 3°C (5.4°F) temperature increase (McDonald and Brown, 1992; see Chapter 1) may be overstated because dispersal potential was underestimated for many Great Basin species (Grayson, 2006; Waltari and Guralnick, 2009).

Few if any studies have evaluated effects of climate change on mammals elsewhere in Oregon, other than a range-wide assessment of pika that included habitat in the Cascade Mountain

Range (Galbreath et al., 2009). Because most Oregon mammal species are not endemic to the state (Verts and Carraway, 1998), some climate change research on mammals outside Oregon is relevant. Most such research has occurred in California, which has a similar range of habitats and high faunal overlap with Oregon. Moritz et al. (2008) evaluated changes from historic (early 20th century) to current distributions of 28 small mammal species in the Sierra Nevada mountains of California. They found that half of those species shifted their ranges to higher elevations over that period of warming, including Belding's ground squirrel (*S. beldingi*), water shrew (*Sorex palustris*), American pika (*O. princeps*), bushy-tailed woodrat (*N. cinerea*), golden-mantled ground squirrel (*Spermophilus lateralis*), and long-tailed vole (*Microtus longicaudus*). However, some lower-elevation species, such as the western harvest mouse (*R. megalotis*) and the montane shrew (*Sorex monticolus*), expanded their ranges. Also, migration appeared to moderate some of the apparent impacts of climate change over the last century (Moritz et al., 2008). Desert bighorn sheep (*Ovis canadensis nelsoni*) in the Mojave, Great Basin, and Sonoran Deserts of California likewise showed a range contraction to higher elevation and wetter mountain ranges during the period 1940–2000; populations in higher elevation habitats also retained greater genetic diversity (Epps et al., 2006). After observing recolonization of some lower elevation habitats by desert bighorn sheep, Epps et al. (2010) argued that maintaining connectivity among fragmented populations of climate-sensitive species may offer the best opportunity to manage impacts of climate change at local and regional scales. Wolverine (*G. gulo*), possibly extirpated from Oregon but still occasionally reported, require persistent winter snows for successful reproduction and, thus, have been negatively affected by declining snowpack across North America (Brodie and Post, 2010). Canada lynx are also associated with winter snow cover (Verts and Carraway 1998) and could be affected by changes in snowpack. There is little research on the effects of climate change on bats in the western United States, although Adams and Hayes (2008) determined that the fringed bat (*Myotis thysanodes*) had high water requirements during lactation and would have less successful reproduction if the climate becomes more arid. Reproductive success in many temperate bat species is linked to precipitation (e.g., Frick et al., 2010).

Climate envelope modeling of the responses of land mammals to climate change in California suggested that the greatest potential for changes in species distributions was in the arid eastern regions, while mammal distributions in the Sierra Nevada and Central Valley remained relatively stable (Parra and Monahan, 2008), suggesting that similar patterns might be observed in the arid regions of eastern Oregon. Precipitation, rather than temperature, often has the strongest influence on mammalian body condition or population dynamics, particularly in arid regions. For instance, precipitation was the stronger determinant of body size of California ground squirrel (*Spermophilus beecheyi*; Blois et al., 2008) as well as diet quality and reproductive success of desert bighorn sheep (Epps, 2004; Wehausen, 2005). However, predicted changes in precipitation are much more variable than predicted changes in temperature among the current spectrum of global climate change models (e.g., Loarie et al., 2008; Parra and Monahan, 2008; see Chapter 3), rendering impacts on species in arid lands and other habitats even less predictable.



#### 7.2.4.1 Research needs

Anticipating the impacts of future climate change on mammals requires (1) understanding how to accurately downscale global climate change models to regional scales; (2) understanding the effects of climate on habitat (in particular, vegetation and surface water); (3) understanding the effects of changes in habitat, precipitation, and temperature on physiology, behavior, and population dynamics; and (4) understanding complex interactions among species and with other factors, such as disease. The first two areas are being addressed in other arenas of climate change research, whereas the third often must be approached on a species-by-species basis. Species inhabiting deserts (Loarie et al., 2009), high elevations (Parmesan, 2006), and other ecosystems already identified as “high risk” are the most obvious candidates for future research. Some interactions between species are already anticipated. For instance, American beaver (*Castor canadensis*) dams may retain water for longer periods in freshwater streams, which could help mitigate impacts of early snowmelt or changes in precipitation (Hood and Bayley, 2008) on freshwater ecosystems (see Section 7.3). Other important considerations include how predicted climate changes that affect human activities on agricultural lands (Chapter 4) and managed forests (Chapter 5) may affect mammal species restricted to such habitats, such as the Camas pocket gopher (*T. bulbivorus*), which are found only in the intensively-farmed Willamette Valley. Refining predictions for future precipitation and identifying basic relationships among mammalian population dynamics and climate variables may be the highest priorities for future research.

### 7.3 Freshwater Fishes and Invertebrates

Land use change and industrial/municipal development have directly and indirectly warmed streams and rivers throughout Oregon, contributing to the decline of anadromous salmon and trout, resident salmonid fishes, and other cold water species (USACE, 2008; NWPCC, 2004). More than 11,000 miles of streams and rivers in Oregon have been listed as impaired based on temperatures that exceed the water quality standard. In a recent analysis of water quality in the Willamette River basin, more than 35% of the streams were classified as poor quality (Annear et al., 2004). The human population in the Willamette Basin is projected to double over the next 50 years (Hulse et al., 2002), creating more pressure to convert riparian areas and floodplains, develop more roads and drainage ditches, and generate greater volumes of thermal effluents that heat streams and rivers. In addition to accelerated human impacts on river systems, the regional and global climate is projected to warm substantially in coming decades (Chapter 1). The distribution of cold-water species will potentially shrink and become disconnected as thermal regimes in river networks warm more rapidly due to human influences and climate warming.

#### 7.3.1 Freshwater Invertebrates

Aquatic invertebrates are present in all Oregon freshwater habitats, from seasonal alpine ponds and temporary (ephemeral) desert streams, to permanent (perennial) lakes and rivers. Broadly speaking, “aquatic invertebrates” include all of the aquatic insects (mayflies, dragonflies,

stoneflies, etc.) as well as crayfish, snails, fairy shrimp, clams, and related groups. Aquatic invertebrates are key consumers of aquatic plants and forest leaf litter, and in turn they constitute a critical food source for fish (including young salmon and steelhead), birds, bats, and other animals. Recreationally, many groups of aquatic insects are important for trout fisheries and the fly fishing industry. Many aquatic invertebrate species require clean, cold water year-round, and for this reason they are used to monitor the ecosystem status of rivers and streams (Carter et al., 2007).

Oregon possesses a great diversity of aquatic invertebrate species, due largely to the sheer volume and diversity of aquatic habitats distributed across the state. For example, Oregon is home to at least 88 species of dragonflies and damselflies (Kondratieff, 2000), 116 species of stoneflies (Kondratieff and Baumann, 2000), and 142 species of mayflies (Meyer and McCafferty, 2007). Distinct invertebrate communities are found in springtime ponds, snowmelt-driven headwater streams, isolated desert springs, and large rivers. Of particular interest with respect to climate change are “headwater specialist” species, which are often restricted to high-elevation, cold-temperature mountain streams that are heavily influenced by melting snowpack (Meyer et al., 2007). While no studies have directly examined how climate change might affect any of these habitats in Oregon, we can obtain guidance from studies done in similar habitats in North America, Europe, and Australia.

Aquatic invertebrates are strongly affected by changes in both hydrology (a river’s characteristic pattern of baseflow, flood, and drought) and temperature, and both of these factors are expected to change substantially under most climate change scenarios. For many freshwater aquatic organisms, hydrology is the “master variable” that dictates fundamental aspects of their life cycle, ecology, and distribution (Poff et al., 1997). Similarly, stream temperature affects the growth rate, biomass, and distribution of many aquatic invertebrate species (Vannote and Sweeney, 1980).

In Oregon’s mountain regions, a shift from winter snowpack to winter rainfall could reduce the abundance and diversity of aquatic invertebrates. Although milder winter conditions could create new stream habitat at higher elevations, studies from other regions suggest these habitats might not be suitable for many aquatic invertebrate species. In a long-term study in the Swiss Alps, Finn and coauthors (2010) found that stream habitats became significantly less stable (higher flow variability) as permanent snowpack retreated over a five decade period. This instability was also linked to fluctuations in aquatic invertebrate community structure over shorter timescales. This change may have been due to decreasing or more erratic groundwater recharge as glaciers receded, as documented by Haldorsen and Heim (1999) for Arctic streams.

Climate predictions for mountain regions also include more winter precipitation falling as rain instead of snow, as well as earlier melting of accumulated snowpack (Chapter 3). This change will create a substantially different environment for aquatic invertebrates because in snowpack-dominated streams, winter flows are relatively constant, and there is a pronounced but predictable spring flood associated with melting of the snowpack. By contrast, rainfall-dominated streams can experience major floods during the winter season. Studies of streams in the Oregon Cascades have shown that flow variability influences communities of aquatic invertebrates, with more stable stream types generally exhibiting higher density and greater

biodiversity (Yamamuro, 2009). In some parts of Oregon, deep volcanic aquifers might be expected to buffer stream hydrology and maintain stable flows, even as more precipitation falls as rain instead of snow (Chapter 3). For most streams, however, a shift towards more variable winter flows may result in lower biodiversity and abundance of aquatic invertebrates.

In Oregon's arid regions, less frequent or more variable precipitation may cause some streams and ponds to shift from perennial (surface water year-round) to intermittent (surface water for only part of the year). The transition from perennial to intermittent water bodies can bring major shifts in invertebrate community structure as well, due to differences in nutrient dynamics and predator communities (e.g., intermittent habitats often are fishless). The differences in water permanence alone may be sufficient to produce differences in invertebrate communities, because many invertebrate species are unable to survive prolonged periods of drought and desiccation (drying). In other arid regions, decreased precipitation is expected to be especially problematic because groundwater and stream flows already are compromised by increasing human demand and extraction in the American Southwest (Grimm et al., 1997; Deacon et al., 2007). The situation likely will be similar in Oregon's arid regions, where high demand for limited water supplies will only exacerbate the ecological changes produced by a changing climate.

Increasing temperatures may reduce the biodiversity of aquatic invertebrate communities, especially when the temperature tolerances of some species are exceeded. Most aquatic invertebrates have a defined range of stream temperature tolerance within which they can survive, with some species adapted to warm, oxygen-poor waters and others specializing on colder, oxygen-rich habitats. Studies in European alpine zones have noted a local increase in the number of species as cold snowmelt-driven streams became warmer due to climate change (e.g., Brown et al., 2007, and Jurasinski and Kreyling, 2007, for plant communities), possibly because of the enhanced ecosystem productivity that can be associated with warmer temperatures. At face value, this increase in species diversity at a single site may seem like a positive effect of a warming climate. However, these same studies found that overall diversity across sites actually decreased, primarily because alpine headwater specialists were being replaced by widespread generalist species from lower elevations. Several species that require cold temperatures had declined greatly and were predicted to become locally extinct if the warming trend continued. To some degree, the combined effects of changing hydrology and increasing stream temperatures might eventually push many headwater species "off the top of the mountain," as has been extensively documented for many terrestrial plant and animal species (e.g., Section 7.2.4). Overall, warming temperatures in Oregon mountain streams can be predicted to provide some positive benefits at the local scale (increased local diversity), but these benefits are predicted to be outweighed by negative impacts at the regional scale (decreased overall diversity and loss of some specialist species).

Aside from altering patterns of aquatic invertebrate biodiversity and distribution, changes in water temperature alter the population dynamics of individual species. The "phenology" of aquatic invertebrates refers to their cycle of growth, maturation, and reproduction. For many species, if not most, phenology is strongly determined by temperature. Thus, a shift towards warmer spring temperatures might produce a much earlier phenology, such that aquatic invertebrates reach reproductive maturity at an earlier date (e.g., Section 7.2.1). This

phenomenon is well-documented in plants, insects, and birds, with similar patterns occurring in aquatic invertebrates (Finn and Poff, 2008; Strayer and Dudgeon, 2010). Mayflies in the Rocky Mountains have been observed to emerge earlier during periods of lower snow pack and earlier snowmelt (Harper and Peckarsky, 2006). The ramifications for entire aquatic communities of such shifts in the phenology of single species remain unknown. It is possible that some aquatic invertebrate prey species could become unsynchronized with their predators (fish, birds, or other animals), but this outcome remains to be demonstrated directly.

In summary, Oregon has a great diversity of aquatic habitats that likely will be affected by climate change. The most immediate effects are likely to arise from changes in aquatic hydrology and temperature. The expectation from studies in other regions similar to Oregon is that biodiversity will decrease in general, although local increases are possible. Headwater specialists that depend on cold water and snowmelt are especially vulnerable, as are arid land species that depend on year-round water.

### **7.3.2 Salmon and other freshwater fishes**

Projection of the effects of climate change on 57 species of North American freshwater fish indicated that 37% of the current locations inhabited by cold-water fishes would not support these species over the next century (Mohseni et al., 2003). Another study of climate effects on coldwater fishes concluded that trout habitats throughout the U.S. would be reduced by 15–40% by 2090 (O’Neal et al., 2002). This study provided regional estimates as well, and projected that trout habitat in the Pacific Northwest would decline by 8–33% by 2090. Salmon habitat is even more vulnerable to the effects of climate change because more of the habitat of salmon is at lower, warmer elevations. O’Neal et al. (2002) projected that suitable salmon habitat in Oregon and Idaho would shrink by 40% by 2090, but Washington would experience only a 22% loss, reflecting the cooler temperatures found in more northerly coastal drainages. Bull trout (*Salvelinus confluentus*) require colder temperature than other salmonid fishes and may be more sensitive to regional climate warming. Estimates of climate-related habitat loss for bull trout in the Columbia River basin range from 22% to 92% (B. Reiman, personal communication, as cited by ISAB, 2007).

Similar results have been projected for other regions with native salmonid fishes. Estimates of habitat loss for brook trout (*Salvelinus fontinalis*) in the Appalachian Mountains range from 53% to 97% (Fleebe et al., 2006). Habitat for trout in the North Platte River in the Rocky Mountains of Colorado is projected to shrink by 7–72% as a result of climate change (Rahel, 1996). Species of cold-water fish in the Muskegon River basin in Michigan are projected to decline by 2100, but the geographic ranges of cool-water and warm-water species are predicted to expand (Steen et al., 2010).

The context for analyses of habitat losses related to climate change assumes that air surface temperatures will change, leading to increased rates of warming from headwater streams to large rivers (Chapter 3). Temperatures at stream sources will change slightly but warm more rapidly, and higher temperatures in large rivers will reflect the increases in surface air temperatures. Summer droughts and reduced snow pack will cause contraction of the stream network and current year-round headwater streams will become intermittent seasonal streams.

Rain-on-snow zones will extend higher in elevation and winter flood magnitudes may increase. Human population growth will increase demands for water, and withdrawals from surface water and groundwater will exacerbate effects of climate change on water temperatures and low-flow stream networks.

Various native freshwater fishes in the Pacific Northwest require cold water and are potentially vulnerable to warming associated with climate change. Coho salmon (*Oncorhynchus kisutch*), rainbow trout (*O. mykiss*), cutthroat trout (*O. clarki*), and five species of sculpin (*Cottus* spp.) normally are found in waters less than 17°C (63°F) (Huff et al., 2006; Fig. 7.6). Columbia River white sturgeon (*Acipenser transmontanus*) spawn at temperatures in the range of 10–18°C (50–64°F) (Parsley et al., 1993). Sturgeon eggs die at 20°C (68°F) (Wang et al., 1985). The upper lethal temperature limit of eggs and larvae of Pacific lamprey (*Lampetra tridentata*) is 22°C (72°F) (Meeuwig et al., 2005). The state of Oregon has reviewed thermal tolerances and upper incipient lethal levels in establishing temperature standards under the Clean Water Act (see tables in Oregon Department of Environmental Quality, 1995; McCullough et al., 2001). In the face of climate change, the length of streams and rivers that exceeds the upper incipient lethal levels for species of native fish would likely expand.



**Figure 7.6.** Cutthroat trout, one of many native Pacific Northwest freshwater fishes potentially vulnerable to a warming climate.

Climate change scenarios in the Pacific Northwest project increased frequency and duration of summer drought (Chapter 3). Small headwater streams will become intermittent, increasing the death rate of eggs and juvenile fish. Extension of drought into early autumn can have substantial negative impacts on salmonid fishes. Populations of spring Chinook salmon (*Oncorhynchus tshawytscha*) in the Salmon River in Idaho increase with the size of autumn water discharges (Crozier and Zabel, 2006). Chinook salmon juveniles in wide and shallow streams are affected by summer low flows and maximum temperatures more than fish in deeper channels (Torgerson et al., 1999; Crozier and Zabel, 2006).

Water temperature influences the time required for fish eggs to develop and the rate at which fry and juvenile fish grow. Life histories of freshwater fishes are closely tied to habitat conditions, food supplies, migration, and transitions between freshwater and saltwater for anadromous species. Shifts in timing and the consequences for critical life-history requirements (such as migration, egg development, juvenile rearing, ocean entry and migration, adult return)

make projections related to timing highly variable, but such changes have substantial potential to negatively affect hatching, growth, migration, and survival. Warmer water temperatures are likely to lead to shorter incubation periods and faster growth and maturation of young fish (Beckman et al., 1998). Faster growth and maturation can have positive effects because young fish attain larger sizes before winter, which increases their survival potential (Quinn and Peterson, 1996). High summer temperatures can also increase metabolic costs and decrease growth during summer (Healy, 2006). However, accelerated growth can also cause earlier entry of juvenile salmon into the ocean. Because salmon and steelhead stocks have evolved to migrate and enter the ocean at specific times of the year, changes in that timing could have either negative or positive outcomes. Timing of ocean entry is known to be a primary factor in survival and production of pink salmon (*Oncorhynchus gorbuscha*) in the ocean (Henderson et al., 1992; Pearcy, 1992). In Carnation Creek, British Columbia, increased stream temperatures due to logging caused more rapid growth in coho salmon, and juveniles entered the ocean two weeks earlier than normal. Returns of adult coho salmon decreased, and the authors hypothesized that change in timing of ocean entry resulted in higher consumption of young salmon by marine predators (Holtby et al., 1990).

Migration of salmon in the Columbia River is strongly influenced by river temperatures (Gonia et al., 2006; ISAB, 2007). Movement of adult steelhead trout and Chinook salmon decrease sharply at temperatures greater than 18°C (64°F) (Richter and Kolmes, 2005). Others have suggested that 16°C (61°F) is the upper limit for migration of salmon in the upper Columbia and Snake Rivers (Salinger and Anderson, 2006). At higher temperatures, migrating salmon move into cold water refuges in tributaries or deep pools, and hold position until temperatures in the mainstem river decrease (Perry et al., 2002). Adult Chinook salmon did not survive when exposed to a constant temperature of 22°C (72°F) (McCullough et al., 2001).

#### 7.3.2.1 Cold-water refuges

Cold-water refuges for aquatic organisms are created by the exchange of stream waters and ground waters throughout river networks and deep aquifer sources in specific geologic landscapes. Cutthroat trout use cold-water refuges in the mainstem Willamette River disproportionately during summer periods of high temperature (Hulse and Gregory, 2007). Similar results have been observed for coho salmon in the Smith River, and Chinook salmon east of the Cascades (Raskauskas, 2005). Aquifers with sources in the High Cascades create cold-water springs that provide a substantial portion of the water in some tributaries during summer low flow (Tague and Grant, 2004). Distributions of different types of cold-water refuges could determine the future distributions and abundances of native cold-water fishes under warmer climate regimes.

Cold-water habitats occur in alcoves (side channels) on floodplains and in-channel gravel bars (Hulse and Gregory, 2007; Burkeholder et al., 2008). In the upper Willamette River, more than 68% of the sites sampled in floodplain alcoves were colder than the mainstem river, and 37% were 2–9°C (4–16°F) colder than the mainstem sites. Cold-water habitats created by the exchange of stream waters and ground waters provide critical refuges for native salmonid fishes, but few studies have directly linked the use of cold-water habitats with the processes that create and maintain these essential refuges. Chinook salmon in the Yakima River exhibited core

body temperatures 2.5°C (4.5°F) lower than the surrounding river temperature (Bermann and Quinn, 1991), demonstrating a need for cold water habitats throughout the river network for adult salmon. The availability of suitable thermal refuges and appropriate holding habitat within mainstem rivers may affect long-term population survival. Torgerson et al. (1999) found Chinook salmon in the John Day River system primarily in deeper pools or tributary junctions with cooler temperatures. Subsequent studies revealed little exchange of stream waters and ground waters in these reaches, so the cooler temperatures were source-related and not exchange-related (Wright et al., 2005). Juvenile coho salmon in the Smith River avoided warmer mainstem river habitats (up to 25°C or 77°F) and aggregated in cold-water habitats (Raskauskas, 2005). Fifteen cold-water refuges identified in 15 km (9 mi) of stream contained the majority of coho salmon in the reach. In floodplain alcoves of the Willamette River colder than the mainstem, more than 80% of the fish species observed were native species; but in floodplain alcoves warmer than the mainstem, 60% of the species observed were non-native species (S. Gregory and D. Hulse, unpublished data). Studies of fish distributions and water temperatures in Oregon demonstrated that most native fish in the Willamette River occurred in waters less than 20°C (68°F), with only reddsideshiner (*Richardsonius balteatus*) and speckled dace (*Rhinichthys osculus*) normally occupying waters as warm as 23-25°C (73-77°F) (Huff et al., 2005).

#### 7.3.2.2 *Effects of increased flooding*

In the Pacific Northwest, climate change assessments indicate that winter floods may increase as a result of expanded rain-on-snow zones (Chapter 3). Expanded area of floodplain could have both positive and negative effects on aquatic ecosystems. Floods remove silt from streambeds, create spawning gravel deposits, create pools, deposit riffles, accumulate wood in complex habitats, deliver food resources from adjacent terrestrial ecosystems, and shape diverse and productive floodplains (Swanson et al., 1998, Hulse and Gregory 2004). Increased flooding would provide more of these benefits and possibly restore flood processes in tributaries where flood control has greatly decreased the frequency and magnitude of flooding. But floods also can have detrimental effects on aquatic communities, especially in reaches where channel simplification and bank hardening increase the power of floods but eliminate access to lateral floodplain and riparian refuges. Winter floods can scour gravel nests (redds) while the eggs of Pacific salmon and other salmonid fishes are in the gravel (Jager, 1997). Earlier snowmelt can result in exposure of redds if water levels drop sooner and more rapidly. Siltation during flood events also has the potential to blanket gravels with silt and smother eggs or trap fry.

#### 7.3.2.3 *Effects of increased diseases and parasites*

Warmer waters also increase exposure of fish to diseases and potentially alter the resistance of aquatic organisms to pathogens and parasites (Marcogliese, 2001). Recent studies have documented pre-spawning death rates of 65-90% in spring Chinook salmon in the Willamette River system (C. Schreck, unpublished data). These mortalities occur after migration to their spawning grounds but before spawning, losses not included in regional estimates of returning adult salmon. Disease, exposure to environmental contaminants, and the stress of high temperatures are potential causal factors. Native salmonid fishes in the Willamette River system also are noted for their high susceptibility to bacterial disease. Several of these diseases also have intermediate hosts (e.g., *Ceratomyxa shasta* with a ploychaete worm host *Manayunkia*

*speciosa*) likely to increase at higher temperatures and in areas of increased sediment deposits, both of which could be worsened by changes in water temperature and flow rates as a result of climate change and human population growth. Elevated temperatures and diseases (primarily the bacterial disease columnaris) were the major causes of the deaths of 33,000 Chinook salmon in the lower Klamath River in 2002 (California Department of Fish and Game, 2003).

#### 7.3.2.4 Effects of community interactions and invasive species

Biotic interactions (competition, predation, etc.) have major influence on the performance of freshwater fishes. Many native species are territorial and compete for feeding positions, hiding cover, and spawning locations. In the Umpqua River, Oregon, juvenile steelhead trout were dominant over redbreast shiners and occupied the most effective feeding locations at temperatures less than 15°C (59°F) (Reeves et al., 1987). However, at temperature above 19°C (66°F), redbreast shiners were dominant and steelhead growth rates declined. In the Rocky Mountains, native cutthroat trout and non-native brook trout were equally competitive in feeding at 10°C (50°F), but brook trout were more efficient in feeding at 20°C (68°F) (DeStaso and Rahel, 1994).

Predation is a major biotic interaction that strongly influences the survival of freshwater fishes. As described earlier, shifts in the timing of migration may expose fish to higher predation in freshwater or marine environments than they would experience under current run timing (Holtby et al., 1990). Consumption of juvenile salmonid fishes by northern pikeminnow (*Ptychocheilus oregonensis*), smallmouth bass (*Micropterus dolomieu*), and walleye (*Sander vitreus*) was greatest as temperatures increased in midsummer (Vigg et al., 1991). In addition, fish may be less able to avoid predators under thermal stress. Chinook salmon were less able to avoid predatory northern pikeminnow at temperatures higher than 20°C (68°F) (Marine and Cech, 2004). Migrating juvenile salmon in the Willamette and Columbia Rivers use shallow margin habitats (Friesen et al., 2004; Tiffan et al., 2006). Increasing temperatures in these lateral habitats would cause these migrating juveniles to move to deeper waters and experience greater risk of predation (Poe et al., 1991).

Many non-native fish species that have been introduced into the Pacific Northwest are warm-water species. There are increased proportions of non-native species and decreased richness of native species in warmer reaches of the Willamette River (Hughes et al., 2005). Non-native species can cause extensive habitat degradation (e.g., carp, catfish), prey on native fish species (largemouth bass, smallmouth bass, walleye, yellow perch, bluegill, warmouth, etc.), hybridize with native species (e.g., brook trout and bull trout), and compete with native species for habitat and food resources. Many invasive species benefit simply from increased maximum temperatures, but increased minimum temperatures in winter may allow non-native species to successfully invade streams and rivers where they currently are excluded by low winter temperatures. Distributions of non-native species have been documented in the Pacific Northwest (LaVigne et al., 2008), but there has been little research on factors that determine their success or their impacts on native communities (see Case Study 7A).



#### 7.3.2.5 *Adaptation to temperature increases through contemporary evolution*

Surface water temperatures are projected to increase by roughly 2–4°C (4–7°F) over the next 100 years (Chapter 3). In many streams and rivers, these temperature increases will either exceed the lethal level for some species or lead to declines caused by physiological and reproductive stress, disease, competition, predation, or presence of invasive species at temperatures lower than lethal levels. This scenario assumes that these species have no ability to adapt to changing temperature. Recent research in New Zealand observed that fall Chinook salmon transplanted from the Sacramento River in 1901 and subsequently outplanted or migrating to warmer rivers in New Zealand have evolved in response to the warmer rivers (Quinn et al., 2001; Kinnison et al., 2008). In less than 30 generations, there was divergence of traits (such as age at maturity, date of return to freshwater, reproductive morphology, reproductive allocation) and shifts in physiological performance (survival and growth) (Quinn et al., 2001; Kinnison et al., 2008). Physiological responses have shifted their maximum physiological performances by as much as 2°C (4°F), indicating that some species like salmonid fishes might be able to adapt to and survive projected temperature increases. Others have observed heritable shifts in traits of sockeye salmon populations in fewer than 13 generations (Hendry et al., 2000). Ecological adaptation and contemporary evolution could allow some species to “keep up” with changing temperature regimes in the Pacific Northwest. Note that salmonid fishes exhibit faster trait divergence and evolutionary rates than many other fish species. Contemporary evolution may not be effective in helping other species of native fish adapt to climate change.

#### 7.3.2.6 *Restoration actions to moderate the effects of climate change*

The major actions that could be taken to minimize habitat losses and ecological consequences of climate change for freshwater fishes in the Pacific Northwest include (1) maintaining water volumes in streams and rivers, (2) improving water quality and habitat complexity in degraded reaches, (3) maintaining natural flow regimes to the extent possible, (4) protecting and restoring riparian and floodplain vegetation, (5) maintaining dynamics floodplains and channels, (6) protecting existing cold-water refuges, and (7) restoring watershed conditions in uplands. These actions are not novel or unique to climate change. These are conservation actions repeatedly called for by all resource management agencies in the Pacific Northwest for the last 50 years. The challenge of climate change in freshwater ecosystems is not a need to respond to a new change but rather the need to implement existing conservation strategies more widely and successfully.

Life histories of aquatic organisms in freshwaters of the Oregon are complex. Some fish species, such as rainbow trout (*O. mykiss*) and cutthroat trout (*O. clarki*), have both resident and anadromous life histories (anadromous rainbows are called “steelheads”). Responses to changes in water temperature and discharge related to climate change may include complex shifts in proportions of life history types, distributions, and timing of life history stages. Changes in freshwater streams, lakes, estuaries, or ocean can be modified by differences in changes in these other major regional habitats within the geographic range of the species. Management decisions will be complex, possibly amplifying, counteracting or altering the biological responses to environmental shifts related to regional climate change. Monitoring of resource trends and

anticipating alternative trajectories of change will be essential for effective adaptive management (see Case Study 7B).

Many ecosystem services, such as flood storage in river floodplains, habitat for aquatic communities, cold-water refuges, and riparian (riverbank) wildlife habitats have been dramatically reduced over the last 150 years in the Pacific Northwest as a result of channel alteration, dikes, riprap, flood control, water withdrawal, and waste discharge. River and stream channels have been straightened and hardened and channel-forming high water flows have been reduced. Floodplain forest and riparian habitats have been reduced by more than 80% in the lowlands. River temperatures have increased and many cold-water refuges along river margins have been destroyed. Restoration measures include efforts to repair channel dynamics (e.g., removal of bank-control structures, reconnection of historical alcoves and other lateral habitats), revegetation (e.g., reforestation, restoration of non-forest wetlands), decreased consumption and removal of surface water, water reuse, and matching various uses to different water-quality sources (Battin et al., 2007). The scientific and logistic challenges of these restoration efforts are substantial, but the rate of restoration mostly is limited by social constraints (e.g., land owner participation and attitude, effective incentives, policies and governance structure).

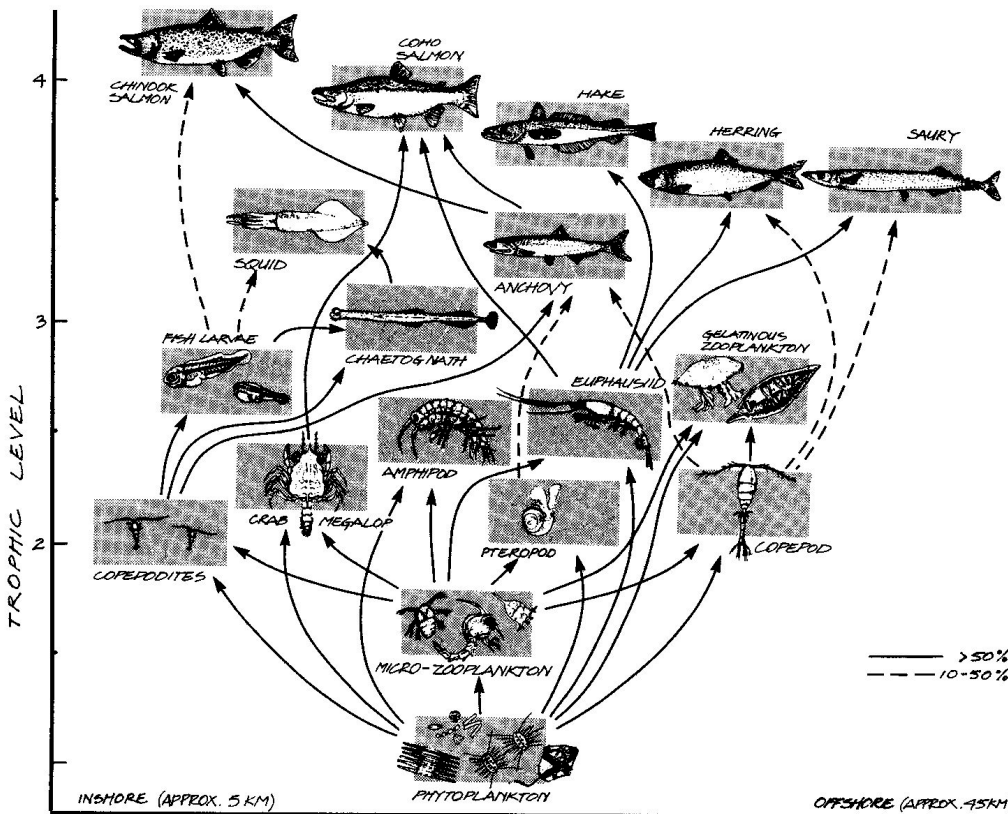
## 7.4 Ocean Life

Oregon's territorial sea extends from the beach to 3 nautical miles offshore, yet is part of a much larger ocean region known as the California Current Large Marine Ecosystem (Sherman, 1991). The chemical and physical properties of Oregon's ocean environment, including past and predicted changes due to warming and acidification, are reviewed in Chapter 1. Regarding sea life, our region is part of the Columbian Pacific Marine Ecoregion, extending coastally from Vancouver Island south to Cape Mendocino in northern California (Wilkinson et al., 2009). A region of seasonal upwelling that fertilizes nearshore waters and supports a productive ecosystem, Oregon's territorial sea and numerous estuaries at the mouths of major watersheds support a broad variety of plant and animal life of immense ecological, cultural and economic value, especially in terms of tourism and fishing.

This rich cornucopia of ocean species lives as a web of consumers and prey (Fig. 7.7), the basis of which are the tiny, single-celled, drifting phytoplankton that are the grasses of the sea. These plant-like organisms are eaten by zooplankton, tiny drifting animals that include both permanent forms and the early life stages (larvae) of fishes and larger invertebrates. Many larger animals eat zooplankton, and so the web builds upwards to the top predators, including large fishes, seabirds, marine mammals, and, of course, humans. Because this complex food web interconnects so many species, and because each part of the web faces specific issues with respect to ocean warming and acidification, this section covers in turn phytoplankton, zooplankton, seafloor life, fishes and fisheries, seabirds, and marine mammals.

It is important to keep in mind that predicted future changes in each of these groups of sea life will propagate through the entire food web in ways that may not be predictable. Such indirect

effects include both bottom-up processes, involving changes in the productivity of phytoplankton and seaweeds that feed higher levels in the food web, as well as top-down processes, involving changes in the distribution and abundance of top predators that affect lower levels. Overall, it is highly likely that substantial surprises will be forthcoming in ocean ecosystems during this century as the ocean warms and acidifies.

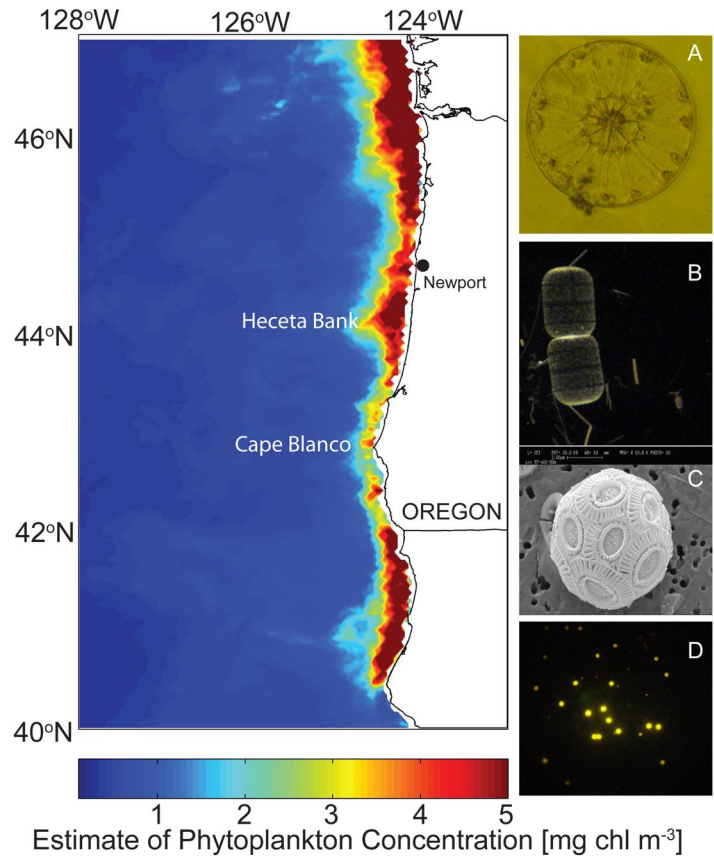


**Figure 7.7** Partial food web in Oregon's ocean. Arrows flow from prey to predators, with dashed arrows representing minor links (10–50% consumption). Lower trophic levels feed higher trophic levels. Many species are missing, including larger fishes, seabirds, marine mammals, and human fisheries, as well as all seafloor species. (From Oregon Ocean Resources Management Task Force, 1991.)

#### 7.4.1 Phytoplankton: base of the ocean food web

The term phytoplankton, from the Greek “phyton” (plant) and “planktos” (wanderer), encompasses all microalgae and bacteria that, in the same manner as terrestrial plants, are able to use inorganic nutrients and sunlight to fuel photosynthesis, growth and reproduction. Although they are generally small in size, ranging from 1 to 50  $\mu\text{m}$  (micrometer), phytoplankton are responsible for the production of food and energy that supports most forms of life in the coastal marine environment (Fig. 7.7). Although most phytoplankton are harmless to higher trophic levels—including humans—a few species can develop into harmful algal blooms. Living at the base of the food web, phytoplankton will be the first responders to climate change. Thus,

efforts to monitor alterations in the patterns of abundance, diversity and activity of this vital component of the ocean ecosystem are necessary to inform our understanding of potential impacts on higher trophic levels.



**Figure 7.8.** Annual mean phytoplankton concentrations for the Oregon region in 2009, where blue represents low levels and red, high levels. The location of Newport, the coastal outcropping at Cape Blanco, and the offshore rocky region, Heceta Bank, are noted. Images to the right illustrate phytoplankton groups common to local waters, including (A–B) diatoms, (C) coccolithophores, and (D) small single-celled cyanobacteria.

#### 7.4.1.2 Variation in time and space

The marine environment over the continental shelf off the Oregon coast supports a large diversity of phytoplankton (Fig. 7.8), including all major classes of microalgae and photosynthetic bacteria (Rappe et al., 1998). However, the abundance of these classes varies in space and time, with primitive microalgae dominating in coastal regions and during periods of high nutrient concentrations, while small marine unicellular photosynthetic bacteria increase in relative abundance as nutrient and productivity levels decrease offshore. Furthermore, phytoplankton concentrations and productivity display a strong seasonal cycle, with maximum values observed during summer upwelling (Thomas et al., 2001; Chapter 1). As these upwelled, nutrient-rich waters move from the coast into the open ocean, phytoplankton grow, remove excess nutrients and form large accumulations (termed "blooms") that ultimately support higher trophic levels and enhance fishery yields.

The accumulation of phytoplankton along the Oregon coast is not uniform as the distributions of these photosynthetic organisms are affected by ocean currents, seafloor contours, and river inputs (Barth and Wheeler, 2005). For example, during summer months, the southward movement of the Columbia River plume acts as a boundary for the offshore extent of elevated concentrations of phytoplankton along the northern Oregon coast. South of Newport, phytoplankton blooms move offshore, as currents flow around the west side of the prominent Stonewall and Heceta Banks and then return to the coast (Barth 2003). The return flow often tends northward, making these banks retentive features that contribute to the accumulation of organic matter resulting from phytoplankton productivity. Finally, the outcropping of Cape Blanco is another topographic feature that forces coastal currents offshore, transporting plankton into the open ocean as well as creating a region of high retention for phytoplankton and larvae south of the Cape. Thus, during the summer months, Heceta Bank and Cape Blanco are zones of persistent and elevated productivity, supporting major fishing grounds. In contrast to the summer upwelling dynamics, the delivery of nutrients into the coastal ocean by rivers becomes an important factor during winter months, affecting the growth and distribution of nearshore phytoplankton. Recent studies suggest that inputs from rivers contribute significantly to the availability of iron and other essential micro-nutrients in these coastal ecosystems (Chase et al., 2007).

In addition to seasonal and latitudinal variability in phytoplankton production, there is also strong between-year variability caused by two main factors: (1) the onset and strength of the upwelling season, and (2) the occurrence of El Niño events. The timing and strength of the upwelling season, possibly caused by the latitudinal position of the jet stream in the upper atmosphere (Bane et al., 2007, Barth et al., 2007) or other atmospheric forcing anomalies (Schwing et al., 2006), not only affects the delivery of nutrients to the well-lit upper layers of the water column, where phytoplankton have sufficient light to grow, but also can delay the transfer of energy to higher trophic levels (Barth et al., 2007). This timing of food availability may be critical to species with strong seasonal reproductive or migratory cycles.

El Niño events, as well as longer-term inter-decadal changes in ocean conditions over the North Pacific, termed the Pacific Decadal Oscillation (PDO, see Chapter 1), can bring warmer waters along the Oregon coast that appear to displace zooplankton populations northward, and probably phytoplankton species as well (Peterson and Keister 2002). In addition, these warm waters deepen the position of cold and nutrient rich waters along the coast, causing a reduction in the availability of nutrients in the well-lit surface layers that support phytoplankton growth and accumulation during the upwelling season. As a result, fisheries production typically drops during El Niño events and warm phases of the PDO (Pearcy and Schoener, 1987; Mantua et al., 1997).

#### *7.4.1.3 Effects of climate change*

Although we do not have extensive data characterizing long-term changes in phytoplankton abundance, diversity, and productivity in response to climate trends, we can still assess the potential effects of predicted changes in environmental factors (previously described in Chapter 1). At a regional scale, long-term changes in the position of the upper atmospheric jet stream affect the timing and duration of upwelling, and hence the delivery of nutrients to the surface

ocean and the magnitude of annual primary production in coastal waters. In addition, these changes have substantial effects on annual precipitation and evaporation over the continent, causing changes in the magnitude of terrestrial nutrient inputs to coastal ecosystems through river discharges. However, land and water use changes in the Columbia and Klamath Basins may need to be considered when assessing long-term changes in river inputs along the Oregon Coast and their impact on coastal phytoplankton dynamics (see Chapter 3).

At a broader scale, potential changes in the dynamics of the offshore North Pacific Ocean, including changes in large-scale currents and increasingly warm surface waters that form a barrier to vertical mixing, may affect the chemical composition of seawater being delivered to and upwelled near the coast of Oregon. Several recent studies have suggested that significant changes in water chemistry can already be observed at large scales, including a decrease in oxygen content (Chan et al., 2008) and an increase in acidity (Feely et al., 2009). Alterations of the rate and magnitude of the delivery of nutrients to the surface ocean could not only alter primary productivity but also lead to changes in the decomposition of this organic matter and a biological drawdown of oxygen (via respiration) which could worsen regions of hypoxia, better known as “dead zones.”

#### *7.4.1.4 Dead zones*

Off the coast of Oregon, hypoxic (low oxygen) and anoxic (effectively no oxygen) events have affected both the water column and the benthic environment during the past decade (see also Sections 7.4.2 and 7.4.3). However, the strength and duration of these events displays strong inter-annual variability (Grantham et al., 2004; Chan et al., 2008) resulting from chemical properties of upwelled water, the strength and frequency of upwelling favorable winds along the coast (see Chapter 1), and the ensuing rates of primary production and subsequent microbial respiration over the continental shelf. Although the production and sedimentation of organic matter by phytoplankton plays an important role in the enhancement of hypoxic and anoxic environments over the shelf, it is less clear how the reduction of oxygen in subsurface waters affects phytoplankton diversity and abundance in surface waters. A loss of upwelled nutrients through denitrification (nitrogen gas releasing) processes in hypoxic waters can also occur. However, this loss is relatively small compared to the availability of nutrients during upwelling periods. In coastal regions experiencing severe hypoxia during summer months, such as the central coast of Chile and off Peru, phytoplankton abundance and diversity in surface waters remains high (Escribano et al., 2003), suggesting that an expansion in space and time of hypoxia over the Oregon continental shelf will primarily affect higher trophic levels, subsurface and seafloor microbial processes, and the nutrient cycles they control.

#### *7.4.1.5 Ocean acidification and phytoplankton*

The human-induced rise in atmospheric carbon dioxide (CO<sub>2</sub>) and subsequent transfer of a portion of this anthropogenic CO<sub>2</sub> to the oceans may also impact the chemical and biological function of our ecosystems (Doney et al., 2009). By removing CO<sub>2</sub>, oceanic uptake has slowed the pace of human-induced climate change while creating another problem: a change in ocean carbonate chemistry and a decrease in ocean pH levels. This phenomenon, termed “ocean acidification,” has already led to a decrease in the mean pH of the California Current system to

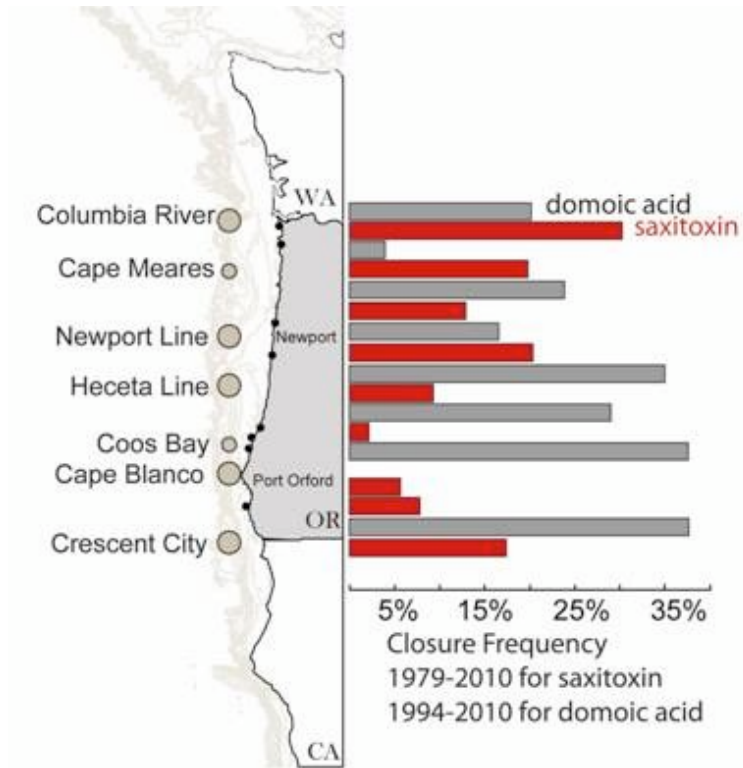
levels that previously were not expected to occur for decades (Hauri et al., 2009). It is not clear to what extent these changes have affected the diversity and activity of phytoplankton. However, output from models and our understanding of the physiology of organisms cultured in a laboratory setting suggest that there will be clear winners and losers emerging as the ocean acidifies (Doney et al., 2009; Hauri et al., 2009).

#### 7.4.1.6 Harmful algal blooms (HABs)

Major groups of phytoplankton observed along the Oregon coast include a variety of types and cell sizes (Anderson, 1965; Sherr et al., 2005). As outlined above, phytoplankton form the primary source of food sustaining coastal fisheries. However, phytoplankton blooms can also be detrimental to local ecosystems and the economy. Although we have adequate knowledge of the major factors controlling the distribution of total phytoplankton abundance and productivity along the Oregon coast in time and space, we still have only a rudimentary understanding of the factors controlling variability in the distributions of particular species of phytoplankton. The issue of which species dominate the composition of phytoplankton is of particular importance when trying to characterize and predict the abundance of species that have a strong negative impact on human health and the local economy. Some of these species include those that generate harmful algal blooms (HABs).

Of the major phytoplankton groups, diatoms and dinoflagellates are known to include species that can have adverse ecological and socioeconomic effects through the generation of HABs off the Oregon coast. Of particular interest are the diatoms *Pseudo-nitzschia* spp., and the dinoflagellates *Alexandrium* spp. and *Akashiwo sanguinea*. Certain, but not all, strains of *Pseudo-nitzschia* produce a neurotoxin called domoic acid which accumulates in coastal shellfish such as razor clams and mussels and can lead to amnesic shellfish poisoning (ASP) in humans. Similarly, armored dinoflagellates of the genus *Alexandrium* produce saxitoxin, a potent neurotoxin responsible for paralytic shellfish poisoning (PSP) in humans (Horner et al., 1997).

Long-term monitoring efforts off the Oregon coast indicate that *Alexandrium* blooms appear to predominate south of Cape Blanco, whereas along the central and northern Oregon coast, *Pseudo-nitzschia* seems to be the major group responsible for HABs and the closure of commercial shellfisheries (Fig. 7.9). In addition, the dinoflagellate *Akashiwo sanguinea* was responsible for an extensive bloom off Washington and northern Oregon in 2009 that caused significant seabird mortality as a result of algal production of chemicals that dissolved the natural oils found in feathers. Without these oils, seabirds can lose body heat and die of hypothermia (see Section 7.4.5).



**Figure 7.9** Left: Current sites in the Oregon surf zone (dots) and offshore sampling lines (circles) sampled for harmful algal blooms relative to ocean depth contours (gray lines). Regions near the Columbia River outflow, Heceta Bank and Cape Blanco are sites of strong summer phytoplankton blooms. Right: The percentage of positive samples exceeding shellfish fishery closure limits are shown as bars for domoic acid (grey) and saxitoxin (red) at different latitudes along the coast.

HABs have afflicted the west coast of the United States for decades. However, over the past 15 years their frequency has increased significantly (Hallegraeff, 1993; Anderson et al., 2008). In Oregon, HAB events have led to more frequent closures of commercially important razor clam and mussel fisheries and exerted a considerable economic impact on coastal communities in Oregon.

At present, although we understand the environmental conditions leading to the development of phytoplankton blooms along the Oregon coast, we still do not know what combination of physical, chemical, and biological factors select for the development of a specific harmful algal bloom. Recently, Tweddle et al. (2010) reported that saxitoxin contamination of mussels south of Cape Blanco is strongly associated with late-summer upwelling. Thus, latitudinal variations in upwelling expected under various climate change scenarios (Bakun, 1990; Schwing and Mendelssohn, 1997) may significantly affect the frequency and distribution of this HAB along the west coast. For this reason, the effect of both the timing of upwelling and the spatial patterns of bloom formation along the Oregon coast must be better understood to improve our capacity to assess how and to what extent climate change may affect the diversity of phytoplankton species that cause harmful algal blooms.



### 7.4.2 Zooplankton: Food for Sea Life

Zooplankton are small animals—often 0.2 to 40 mm (0.008 to 1.6 in) in body length—that inhabit open marine waters, including the estuaries, nearshore ocean, and offshore areas off Oregon. Zooplankton are diverse, with representatives from most major animal groups (phyla). Peterson and Miller (1976) found close to 100 species of zooplankton (excluding protists) on the inner-middle continental shelf of Oregon, with the greatest diversity within the copepods (estimated 58 species). Some of the most important zooplankton in our region are tiny and relatively poorly studied protists (Neuer and Cowles, 1994), euphausiids (Gomez-Gutierrez et al., 2005), copepods (Peterson and Miller, 1975, 1976), and a group collectively known as gelatinous zooplankton: pelagic tunicates (salps and doliolids) (Lavaniegos and Ohman, 2007) and jellyfish of various kinds (Suchman and Brodeur, 2005). Some gelatinous zooplankton are relatively large, and in some summers can become very abundant, with blooms developing rapidly. However, these events are intermittent, often short-lived, and difficult to predict or relate to specific ocean conditions.

This review considers only euphausiids (commonly called "krill") and copepods for two reasons. First, euphausiids and copepods, especially the latter, dominate the abundance and species diversity of mid-sized zooplankton off Oregon, and second, the other types of zooplankton have not been sufficiently studied to examine seasonal and interannual variability and long-term trends. The life spans of many copepods are several weeks to 4–5 months, while the dominant euphausiids off Oregon have 1–2 year life spans. These mid-sized zooplankton are important ecologically because they are a key conduit for the transfer of photosynthetic production by phytoplankton (Section 7.4.1) to higher trophic levels, such as forage fish, harvested fish species, and marine birds and mammals (Sections 7.4.4–7.4.6). The type of copepods, their individual size, and their lipid (fat) content, may be important in determining whether the food web of the Oregon shelf is good or bad for growth and survival of organisms at higher trophic levels, such as anchovies and salmon (Fig. 7.4.A). Because of their small size and relatively weak swimming ability, zooplankton drift with the ocean currents. Thus, unlike stronger swimming fish, their distributions are strongly controlled by physical processes rather than biological movements.

#### 7.4.2.1 Variation in time and space

Climate variability may affect zooplankton populations in several ways, perhaps altering species composition, relative abundances, reproductive output, and the magnitude and timing of changes in these factors. Also, because zooplankton, by definition, drift with ocean currents, species distributions may change due to altered currents. Many of these factors are unknown for most species, and what is known focuses on zooplankton variability derived from sustained sampling programs off the coast of Oregon. In some cases, zooplankton patterns off northern California or southern British Columbia are similar to those off Oregon (e.g., Mackas et al., 2004, 2006), and so provide information relevant to Oregon. Temporal variability in zooplankton biovolume is spatially coherent along the coast of California (Chelton et al., 1982; Roesler and Chelton, 1987). Given significant alongshore covariability of zooplankton biomass within the California Current Large Marine Ecosystem, it should be noted that Roemmich and McGowan (1995ab) reported that the total biomass of zooplankton off southern California declined by 80%

between the late 1960s and the mid-1990s. However, this result has been rebutted by several subsequent papers (Lavaniegos and Ohman, 2003, 2007) that showed that zooplankton biovolume (used by Roemmich and McGowan) was biased by the decline of pelagic tunicates, which have large biovolumes but small carbon biomass. There was in fact no long-term trend in total zooplankton carbon biomass nor of the dominant planktonic copepods or euphausiids off southern or central California, in contrast to the earlier reported multidecadal decline in zooplankton biovolume (Lavaniegos and Ohman, 2007).

The section of Chapter 1 on physical changes in the marine environment concludes that, during the past 30–50 years, Oregon's coastal ocean has experienced (1) increased intensity of upwelling, (2) increased variability of upwelling, (3) increased summer water temperatures, (4) reduced spring-summer Columbia River discharge of freshwater, (5) decreased summer salinity of subsurface waters, and (6) declines in near-bottom oxygen concentrations, especially close to shore. Zooplankton off Oregon are strongly influenced by both regional coastal and global marine environmental factors. Important regionally is the seasonal influence of alongshore winds that affect upwelling of deeper nutrient-rich waters, and the role of freshwater from the Columbia River (Huyer et al., 2007). In the winter, winds blow from the south along the Oregon coast. This causes surface waters to move onshore, and pile-up at the coast, pushing inshore waters downward in the water column and offshore, a process called "downwelling." However, sometime in spring, often in April but varying in time from year to year (Pierce et al., 2006), the large-scale atmospheric pressure systems over the Pacific and North American continent shift, and the wind off Oregon shifts to blowing from the north, a seasonal change known as the "spring transition" (Checkley and Barth, 2009). With southward winds, surface water is pushed offshore and is replaced near the coast with water that ascends from deeper depths, a process called "upwelling." Upwelled water is cold, salty and rich in the inorganic nutrients required to fuel photosynthesis by phytoplankton (see Chapter 1 and Section 7.4.1). The copepods, euphausiids and gelatinous zooplankton consume phytoplankton to support their growth and reproduction. A second effect of the change in wind direction is that, prior to the spring transition (e.g., in winter), alongshore flow is primarily from the south, transporting zooplankton species that are more common in California northward into Oregon waters. After the spring transition (e.g., in summer), alongshore flow is to the south, transporting northern species of copepods to Oregon.

Oregon's ocean is also affected by changes occurring elsewhere in the Pacific Basin. For instance, changes in atmospheric pressure systems, winds and ocean surface temperatures in the equatorial Pacific associated with El Niño can have effects that influence seawater characteristics and temperatures as well as species composition and abundance of zooplankton off Oregon (Peterson et al., 2002; Keister et al., 2005). Longer-term, interdecadal changes in North Pacific atmospheric pressure systems and ocean conditions—the Pacific Decadal Oscillation—can change ocean current strengths and water temperatures off Oregon that affect the species composition, distribution and abundance of zooplankton and fish off Oregon over periods of years (Batchelder et al., 2002; Peterson and Schwing, 2003).

To evaluate whether climate change affects zooplankton biomass or community structure, one must first examine and account for the influence of seasonal factors and between-year variability on zooplankton. Off the U.S. west coast generally, two specific North Pacific climate

indices, the Pacific Decadal Oscillation (PDO) and the North Pacific Gyre Oscillation (NPGO) (Di Lorenzo et al., 2008), explain significant annual-to-decadal variability in temperature, salinity, nutrient concentrations, phytoplankton and zooplankton. Hooff and Peterson (2006) documented the mean seasonal cycle of copepod biomass and number of species at a permanent station off Newport. Both measures exhibited strong seasonality reflecting the influence of upwelling on productivity (abundance is highest during the May to September summer upwelling) and coastal currents (number of species is lowest during May to September). The number of species reflects the influence and mixing of different sources of seawater that have different copepod species, with northern sources having generally fewer species than southern sources. To remove the strong seasonal influence, we focus here on the summertime (May to September) period, where abundance is high and species richness relatively low. Using data collected from the summers of 1969–2007, we find that the number of copepod species and the biomass of warm water copepods is greatest when the PDO index value is positive and the ocean off Oregon is anomalously warm, and that there is not a long-term “ocean warming” trend in total copepod biomass (including both cold and warm water types). Using data from Hooff and Peterson (2006), Peterson (2009) argued that copepod species richness on the inner-shelf of central Oregon has increased by 2–3 species over this 40-year interval. However, an analysis that accounts for the effect of the PDO on the number of species during the summer months, suggests that there has been no detectable long-term increase in the number of copepod species in our region (Batchelder and Peterson, unpublished data).

Mackas et al. (2007) recently summarized changes in zooplankton in the region immediately to the north of Oregon during 1979–2005. Their results have some relevance to the Oregon region because many of the seasonally dominant species off Oregon are shared with British Columbia (BC). Overall, zooplankton populations between Oregon and BC have exhibited northward latitudinal shifts in their geographic centers of abundance in response to episodically warm conditions (Mackas et al., 2001; Batchelder et al., 2002; Peterson and Keister, 2003; Keister et al., 2005). Throughout this period, biomass of northern copepods and southern copepods have varied inversely. Northern copepods increase off Oregon and BC when temperatures are cool and southward currents are stronger, while southern copepods are associated with warm temperatures and northward transport. This effect is most evident during strong El Niños and La Niñas (the opposite conditions of El Niño), but is also observed in relation to longer-term temperature fluctuations associated with the PDO (Mackas et al., 2004; Keister and Peterson, 2003; Keister et al., 2005). These PDO-associated variations in species composition between “northern” and “southern” species influences the overall bioenergetic content of the food web—northern species are lipid-rich whereas southern species are lipid-poor (Lee et al. 2006). Thus, fish such as salmon which need lipid-rich prey (euphausiids and small pelagic fishes such as smelts and anchovies) have higher survival when cold water zooplankton dominate. Similar shifts in species composition and community structure have been observed in four copepod species assemblages in the Northeast Atlantic (Beaugrand et al., 2002). Such changes may become more common as ocean warming progresses, with effects on other zooplankton species (which may also move northward), as well as on higher trophic levels that are accustomed and adapted to feed on the “normal” zooplankton that were typical until recently.

The large copepod *Neocalanus plumchrus* is abundant in the Gulf of Alaska and off Canada, but is usually less important off Oregon (but see Liu and Peterson, 2010). Mackas et al. (2007) have

documented phenological (life history timing) changes in *N. plumchrus* that appear to be due to warming of the surface waters providing faster growth and development. The same observation has been made off Oregon (Liu and Peterson, 2010). Interestingly, in 2007 and 2008, copepods of the genus *Neocalanus* have been more important and constituted a greater fraction of the spring zooplankton biomass on the Oregon continental shelf than during earlier years. Since these species are typical of northern waters, this pattern suggests that there was greater southward inflow to the Oregon system during those years. The cause of this sudden brief increase in biomass is not known.

#### 7.4.2.2 Ocean acidification and zooplankton

Observed and projected human-caused increases in atmospheric concentrations of the greenhouse gas carbon dioxide suggest that concentration of this greenhouse gas in seawater has increased and will increase, increasing the acidity of the ocean as carbon dioxide reacts with water and forms carbonic acid, a phenomenon called "ocean acidification" (OA). Regions of the west coast, including Oregon, have recently been found to be particularly susceptible to OA, due to the upwelling of deep waters having high carbon dioxide content and low pH (Feely et al., 2008; Hauri et al., 2009). More acidic conditions reduce the availability of carbonate ions to marine organisms that form calcium carbonate (essentially, limestone) skeletons or shells. One group of zooplankton, the pelagic pteropod snails, use calcium carbonate to form their thin and fragile shell, and are particularly susceptible to more acid ocean conditions (Orr et al., 2005; Fabry et al., 2008). The ability of these pelagic snails to form or maintain the integrity of their shells is reduced in more acidic waters. The pteropod *Limacina helicina* was present in more than half of the Oregon nearshore samples of Peterson and Miller (1976), and was most abundant in May and June. Seasonal upwelling enhances the development of high acidity, corrosive waters in spring and summer, which might affect these marine snails. To date, there have been no specific studies to evaluate shell dissolution rates or growth rates of these snails off Oregon, but studies on *L. helicina* elsewhere suggest they experience significant shell dissolution in high carbon dioxide waters (Orr et al., 2005). One ecological significance of pteropods is that they are prey for the larvae of some marine fishes.

In summary, because of a concerted and ongoing effort to sample zooplankton at a variety of scales of time and space during the past decade off Oregon, we have learned much about the temporal and spatial patterns of fluctuations in abundance and species composition. However, this decade of sampling has also shown the tremendous amount of variability in "climate forcing" and how that has influenced the ocean ecosystem, including the zooplankton. Several "anomalous" events, including (1) one of the strongest recorded El Niños in 1997–1998, (2) a strong La Niña in 1999, (3) a prolonged three-year cold period through 2003, including anomalously strong southward flow of subarctic waters in 2002, and (4) a very late spring transition to upwelling in 2005, have clearly shown that the zooplankton assemblage, production, and abundance respond strongly and rapidly to environmental variation at multiple spatial scales. This variability is superimposed on strong seasonal cycles. Although there are hints of how zooplankton populations on the Oregon shelf may respond to climate variability and global warming, there are no well documented trends as yet that indicate clearly the direction or magnitude of future changes. Clearly two physical factors seem to control species composition and rates of production, the Pacific Decadal Oscillation and strength of

local upwelling. However, it is not clear how either will change in the future (Chapter 1). Only a handful of global climate models include the PDO, but those that do project that the PDO will continue into the future (Wang et al., 2010). Bakun (1990) suggested that local upwelling will intensify due to stronger gradients between the North Pacific high and the low pressure system centered over the western United States, yet there is as yet no evidence that this is happening.

### **7.4.3 Seafloor Species: Invertebrates and Seaweeds**

The responses of seafloor-dwelling invertebrates and seaweeds to ocean warming and acidification are likely to be complex, with a host of factors changing and a variety of consequences arising (Harley et al. 2006). Evaluating how seafloor species along the Oregon coast have responded to climate change is severely compromised by the general lack of long-term data sets on these organisms. Although research on populations and communities of organisms that live along the Oregon shore has been ongoing for decades, funding patterns typically have limited the duration of studies to relatively short periods, usually a few years at a time. The primary exception has been research on rocky intertidal zones conducted by the Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO) program, a consortium of four universities along the U.S. west coast, with Oregon State University as the lead institution (<http://piscoweb.org>).

If one moves beyond Oregon to consider the entire coast of the California Current Large Marine Ecosystem (CCLME), which ranges from the Straits of Juan de Fuca in Washington to the tip of the Baja California peninsula, a few additional data sets become available. The following summarizes trends seen in these limited data sets, focusing first on Oregon and then adding insights obtained from the broader CCLME. Examined are the extents to which these changes may reflect responses to climate change, and conclusions focus on the kinds of threats faced by marine organisms from well-documented changes that are currently underway in the climate of the northern CCLME (Chapter 1).

#### *7.4.3.1 Rocky intertidal invertebrates*

Data gathered for up to 20 years along the Oregon coast have revealed that the abundance of phytoplankton and the recruitment of mussels (clam-like species that attach to rocks) increased dramatically during the 2000s (Menge et al., 2009). Mussel growth rates have also increased in response to the increases in phytoplankton, an important food source for mussels, which filter such food particles out of seawater (Menge et al., 2008). These changes are linked to climate fluctuations, as reflected in El Niño Southern Oscillation (ENSO), the North Pacific Gyre Oscillation (NPGO), and the Pacific Decadal Oscillation (PDO) (see Chapter 1). Such climatic cycles vary in duration from the relatively short ENSO (3–7 years) to moderate NPGO (10–15 years) to long PDO (20–30 years). Each has been found to underlie major natural shifts in marine ecosystems (e.g., Glynn, 1988; Chavez et al., 1999; Peterson and Schwing, 2003; Di Lorenzo et al., 2008).

Off Oregon, strong links have been detected between the NPGO and large increases in phytoplankton and mussel recruitment (Menge et al., 2009). ENSO and PDO did not appear to

have an influence, suggesting that the 10–15 year shifts in winds that are reflected in the NPGO are the primary drivers of these changes. The suggested mechanism causing this link is that, with stronger winds over the North Pacific, coastal phytoplankton blooms are denser, leading to higher survival of larvae of mussels, and perhaps more favorable conditions for movement of larvae to the rocky shore. Whether or not these changes are a result of climate change is not clear as data sets are not yet long enough to resolve long-term trends.

The rate of mussel growth is a potentially valuable indicator of mussel well-being. Faster growth resulting from higher food likely decreases the time to maturity and enhances reproductive output. Faster growth also influences competitive ability; in the mussel world, large size means an ability to overgrow and smother other organisms competing for attachment space on rock surfaces (Paine 1966). The increase in phytoplankton in the 2000s led to a surge in growth of mussels along the Cape Foulweather region of Oregon, which brought their growth on par with mussels along the Cape Perpetua region to the south, but did not change growth rate in the latter region (Menge et al., 2008). This finding likely indicates that mussel feeding capacity is limited (e.g., Hawkins and Bayne, 1992), such that, above some threshold level, mussels are unable to consume additional food. In this case, mussel growth was linked to both ENSO and PDO climate patterns, with faster growth occurring during warm-phase events of both of these cycles. This pattern indicates that temperature also affects mussel growth. The stimulating effect of warmer water likely is limited because, like most invertebrates, mussels have an upper temperature tolerance limit, beyond which they die (Somero 2002, Jones et al. 2009). This link to water temperature, which has shown long-term increases over the Oregon continental shelf (Chapter 1), predicts that mussels will initially benefit from warming of coastal waters, but unless they can adapt rapidly, will eventually decline.

How have intertidal ecosystems responded to these changes in the coastal ocean? Have mussels become more abundant? Scientists have thus far found no persistent change in the abundance of mussels, barnacles, and other rocky intertidal organisms (Menge et al., 2010). Thus, despite recent large inputs of new mussels, the abundance of large mussels has not yet changed. The reasons for this lack of response are unknown. In contrast to mussel recruitment, barnacle recruitment did not change in the 2000s (Menge et al., 2010). This result is important because the tiny mussel recruits depend on the textured surfaces provided by barnacle populations already attached to the rock. So, if barnacle populations have not changed, there is no way for mussel colonization to increase despite the large numbers of larvae seeking an attachment location. This result suggests that responses to climatic variation differ among the different species of the rocky intertidal ecosystem.

At present, our ecological information for rocky intertidal invertebrates in Oregon is limited to the above summary, which is clearly inadequate for detection of responses related to climate change. The linkage of some of these patterns or processes to climatic variation, which is expressed in physical conditions such as air or water temperature, wind and current strength, upwelling intensity, wave height, sea level height, and other factors (Chapter 1), potentially could inform forecasts of expected biological changes. When considered in the context of entire ecosystems, however, such efforts are likely confounded by multiple sources of complexity, as suggested by the differential responses of mussel and barnacle recruitment. Thus, one can presently say little that is definitive about how rocky intertidal systems in Oregon are

responding to climate change, or about how they will respond in the future, although modeling approaches may help.

#### 7.4.3.2 *Rocky intertidal seaweeds*

The ecological survey data referenced above also have not revealed any longer-term changes in abundances of seaweeds and other marine plants. Although losses in abundance of giant kelp have been attributed to El Niño events in California (e.g., Paine, 1986; Dayton et al., 1999), no response of intertidal seaweeds (or invertebrates) to El Niño conditions was detected in moderately long-term studies on Tatoosh Island, Washington (Paine, 1986). On the Oregon coast, however, the 1997–98 El Niño led to massive losses of intertidal kelps, such as *Saccharina sessile* and *Lessoniopsis littoralis* (Freidenburg, 2005), likely due to a combination of warm water and low nutrients. Complete recovery occurred within two years, however, and no comparable changes have occurred since, despite the occurrences of weak El Niños in 2003, 2005 and 2007. These perturbations suggest that at least kelps (the large brown algae that dominate kelp forests and exposed rocky shores) would be negatively affected by large increases in temperature and sharp declines in nutrients associated with a warming ocean. As noted in Chapter 1, data are insufficient to determine long-term trends in nutrients, but seawater temperatures off the Oregon coast have definitely been rising, thus suggesting potential negative effects through time. But as also noted in Chapter 1, and as predicted by Bakun (1990), upwelling intensity has been increasing as well, implying colder summer temperatures and higher nutrients inshore, up to about 10 km (6 mi) from shore. These changes may positively affect nearshore marine ecosystems.

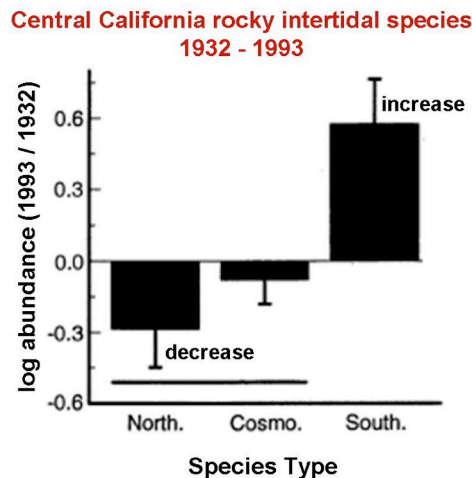
#### 7.4.3.3 *Ocean acidification and rocky intertidal species*

A potentially more serious effect of climate change is acidification of seawater as excess atmospheric carbon dioxide absorbed by the oceans is converted to carbonic acid, which lowers the pH (Orr et al., 2005). Ocean acidification has been forecast as an issue of great concern by chemical oceanographers (e.g., Orr et al., 2005; Doney et al., 2009; Feely et al., 2009), and changes in the acidity of seawater have already been detected (Feely et al., 2004; Fabry, 2008). Importantly, a recent survey of waters along the coast of Oregon and northern California revealed that seawater acidity and levels of aragonite saturation (a measure of the ability of calcifying organisms to precipitate carbonate-based hard parts such as shells) are already at levels not forecast for another 150 yr for the ocean in general (Feely et al., 2008). Thus, it is possible that calcifying species, including animals (mussels, oysters, scallops, clams, limpets, snails, echinoderms, crustaceans) and seaweeds (coralline algae), may be under severe stress in nearshore habitats of the Oregon coast (Pörtner et al., 2004; Vézina and Hoegh-Guldberg, 2008, and included papers; Kroeker et al., 2010). Field evidence suggests that these calcifiers are generally inhibited by high levels of carbon dioxide and resulting acidification of the oceans (Hall-Spencer et al., 2008), although lab studies have yielded more mixed results (Ries et al., 2009). Larvae of calcified marine invertebrates may be especially at risk (O'Donnell et al., 2009). Failure of oyster recruitment has occurred in Oregon in recent years, and studies are underway to determine whether this failure is a consequence of ocean acidification (C. Langdon, OSU, personal communication). Investigation of the impacts of acidification on calcified species in coastal environments will be a research area of high activity in the coming years. At present it is

unknown whether invertebrates and seaweeds in Oregon have already been affected by this new challenge.

#### 7.4.3.4 Changes in California rocky intertidal systems

In a recent review of how intertidal ecosystems have responded to climate change, Helmuth et al. (2006) documented 21 instances of change, yet only two of these were from the CCLME and both were in California. In central California, re-sampling in the 1990s of plots originally sampled in the 1930s revealed substantial northward shifts in distribution had occurred for 15 of 18 species (Barry et al., 1995; Sagarin et al., 1999; Fig. 7.10). Average water temperature had increased by 0.79°C (1.42°F) and average summer temperature by 1.94°C (3.49°F) over this 60-year period. In southern California, evidence suggests that the northern range limit of the whelk *Kelletia kelletii* had moved northward from about 1980 to 2000 (Zacherl et al., 2003). Finally, Smith et al. (2006) documented a sharp decline in the number of species (average 58.9% loss, maximum 80% loss) associated with intertidal mussel beds. The authors attributed these declines to climate change, but could only speculate on the specific mechanism(s) underlying the loss of species. In any case, Oregon has gained 10 species of invertebrate from California over the past three decades (Carlton, 2000).



**Figure 7.10** Relative changes in the abundance of (left to right) northern cold-water species, cosmopolitan species, and southern warm-water species of rocky intertidal organisms in Monterey, CA, between 1932 and 1993 (modified from Barry et al., 1995).

#### 7.4.3.5 Changes in estuaries

The Oregon shoreline is interrupted by over thirty major and minor estuaries that encompass a broad range of land-margin habitats located at the nexus of land and sea. Estuaries are important nursery habitats for some salmon and marine fishes, feeding habitats for shorebirds, and natural flood buffers, among other ecosystem services. The structure of Oregon's estuaries



is diverse and includes: (a) river-dominated drowned river mouths (i.e., Columbia, Umpqua, Coquille, Rogue, Chetco); (b) tidal dominated drowned river-mouths (i.e., Tillamook, Siletz, Yaquina, Alsea, Coos); (c) bar-built coastal lagoons (i.e., Netarts, Sand Lake, New River); and (d) numerous tidal creeks (Rumrill, 2006).

The combination of these meteorological and nearshore ocean changes reviewed in Chapter 1 will exert stress on the communities of estuarine organisms. The range of estuarine community responses to the climate change stressors is anticipated to include elevational shifts in the distribution of submerged aquatic vegetation, disruption of shell formation for calcifying organisms, alteration of the phenology of phytoplankton blooms, shoreward migration of tidal marshes, and increased colonization by non-indigenous aquatic species. It is important to note, however, that these anticipated shifts are largely speculative and that long-term time-series data are lacking to definitively identify perturbations of the estuarine communities that can be attributed to human caused climate change.

As one example, shifts in the acidity of nearshore ocean waters has adverse impacts on the larvae of native Olympia oysters (*Ostrea lurida*) and non-native Pacific oysters (*Crassostrea gigas*) that inhabit the intertidal zone of Netarts Bay (Langdon and Hales, personal communication). Water conditions in Netarts Bay during the summer upwelling season are influenced directly by ocean waters, and the estuary receives very little influence from the adjacent coastal watershed. Like the larvae of several other groups of marine invertebrates that require calcium carbonate for their shells and other structures (Orr et al., 2005; Kurihara, 2008), oyster larvae are sensitive to acidified marine waters, which dissolve their thin calcified shells (Miller et al., 2009). In addition, the upwelled waters that are brought to the surface along the Oregon coast (cold, hypoxic, nutrient-rich), intensified by climate change, are highly conducive to outbreaks of the pathogenic bacterium (*Vibrio tubiashii*), which is lethal to oyster larvae and early juveniles.

#### 7.4.3.6 Subtidal and deepsea species

This section focuses almost exclusively on rocky intertidal and estuarine species because subtidal and deepsea invertebrates and seaweeds are poorly studied in our region. It is nonetheless likely that seafloor species throughout Oregon's territorial sea will be affected by a warming ocean. Invertebrate species at risk include commercially valuable flat abalone (*Haliotis walallensis*), which is taken off southern Oregon (Rogers-Bennett, 2007).

It is especially important to note that, regardless of the specific habitat, shellfish and other species with calcium carbonate structures will be adversely affected by ocean acidification (Orr et al., 2005). Species at risk from acidification include Dungeness crab (*Cancer magister*), which the target of the most valuable marine fishery in Oregon. However, a recent review suggested that crustaceans (crabs and relatives) are less susceptible to ocean acidification than other calcified invertebrates (Kroeker et al., 2010). Especially at risk are deep-sea corals with calcium carbonate skeletons (Guinotte et al., 2006).

#### 7.4.3.7 Future changes

Based on species-level responses to factors expected to change in ocean waters, including acidity, temperature, upwelling intensity, sea level, and oxygen concentration, one can predict that abundances of many seafloor organisms, particularly those with calcified structures, likely will decline during this century. However, Menge et al., (2010) suggest that simple predictions based on how individual species are expected to respond may be misleading. A study on the outer coast of Washington suggests that, while some species (such as mussels) appear to have declined in abundance as ocean acidity increased over the past 10 years, others (such as barnacles and calcifying algae) did not change (Wootton et al., 2008). In this study, species interactions combined with different tolerances of acidity stress appeared to influence the changes that actually occurred. Paradoxical benefits under ocean acidification are also possible. Lab studies suggest that growth rates of the ochre sea star (*Pisaster ochraceus*) increase under high carbon dioxide regimes (Gooding et al., 2009). Fleshy seaweeds may also benefit from the future ocean, because, rates of photosynthesis may increase with higher levels of carbon dioxide (Hall-Spencer et al., 2008; Ries et al., 2009). Nonetheless, it seems likely that the future ocean will not treat most seafloor invertebrates and seaweeds well, and that the ecosystems inhabited by these organisms will undergo major disruptions.

#### 7.4.4 Marine fishes and fisheries

Marine fishes are of substantial economic and cultural value to the people of Oregon, mostly in terms of commercial and recreational fisheries, as well as sports diving. Fish distributions (where fish are found) and abundances (the number of fish) are strongly affected by changes in ocean climate, which is highly seasonal and variable off Oregon (Mantua et al., 1997; McFarlane et al., 2000; Hallowed et al., 2001; Lehodey et al., 2006). As the ocean generally warms and seawater acidifies over the course of this century, the ecology of marine fishes and fisheries in Oregon's ocean are expected to change in two basic ways.

- (1) Distributions will shift poleward (northward off Oregon) and perhaps into deeper, cooler waters.
- (2) Abundances will change, with warmer-water species increasing as cooler-water species decline.

Mechanisms causing these expected changes are both direct and indirect (reviews by Scavia et al., 2002; Roessig et al., 2004; Harley et al., 2006; Brander, 2007). Direct mechanisms involve mostly physiological effects of changes in water temperature on survival, growth, reproduction, and movements (Pörtner et al., 2004; Pörtner and Farrell, 2008). Also a direct mechanism, ocean acidification may inhibit the sense of smell in marine fishes (Munday et al., 2009; Dixon et al., 2010), although a recent review suggested that fishes may be tolerant of acidification relative to many invertebrates (Kroeker et al., 2010). Indirect mechanisms involve shifts in currents, food availability, and the structure of marine ecosystems, including diseases, predators and competitors. As reviewed below, these changes in turn are predicted to affect fisheries yields off the Pacific Northwest. In general, smaller, faster-growing, shorter-lived species are expected to respond more rapidly to climate change than larger, slower-growing, longer-lived species, as

has been documented in the English Channel (Genner et al., 2010). However, the range of possibilities in such predictions is very high due to the immense complexity of marine climates and ecosystems in general. This is especially true given that climate change will interact with fishing intensity and other human effects in unknown and perhaps synergistic ways (Scavia et al., 2002; Roessig et al., 2004; Harley et al., 2006; Brander, 2007; Hsieh et al., 2008).

#### *7.4.4.1 Shifts in fish distributions*

As active swimmers, marine fishes typically have the ability to choose the water temperatures that best fit their physiology, such that the northern and southern range limits of species often are set by temperature tolerances (Horn and Allen, 1978). Therefore, as the ocean warms, the geographical centers of distribution and the range limits of coastal temperate (cool-water) marine fishes are shifting poleward (northward in the Northern Hemisphere), a pattern that has been documented in California (Holbrook et al., 1997; Hsieh et al., 2009), Alaska (Grebmeier et al., 2006; Mueter and Litzow, 2008), the U.S. east coast (Murawski, 1993; Nye et al., 2009), Australia (Figueira and Booth, 2010), and Europe (Perry et al., 2005). Observed and projected rates of poleward shifts are 30–130 km (20–80 mi) per year (e.g., Perry et al., 2005; Dulvy et al., 2008; Mueter and Litzow, 2008; Cheung et al., 2009). Additionally, there is evidence that cool-water species are moving to deeper, cooler waters as surface waters warm, as documented in the North Sea (Dulvy et al., 2008). Note, however, that if climate change causes more intensive upwelling of cooler water along the Oregon coast, then such poleward shifts may not be evident nearshore (see Chapter 1).

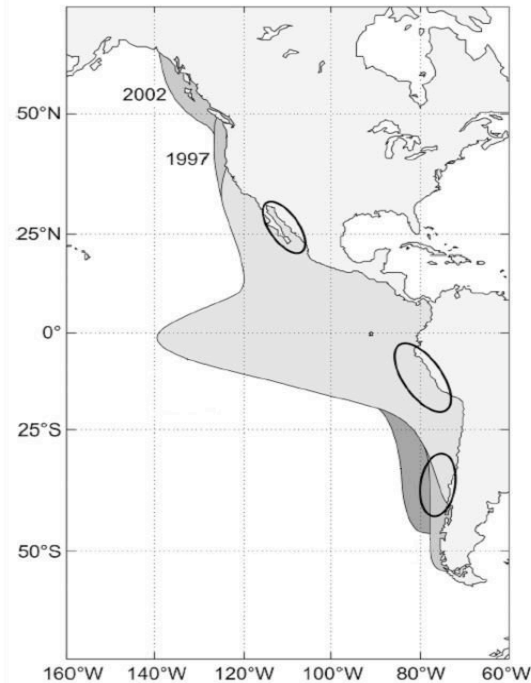
With Northern Hemisphere species often shifting their distributions northward as the ocean warms, will Oregon see an overall increase or a decrease in the number of marine fish species? Along the West Coast from Baja California northward, the diversity of coastal marine fishes peaks in southern California near the Mexican border (about 32°N), where southern warm-water species and northern cool-water species mix, then steadily decreases northward (Horn and Allen, 1978). Therefore, as the ocean warms, Oregon likely will gain more species immigrating into state waters from the south and lose fewer species emigrating out of the state to the north, resulting in a net gain in the number of fish species, as has been documented in the North Sea (Hiddink and Hofstede, 2008). Possible candidates for California fishes immigrating to Oregon are five nearshore species whose present northern range limits are between Cape Mendocino and Crescent City (Table 7.1).

**Table 7.1** (a) Nearshore California marine fishes whose present northern range limits are off northern California (between Cape Mendocino and Crescent City). These species are possible candidates for range extensions into Oregon waters as the ocean warms. (b) Nearshore marine fishes whose present northern range limits are off Oregon. These species are possible candidates for increasing abundance in Oregon waters as the ocean warms. Range limits from Miller and Lea (1972).

Family	Species	Common name	Present northern range limit in California
a. Species with northern range limit off northern California:			
Cebidichthyidae	<i>Cebidichthys violaceus</i>	monkeyface-eel	Crescent City
Carcharhinidae	<i>Mustelus californicus</i>	gray smoothhound shark	Cape Mendocino
Cottidae	<i>Clinocottus analis</i>	wooly sculpin	Cape Mendocino
Embiotocidae	<i>Hypsurus caryi</i>	rainbow surfperch	Cape Mendocino
Pleuronectidae	<i>Hypsopsetta guttulata</i>	diamond turbot	Cape Mendocino
b. Species with northern range limit off Oregon:			
Carcharhinidae	<i>Triakis semifasciata</i>	leopard shark	
Myliobatidae	<i>Myliobatis californica</i>	bat ray	
Argentinidae	<i>Argentina sialis</i>	Pacific argentine	
Ophidiidae	<i>Chilara taylori</i>	spotted cusk-eel	
Exocoetidae	<i>Cypselurus californicus</i>	California flyingfish	
Atherinidae	<i>Atherinopsis californiensis</i>	jacksmelt	
Scorpaenidae	<i>Sebastes rastrelliger</i>	grass rockfish	
Zaniolepididae	<i>Zaniolepis frenata</i>	shortspine combfish	
Cottidae	<i>Clinocottus recalvus</i>	bald sculpin	
Sciaenidae	<i>Seriphus politus</i>	queenfish	
Embiotocidae	<i>Hyperprosopon anale</i>	spotfish surfperch	

The only documented recent first-time immigrant to Oregon waters is Humboldt or jumbo squid (*Dosidicus gigas*), which first appeared in 1997 during the strongest El Niño warm-water intrusion in the past century (Pearcy, 2002). Subsequently, this predator has been observed as far north as southeastern Alaska (Keyl et al., 2008, Fig. 7.4.4.A). Zeidberg and Robison (2007) argue that even though this species is associated with warm-water events, is not dependent on warmer waters. In any case, this large (>2 m [>7 ft]), fast-growing, short-lived (1–2 yr) species is a voracious predator of various fishes (Zeidberg and Robison, 2007; Field, 2008), including Pacific salmon (J. Field, NOAA, personal communication). Zeidberg and Robison (2007) documented that, since 1998—the year Humboldt squid first invaded the West Coast in force—the abundance of Pacific hake (also known as Pacific whiting, *Merluccius productus*) has been low when the abundance of Humboldt squid has been high. By volume, hake comprise the largest fishery off the Oregon coast (ODFW/OCZMA, 2009). In a recent sonar study off Canada, hake were found to be more widely dispersed in the presence of Humboldt squid, indicative of predator-prey interactions (Holmes et al., 2008). Originally a tropical and subtropical species, Humboldt squid also have expanded their range southward to Chile, where they threaten the Chilean hake (*M. gayi*) fishery (Alarcon-Munos et al., 2008; Arancibia and Neira, 2008). They

also may affect marine mammals off Oregon (see Section 7.4.6). Paradoxically, Humboldt squid are predicted to suffer population declines as the ocean acidifies (Rosa and Seibel, 2008)



**Figure 7.11** Geographic spread of Humboldt squid (*Dosidicus gigas*) from its historic range in the eastern tropical and subtropical Pacific (light gray) northward and southward along the west coasts of North and South America (darker grays). Ovals enclose major fishing regions that may be affected by this predator. (Modified from Keyl et al., 2008.)

Projecting into the future, ocean distributions of Pacific salmon (*Oncorhynchus* spp.) generally are predicted to shift northward (Welch et al., 1998; Ishida et al., 2001). More generally, Cheung et al. (2009) predicted the rates of local invasions (such as warm-water fish species shifting northward into Oregon waters) and local extinctions (such as cool-water fish species shifting northward out of Oregon waters) from 2003 to 2050 for 1,066 marine fishery species worldwide (including 228 invertebrate species, Cheung et al., 2010). Their "dynamic bioclimate envelope model" predicted future distributions based on changes in suitable habitat, dispersal, and environmental conditions for each species under a high carbon emissions scenario (IPCC scenario A1B, which is equivalent to 720 ppm CO<sub>2</sub>; see Chapter 1). For the Oregon coast, the model predicted that the number of invasions of new fishery species will be less than 15% of the more than 100 fishery species currently present (i.e., on the order of 15 species), and that the number of extinctions will be less than 2% of the current fishery species (i.e., a couple species) (Cheung et al., 2009). Globally, they predicted that the geographic ranges of demersal (seafloor-associated) fishery species will shift about 200 km (125 mi) poleward by 2050.

As with all models, these predictions are hypotheses with high ranges of possibilities, especially given that the model did not include possible synergistic interactions among known causative factors, and did not include poorly known additional factors, such as ocean acidification. Nonetheless, sensitivity analyses indicated that the predictions are robust with respect to uncertainties in the factors examined, and the predicted rates of poleward shifts correspond to those observed, leading Cheung et al. (2009) to conclude that their predictions are conservative.

#### 7.4.4.2 Shifts in fish abundances

With a warming ocean, the general expectation is that cool-water species will decline in abundance as warm-water species become more abundant (reviews by Scavia et al., 2002; Roessig et al., 2004; Harley et al., 2006; Brander, 2007). There has not been sufficient monitoring of fish populations off Oregon to assess these predictions rigorously, especially given that fish abundance varies with fishing intensity as well as ocean conditions and associated ecological fluctuations (Mantua et al., 1997; McFarlane et al., 2000; Hallowed et al., 2001; Lehodey et al. 2006). However, there are indirect means of addressing this issue.

Periods of warm-water intrusion off Oregon during El Niño (the strongest of the past century being 1997–98) and other variations in ocean conditions (the period of 2003–2006 being unusually warm) have been associated with shifts in the abundance of marine fishes (W. Peterson, NOAA, personal communication). Survival of Sacramento River fall Chinook salmon stocks that went to sea during the spring and summer of 2005 and 2006 became so low that the salmon fishery was closed coast-wide during the summers of 2008 and 2009. This coast-wide closure was necessary because the Sacramento River stocks are major contributors to the Oregon and northern California salmon fishery (W. Peterson, NOAA, personal communication; see also the Pacific Fisheries Management Council web page). Other recent changes include increased abundance of Pacific sardine (*Sardinops sagax*) (Emmett et al., 2005), and the first records of spawning by Pacific hake, a species normally spawns off Baja California (Phillips et al., 2007). Albacore tuna (*Thunnus alalunga*) now occurs far closer to shore than during the 1970s, and has now become a major regional fishery in the Pacific Northwest (W. Peterson, NOAA, personal communication).

Fisheries catch records from Oregon show trends consistent with (but not necessarily demonstrating) shifts expected due to climate change. The Pacific States Marine Fisheries Commission maintains commercial catch records in the Pacific Fisheries Information Network (PacFIN) database ([pacfin.psmfc.org](http://pacfin.psmfc.org)). Examining this database from its inception in 1981 through 2009 for Oregon landings, several patterns suggest that warm-water fishery species are increasing in abundance. First, the annual catch of albacore tuna did not exceed 10,000 pounds until 1998, the year of a particularly strong El Niño. In the 11 years since 1998, annual catch has exceeded 10,000 pounds 3 years (2004, 2007, and 2009). However, catch per unit effort off Oregon has not increased substantially since the early 1960s (A. Phillips, OSU, personal communication, data from NOAA Southwest Fisheries Science Center). Second, although yellowtail (*Seriola dorsalis*) are known to stray into Washington waters, no commercial catch was recorded in Oregon until 2009. Third, "unspecified" squid, a category separate from market squid (*Loligo opalescens*) and probably including immigrating Humboldt squid (see above), first appeared in commercial landing records in Oregon in 2007 and have been recorded annually

since then. Additionally, there is an increasing number of unpublished reports of mahi-mahi (a.k.a. dolphinfish or dorado, *Coryphaena hippurus*) taken by recreational fishermen off Oregon, including during non-El Niño years (M. Hixon, OSU, personal communication).

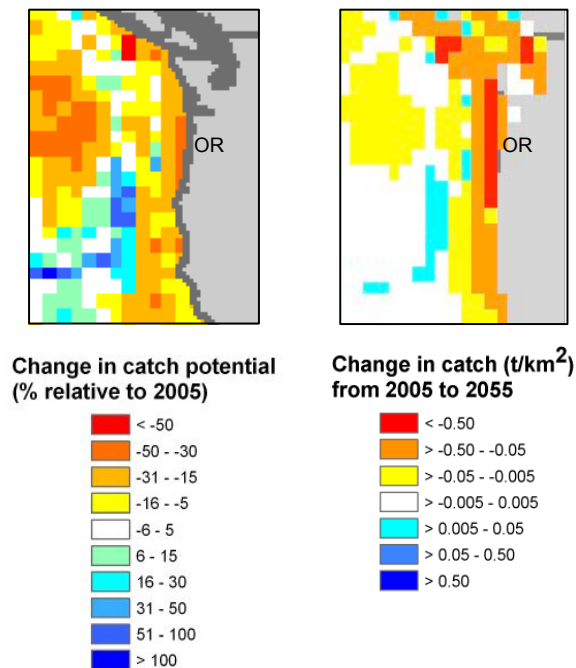
Projecting into the future, warm ocean conditions often cause declines in cool-water species, such as Pacific salmon (Miller and Fluharty, 1992; Pearcy, 1992; Ishida et al., 2001). Ocean climate modeling by Beamish and Noakes (2002) indicates that ocean conditions will become increasingly unfavorable for salmon off Oregon. However, conditions should improve for warm-water species. Of the 554 species of coastal marine fish described in Miller and Lea's (1972) "Guide to the Coastal Marine Fishes of California," 11 nearshore species have present northern range limits along the Oregon coast (Table 7.1). Assuming that water temperature is the primary factor limiting northern distribution limits, it is reasonable to predict that these 11 species will become more abundant off Oregon as ocean waters warm.

#### 7.4.4.3 Shifts in marine fisheries

Climate variability, especially associated with El Niño events (reviews by Diaz and Markgraf, 2000; Glantz, 2001), has long been known to affect marine fisheries, yet human-caused climate change presents new challenges in understanding fish population dynamics (reviews by Cushing, 1982; Glantz, 1992; McGinn, 2002). Catches vary with changes in both fishing intensity and ocean climate, so disentangling these causes is extremely difficult, especially in terms of predicting an uncertain future (Sharp, 1987; Mantua et al., 1997; McFarlane et al., 2000; Hallowed et al., 2001; Lehodey et al., 2006). Nonetheless, it is likely that those species becoming more abundant along the Oregon coast (see above) may benefit local fisheries, just as declining species will reduce catches. In a global analysis, Cheung et al. (2010) combined previously projected changes in species distributions (Cheung et al., 2009, see above) with published projections of changes in primary productivity (Sarmiento et al., 2004; see Section 7.4.1) to predict regional shifts in "maximum catch potential" (MCP) of 1,066 fishery species from 2005 to 2050. They defined MCP as the maximum exploitable catch assuming that the geographic range and selectivity of fisheries remain unchanged over this half-century period. Under a high carbon emissions scenario (IPCC scenario A1B, which is equivalent to 720 ppm CO<sub>2</sub>; see Chapter 1), most of the Oregon coast is predicted to suffer a decline in annual commercial fishery catch of at least 0.50 metric tons (0.55 U.S. tons) per km<sup>2</sup> (1 km<sup>2</sup> = 0.39 mi<sup>2</sup> = 0.29 nmi<sup>2</sup>) between 2005 and 2050, representing an estimated 30–50% loss (Fig. 7.12). Under the unlikely scenario of carbon emissions stabilized at 2000 levels (365 ppm CO<sub>2</sub>), these predictions lower to catch decreases of only 0.05–0.50 metric tons (0.06–0.55 U.S. tons) per km<sup>2</sup> annually, representing only a 5–15% loss (Cheung et al., 2010). The same broad range of possibilities, sensitivity analyses, and conservative conclusions apply to this analysis as discussed above for Cheung et al. (2009).

In a separate modeling effort, Biswas et al. (2009) predicted with a probability of 64% that catches in the Northeast Pacific (from Oregon to Alaska) will decline during this century. A third recent (and as yet unpublished) model predicts that, in addition to sea surface temperatures increasing, nutrients will concentrate below 50–100 m (27–55 fathoms) depth and the northerly flowing California Undercurrent will strengthen (Rykaczewski and Dunne, 2010). The increase in sea surface temperatures, consistent with the other models, should decrease the production of

surface-dwelling salmon species, coho salmon and steelhead in particular, largely because of changes in food web structure associated with changes from a cold-water and lipid-rich copepod and forage-fish community to a warm-water, lipid-poor community (Hooff and Peterson, 2006). If deeper nutrients increase, as suggested by Rykaczewski and Dunne (2010), then there is likely to be a corresponding increase in the production of phytoplankton and zooplankton. However, it is not clear how (or whether) increased production will alter food-web structure because community composition is determined by circulation patterns that may be more important than production rates. Strengthening of the California Undercurrent could benefit Pacific hake because this species takes advantage of the undercurrent during their annual northerly migration, yet a stronger current could also increase the invasion rate of Humboldt squid (see above, W. Peterson, NOAA, personal communication).



**Figure 7.12.** Predicted changes in marine fisheries catch off the Oregon coast from 2005 to 2055. Warm colors indicate predicted decreases and cool colors indicate predicted increases in terms of percent change (left) and absolute change (right) in catch within each 0.5-degree latitude-longitude plot. (Extracted from Cheung et al., 2010.)

Regarding recreational fishing, Bennett et al. (2004) investigated the interactive effects of ocean climate (El Niño events) and fishing intensity on catches of rockfishes (*Sebastes* spp.), comparing southern and northern California. They found that northern California, which is relatively similar to Oregon, experienced increased catch per unit effort during warm-water periods. Rather than this pattern being caused by changes in fish populations (because rockfishes reproduce too slowly to keep pace with El Niño events), the authors suggested that "lower food production and higher metabolic activity in warmer water may result in fish being hungrier and more active, rendering them more vulnerable to a set hook" (*ibid.*, pp. 2507–2508).



In conclusion, there are likely to be "winners" and "losers" among fishery species as Oregon's ocean warms and acidifies. Only time will reveal exactly what changes will occur. In any case, it is important to emphasize that this report focuses entirely on changes within Oregon's ocean. Oregon's fisheries and their income are not restricted to the Oregon coast. Landings in Oregon of marine fish captured in Alaskan waters were valued at about \$1.4 million during 2002–2009 (J. Olsen, Pacific Fisheries Information Network, personal communication). Much more substantially, 271 Oregon fishing vessels fished off Alaska in 2008, and Oregon residents grossed over \$104 million from commercial fisheries off Alaska that year, accounting for about 8% of gross earnings from Alaskan fisheries (ODFW/OCZMA, 2009). The fisheries link between Oregon and Alaska is relevant to this report because arctic and subarctic marine ecosystems are warming and changing much more rapidly than anywhere else in the world's oceans (Ciannelli et al., 2005; Grebmeier et al., 2006; Perovich and Richter-Menge, 2009), so these distant impacts will undoubtedly affect Oregon's economy.

#### 7.4.5 Seabirds

Oregon is home to roughly 1.3 million breeding seabirds, representing more than 15 species (Naughton et al., 2007) and many more seasonal migratory species, and has some of the largest breeding colonies in the California Current Large Marine Ecosystem (CCLME). Oregon's seabirds are both an economically important natural resource and an ecologically important mid- to upper-trophic level foraging guild. Economically, Oregon ranks 7th in per capita wildlife viewing (mostly birdwatching) in the U.S., with 49% (1.29 million) of the population participating ([www.birdiq.com/learn/economics.html](http://www.birdiq.com/learn/economics.html)). The Oregon Coast birding trail ([www.oregoncoastbirding.com](http://www.oregoncoastbirding.com)) includes many seabird viewing opportunities within the Oregon Islands National Wildlife Refuge ([www.fws.gov/oregoncoast/index.htm](http://www.fws.gov/oregoncoast/index.htm)), which, along with Three Arch Rocks National Wildlife Refuge, protects most of the breeding colonies on the coast. Ecologically, Oregon's seabirds forage upon both zooplankton and forage fishes, with the dominant piscivores consuming an estimated 49,000 metric tons (54,000 U.S. tons) of forage fish during the summer season (Wiens and Scott, 1975). A single species, the common murre (*Uria aalge*), is estimated to consume over 225,000 metric tons (248,000 U.S. tons) of prey annually off the California and southern Oregon coasts (Roth et al., 2008). Contemporary estimates of prey consumption by Oregon seabirds are lacking. However, it is clear that seabirds are ecologically important consumers within the marine food web.

No sufficiently long-term studies of Oregon seabirds have been conducted to adequately address the potential effects of climate change. Some effects of changing climate-driven ocean conditions, however, have been documented during long-term studies of seabirds in neighboring regions of the CCLME (see Chapter 1), and therefore, offer some basis for the predicted responses presented here.

Potential effects include the following:

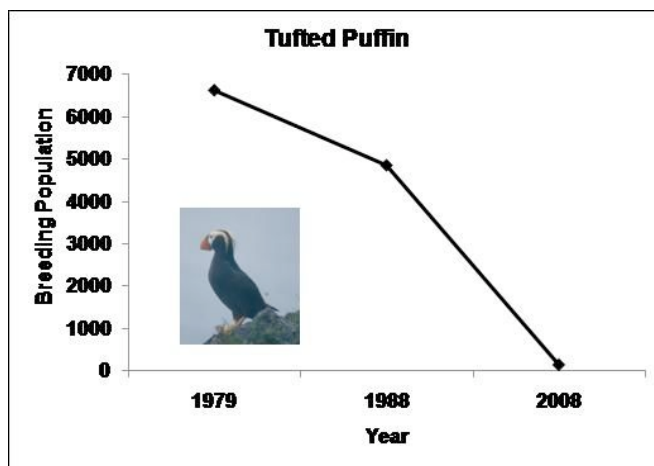
- 1) Ocean warming potentially affecting prey distribution, abundance, or density, and causing reduced breeding success and survival of pursuit-diving seabirds (e.g., murre and puffins), ultimately resulting in population declines.

- 2) Species distributions shifting northward with a warming trend, enhancing (or initiating) breeding populations for species at the northern edge of their range, and negatively affecting species at the southern edge of their range.
- 3) Increased overwinter mortality with increased storm intensity or variability.
- 4) Inundation of breeding colonies from sea-level rise, especially for beach or estuary breeding species.
- 5) Potential increases in the occurrence of harmful algal blooms that can negatively affect seabirds through acute toxicity, lowered immunity, or other physiological stresses (see Section 7.4.1).
- 6) Increased hypoxia (“dead zones;” see Section 7.4.1) affecting seabird prey, potentially either enhancing foraging opportunities (aggregating prey nearer the surface and away from oxygen depleted bottom water) or reducing food availability (through increased prey mortality).
- 7) Potential indirect effects of ocean acidification through alteration of marine food webs and prey availability (see previous sections of Chapter 7).
- 8) Potential decrease in foraging opportunities due to increased between-species competition for prey as population increases and range expansions of other predators occur, such as the recent movement of Humboldt squid into the Pacific Northwest (see Section 7.4.4).

Seabirds along the Oregon coast most commonly are viewed on shore in large breeding colonies and the viewing public often does not appreciate that these animals forage exclusively at sea, some diving to depths of over 150 m (490 ft) and many strictly at sea during most of the year. The fact that seabirds do breed on shore, however, allows researchers to more readily quantify reproductive output, diet, and population change compared with many other marine animals. Consequently, seabirds have been shown to be sensitive indicators, or sentinels, of changing ocean conditions (Aebischer et al., 1990; Piatt et al., 2007). Indeed, one of the first publicly visible signs along the Oregon coast of reductions in prey abundance due to changes in ocean conditions (e.g., 2005) or acute toxicity due to harmful algal blooms (e.g., 2009; see Section 7.4.4) were mass mortalities of seabirds resulting in many carcasses found on local beaches (Shumway et al., 2003; Parrish et al., 2008). Similarly, large increases in numbers of seabirds frequently are evident when prey abundance rebounds in one region and/or declines in another, causing a population shift (e.g., dramatic increases in several species during winter 2009-2010 on the Oregon coast potentially were caused by changes in prey abundance).

One effect of ocean warming is change in the timing of upwelling (Bograd et al., 2009; see Chapter 1) which in turn affects the timing of seabird breeding in our region (Wolf et al., 2009). In general, birds that initiate reproduction earlier in the spring are more successful and delayed upwelling can cause catastrophic breeding failures (Sydeman et al., 2006). Long-term ocean warming has affected the community composition and abundance of seabirds in the southern CCLME (Veit et al., 1996, 1997), with an overall decline in numbers resulting from fewer cold-water associated pursuit-diving seabirds, such as sooty shearwater (*Puffinus griseus*) and rhinoceros auklet (*Cerorhinca monocerata*), and an increase in warm-water associated near-

surface feeding species, such as pink-footed shearwater (*Puffinus creatopus*) and Leach's storm-petrel (*Oceanodroma leucorhoa*; Hyrenbach and Veit, 2003). In the northern CCLME, warming ocean temperatures were correlated with declines in reproductive success of tufted puffin (*Fratercula cirrhata*), whose populations have declined precipitously (<2% of 1979 levels; Fig. 7.13) in coastal Oregon (Kocourek et al. 2009), and marbled murrelet (*Brachyramphus marmoratus*). Both of these species are cold-water associated, pursuit-diving seabirds (Gjerdrum et al., 2003; Becker et al., 2007). Pursuit-diving seabirds are common in highly productive regions (e.g., high latitudes, upwelling regions), where prey densities are sufficient to meet energetic demands of searching for prey while diving (diving birds generally have high flight costs as a trade-off for enhanced diving efficiency). In contrast, surface-feeding birds with low flight costs can better search larger areas for more sparsely distributed prey aggregations. This represents the dominant foraging mode in less productive regions (e.g., low latitude, unproductive regions). Hence, evidence suggests that a shift in the CCLME toward seabird assemblages characteristic of warmer, lower productivity waters has begun, as has as a trend toward decreasing species diversity (Sydeman et al., 2009). Indeed, deteriorating ocean conditions have been linked to reduced overwinter survival of seabirds such as Atlantic puffin (*Fratercula arctica*) in the North Sea (Harris et al., 2010).



**Figure 7.13** Decline in the estimated breeding population size of the tufted puffin, a pursuit diving seabird, on the Oregon coast. Data from Kocourek et al. (2009).

Species range shifts also have been documented for the Oregon coast, in particular the occurrence of California brown pelican (*Pelecanus occidentalis californicus*), a nonbreeding, summer migrant whose numbers in Oregon have increased a hundred-fold during the past several decades (Wright et al., 2007; U.S. Fish and Wildlife Service, unpublished data). While this dramatic increase reflects, in part, an increasing population, major northward expansions have been associated with warm weather anomalies, such as El Niño events. The winter of 2009–2010 saw the first significant over-wintering by brown pelicans along the coast of Oregon (records of pelicans present in all winter months also occurred in 1998 and 2002, but individual sightings were sparse, in contrast to 2010; R. Bayer, Lincoln County bird sighting compiler, personal communication). In contrast to these shifts in post-breeding, migratory range, forced shifts in breeding distribution may be more problematic for seabirds, as sufficient predator-free, breeding habitat (e.g., offshore islands and sea stacks) may become limited.

Increased winter storm intensity also can affect seabird populations, with some species (and age classes) being more susceptible to storm-associated mortality than others (Frederiksen et al., 2008). Sea level rise should have little direct effect on many seabird colonies in coastal Oregon because most tend to be well above the current high tide level (see Chapter 6). However, species nesting adjacent to rocky intertidal zones (e.g., black oystercatcher, *Haematopus bachmani*, see Section 7.2.3. for photo), on beaches (e.g., western snowy plover, *Charadrius alexandrinus*), or on low-lying sandy islands in estuaries (e.g., terns and gulls) will experience habitat loss due to sea level rise (Daniels et al., 1993) and increased storm-driven wave heights (Ruggiero et al., 2010). Potential loss of nesting habitat in estuaries is a particular concern for the Columbia River, which currently provides nesting sites for the Pacific population's largest colony of Caspian tern (*Hydroprogne caspia*, approximately 18,000 birds; Suryan et al., 2004), equally as many double-crested cormorants (*Phalacrocorax auritus*; Adkins and Roby, 2010), and post-breeding feeding and roosting habitat for thousands of brown pelicans (Wright et al., 2007; U.S. Fish and Wildlife Service, unpublished data).

Seabirds exhibit direct responses to inter-annual (El Niño) and decadal (Pacific Decadal Oscillation/North Pacific Gyre Oscillation) changes in ocean climate. The 1982–1983 El Niño, one of the strongest on record, resulted in the death of millions of seabirds in the equatorial Pacific Ocean due to starvation, and also affected reproductive success of some species globally (Schreiber and Schreiber, 1989). In Oregon, the 1982–1983 El Niño caused reduced seabird reproductive success and increased mortality (Hodder and Graybill, 1985; Bayer, 1986). During the 1997 El Niño, common murre colonies along the Oregon and Washington coasts suffered mass abandonment and breeding failure (Parrish et al. 2001; Roy Lowe, USFWS personal observation) and thousands of emaciated birds washed ashore during summer as they made their way north (T. Good and J. Parrish, unpublished data).

Harmful algal blooms (see Section 7.4.1) associated with changes in climate can also have negative impacts on seabirds. Impairment or mortality occurs more commonly through toxicity, such as domoic acid poisoning (Shumway et al., 2003). However, recent events of surfactant-producing red tides also have caused mass mortalities of seabirds (Jessup et al., 2009). In the latter cases, foam from the organic material of the red tide contained surfactant-like proteins coated the feathers of birds and removed the protective oils, causing hypothermia. This was first described during a 2007 mass mortality event in California (Jessup et al., 2009), and was recorded for the first time to cause seabird mortality off Oregon and Washington in 2009. It is not clear to what extent these events are occurring for the first time, or simply being detected for the first time, but such mortality is certainly worthy of close monitoring and documentation in the future (Shumway et al., 2003; Jessup et al., 2009).

The occurrence of low oxygen waters and hypoxia (“dead zones”) in Oregon’s nearshore environment has increased in recent decades (Grantham et al., 2004; Chan et al., 2008; see Chapter 1). The effect of hypoxic marine conditions on seabirds, however, is neither known for the Oregon coast nor under study. One could speculate that the effect would be either positive or negative, depending on the portion of the water column affected and the prey of seabirds affected. A positive response could result from mobile seabird prey being driven away from low oxygen bottom waters and into greater concentrations in the upper water column, thereby

enhancing foraging opportunities. A negative response could result from increased mortality of prey or movement of prey away from nearshore feeding areas and consequent reductions in availability.

Likewise, the potential effect of ocean acidification on seabirds is largely unknown. However, given that Oregon shelf waters are already potentially corrosive to species that form calcium carbonate shells and as the ocean continues to absorb carbon dioxide from the atmosphere causing increasing corrosive effects (see Chapter 1), there are potential food-web level consequences that could affect seabird populations. For example, if marine ecosystems are shifted toward more toward communities with low calcium requirements, such as jellyfish, this shift could affect seabird food supplies. In summary, there are a variety of direct and indirect pathways by which Oregon's seabird populations may be effected by climate change that have population- and community-level consequences.

#### **7.4.6 Marine mammals**

Marine mammals typically are widely distributed, highly mobile and, before human exploitation, most were more abundant than today (Clapham and Baker, 2009). The cool waters off the Oregon coast have a rich diversity of marine mammal species, but few are strictly resident and none are restricted entirely to Oregon waters (Maser et al., 1981). Of the 86 living species of whales and dolphins (cetaceans) currently recognized (Perrin, 2009), 23 have been sighted live or found beached in Oregon. Of the 32 living species of seals and sea lions (pinnipeds) currently recognized (Committee on Taxonomy, 2009), 6 have been sighted live or found beached in Oregon and 2 more (the ribbon seal and the ringed seal) are considered likely to range into Oregon waters based on occasional sightings in California.

A recent review of potential impacts of climate change on marine mammals worldwide did not identify obvious risks to the cetaceans most commonly found in Oregon waters, but highlighted general uncertainty about direct and indirect effects of climate change (Simmonds and Elliott, 2009). Climate change will shift the overall state of the world's oceans toward a future of increased warming and acidity, reduced sea-ice cover, and higher sea levels (Chapters 1 and 6), with a resulting reduction in productivity and loss of marine biodiversity (Moore and Huntington, 2008). However, the impact of these predicted changes on a specific geographic region, such as Oregon, or on a specific taxonomic group, such as marine mammals, is highly uncertain, especially over a few decades. Only in the Arctic, where the effects of reduction in ice cover are already evident, is there likely to be predictable and measurable near-term impacts on ice-obligate and ice-associated species of marine mammals (Laidre et al., 2008). Even here, the impact of climate change will be compounded (or confounded) by two other human-caused threats: hunting and pollution (Laidre et al., 2008).

As with other marine species (e.g., marine fishes, Section 7.4.5), the expected influence of climate change on marine mammals will be both direct and indirect. Unlike other marine species, however, marine mammals are capable of rapid learning and physiological resilience across a relatively long lifespan. This behavioral plasticity and innate resilience should allow many species to respond to environmental changes within a single generation (Learmonth et al., 2006). Off Oregon, the near-term impact of direct mechanisms, such as water temperature, are

unlikely to be as consequential as the indirect influences of shifts in prey and the structure of marine ecosystems, including diseases, predators and competitors.

#### 7.4.6.1 *Distribution and range extensions*

The most obvious effect of warming oceans on marine mammals will be shifts in local distributions or range expansions of species, as individuals respond to temperature tolerances and preferences. Using a classification of cetaceans into climatic groups, MacLeod (2009) predicted that 88% of cetacean species will experience shifts in their geographical distributions in response to changes in water temperature resulting from climate change. For 47% of these species, predicted changes are anticipated to have unfavorable implications for their conservation, and for 21%, the changes could put at least one geographically isolated population of that species at risk of extinction (MacLeod, 2009).

Given Oregon's location in middle latitudes and its cool waters, most marine mammals currently found in our waters are unlikely to be excluded by the modest increase in sea-surface temperatures predicted for the next few decades. The one exception might be the Steller sea lion (*Eumetopias jubatus*), for which Oregon is at the southerly (but not southernmost) extent of its range. Instead, the overall response to warmer waters is likely to be an increase in frequency of more tropical species, resulting in a regional increase in species diversity (Whitehead et al., 2008). Some evidence of this change is already indicated by records of species beyond their normal geographic ranges, such as the subtropical Guadalupe fur seal (*Arctocephalus townsendi*) being sighted off Oregon during 2006–2009. Other species likely to expand their range northwards from California include many of the more subtropical dolphins, such as bottlenose dolphin (*Tursiops truncatus*), rough-toothed dolphin (*Steno bredanensis*), and pantropical spotted dolphin (*Stenella attenuata*; Learmonth et al., 2006). The range expansions of these and other species are likely to result in new interactions among species.

Inshore and offshore shifts in distributions of some marine mammals could result from changes in sea surface temperature and shifts in upwelling, as well as the associated changes in the distributions of their prey (Learmonth et al., 2006). For some seals, particularly harbor seal (*Phoca vitulina*), the predicted rise in sea level and the observed increase in the intensity of waves along the Oregon coast will likely lead to a loss of beach habitat for haul-out (Chapter 6).

#### 7.4.6.2 *Changes in abundance and population growth*

The impact of climate change on abundance and rates of increase of marine mammal populations is difficult to predict, as many species are still recovering from past exploitation, and so, are assumed to be below normal limits set by the environment (Baker and Clapham, 2004). For those species nearing recovery to pre-exploitation numbers, the expected influence of crowding effects, such as increased juvenile mortality, are likely to further confound interpretations of climate change. This situation is likely to be true for the western North Pacific gray whale (*Eschrichtius robustus*) and the North Pacific humpback whale (*Megaptera novaeangliae*), both of which are thought to have recovered to pre-exploitation numbers (although the local population of humpbacks in Oregon remains at low numbers). Nonetheless, efforts to assess the role of climate change or environmental variation on population dynamics

of marine mammals are ongoing in cases where there are long-term data sets of abundance and recruitment (Leaper et al., 2006; McMahon et al., 2009). In Oregon waters, species most likely to show measurable changes in abundance or recruitment are harbor seals, Steller sea lions, California sea lions (*Zalophus californianus*), harbor porpoises (*Phocoena phocoena*), “resident” gray whales, and humpback whales.

#### 7.4.6.3 Changes in migratory distribution and timing

Many marine mammals found in Oregon waters are migratory. For baleen whales (Mysticeti), these migrations extend from subtropical or tropical waters to subarctic or even Arctic waters. For some gray whales and humpback whales, however, the waters of Oregon are the northerly limit of migration and the primary feeding grounds. The influence of climate change on the distribution of these “resident” gray and humpback whales is likely to be dependent on changes in the distribution and abundance of prey (indirect mechanisms), rather than sea-surface temperature itself.

For non-resident gray, humpback and other migratory whales, timing of migration and period of transit through Oregon waters will likely change as a direct result of ocean warming and the retreat of Arctic ice from summer feeding grounds. Such alteration in timing, or shifts in seasonal habitat use, could lead to a mismatch between predator requirements and prey availability on the feeding grounds, as well as reproductive timing on breeding grounds (Moore, 2009). One of the best long-term records of migratory timing is that of eastern North Pacific gray whales. The southbound migration for this population has been documented from a census site in central California over the past 40 years, providing evidence of a delay in migration that coincided with the strong El Niño event that occurred in the North Pacific during 1997-1998 (Moore, 2009). This shift in timing of migration was accompanied by reports of more newborn calves offshore of California, well north of the historical concentration of calving in lagoons of Baja California. Such a shift in migratory timing should also be detectable for gray whales along the migratory corridor of the Oregon coast. A similar shift could be expected for other migratory whales such as humpbacks (Baker and Herman, 1981), fin whales (*Balaenoptera physalus*), and blue whales (*Balaenoptera musculus*), but would be much more difficult to detect given the absence of long-term records of migratory timing.

#### 7.4.6.4 Changes in ecological interactions

Probably the major impacts of climate change will be on ecological interactions involving marine mammals, particularly due to shifts in productivity and prey availability. At a very basic level, one can expect that an increase in coastal productivity will be favorable for most marine mammals in Oregon, whereas a decline will be unfavorable. However, much will depend on which species change in productivity and the oceanographic conditions that concentrate the primary prey for each species, influences that are far less predictable (Learmonth et al., 2006).

The recent range expansion of Humboldt squid (*Dosidictus gigas*) provides an example of the complexity of collateral change in predator-prey interactions that could affect marine mammals of Oregon (see Section 7.4.4). This predatory squid is expanding its range northward, coincident with climate-linked oceanographic conditions and a reduction in competing predatory fishes

(Zeidberg and Robison, 2007). In regards to marine mammals, this squid is both a known prey item for larger sperm whales (*Physeter macrocephalus*) and beaked whales (e.g., *Ziphius cavirostris*) and a potential competitor for the most common prey of smaller cetaceans, such as harbor porpoises. The continued northward expansion of Humboldt squid into Oregon waters is likely to benefit some species of marine mammals and negatively impact others. The Humboldt squid itself, although benefiting from short-term climate and ecological change, is predicted to be threatened by longer-term increases in ocean acidity and temperature (Rosa and Seibel, 2008).

Expanding and overlapping ranges of some marine mammals could introduce further complexity to species interactions, including competition. Along parts of the California coast (and elsewhere in the world [Patterson et al., 1998]), bottlenose dolphins have been observed to attack and kill harbor porpoises (SIMoN, 2009). These fatal interactions could increase as bottlenose dolphins expand their range northward into Oregon.

#### 7.4.6.5 Changes in infectious diseases and toxic algal blooms

Marine mammals are subject to large-scale mortality events due to infectious diseases and harmful algal blooms (HABs; Learmonth et al., 2006; Van Dolah 2005; Section 7.4.1). Rates of development, transmission, and susceptibility are all influenced by climate, with a greater incidence of disease anticipated with ocean warming. Marine mammal deaths associated with HABs and diseases appear to have increased over the past three decades, as have the frequency and geographic distribution of these events (Moore, 2009). Many HABs produce toxins known to affect both humans and marine mammals (e.g., domoic acid, Van Dolah, 2000), as are some of the disease organisms responsible for marine mammal deaths (e.g., *Toxoplasma gondii*, Gulland and Hall, 2007). Consequently, there is concern that the increase in mortality of marine mammals is the result of a general deterioration in the state of the oceans, with direct implications for human health (Gulland and Hall, 2007).



## Case Study 7.1: Climate Change and Invasive Species

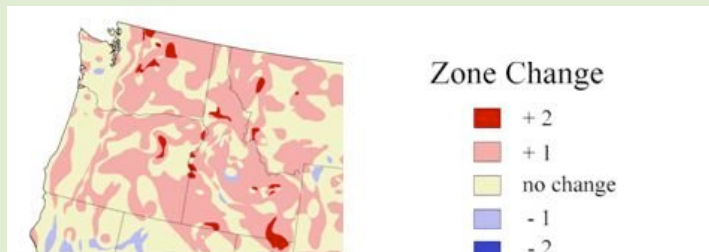
Globalization of trade and travel combined with technology changes over the past two centuries have accelerated the rate of species dispersal worldwide (Office of Technology Assessment, 1993; Ruiz et al., 2000). European settlement of the Pacific Northwest resulted in introduction of nonindigenous plants and fishes that established persistent, and sometimes damaging, populations. Warm water fish, such as catfish, bass, and walleye, impact threatened and endangered native salmonids (Sanderson et al., 2009). Increases in the speed and number of ships calling on Oregon ports, combined with the modern use of water as ballast that transports larvae from port to port, has resulted in an exponential increase in the rate of new aquatic invertebrate species arrivals to Oregon waters. Prior to the 1970s a new, nonindigenous aquatic invertebrate was found, on average, in the Columbia River about every five years; over the past decade, however, a new species is found about every five months (Sytsma et al., 2004).

Nonindigenous species that proliferate and cause ecological, economic, and human health problems are termed “invasive.” Total economic costs are difficult to quantify because invasive species affect nonconsumptive, indirect-use, and non-use values of ecological goods and services (Naylor, 2000; Lovell and Stone, 2005). One frequently cited assessment indicated that economic costs of invasive species in the USA are about \$120 billion annually (Pimentel et al., 2005). In Oregon, just 23 noxious weeds reduce personal income in the state by \$83 million each year, which is equivalent to 3329 jobs (Oregon Department of Agriculture, 2000). If left unchecked, six of these weeds would reduce personal income by another \$54 million and eliminate another 2143 jobs. Quagga and zebra mussel invasion of the Columbia River was predicted to have a \$23 million impact on hydropower facilities alone (Phillips et al., 2005), with a worst case scenario of \$250–300 million/year from lost power production (Independent Economic Analysis Board, 2010).

The impact of climate change on invasive species is difficult to separate from natural climate cycles and the myriad of other factors that influence the rate of spread of organisms. However, changes in USDA plant hardiness zones have already been recorded in much of Oregon (see Map), and will result in concomitant shifts in terrestrial plant communities and open habitats to invasion. There is also strong fossil evidence that ocean warming has resulted in tropical species of planktonic foraminifera moving northward in the California Current (Field et al., 2006; see Chapter 1). Substantial northward migrations of 10 marine invertebrates in last thirty years coincided with increased water temperatures along the Pacific Coast—five of the 10 species exhibited range expansions into Oregon from California (Carlton, 2000). The Humboldt squid, a voracious predator that could affect commercially important fish stocks, also exhibited climate-linked, northern expansion of its range into Oregon. Moreover, this species is physiologically adaptable and its current distribution does not depend upon the higher surface water temperatures typical of the tropics (Zeidberg and Robison, 2007). Similar temperature-related phenomena have been observed in the

distribution of sea squirts (Stachowicz et al., 2006), marine fishes (Perry et al., 2005), and over 100 other species around the world ranging from trees to insects and forest pests (Walther et al., 2009).

Carbon dioxide enrichment of the atmosphere will likely have direct and indirect effects on ecosystem processes and species distributions. Plants with  $C_3$  photosynthetic biochemistry that grow in habitats that are dominated by plants with  $C_4$  biochemistry may gain a competitive advantage with an increase in  $CO_2$ , even though there is no clear link between  $CO_2$ -responsiveness and invasiveness (Dukes, 2000).



Change in plant hardiness zones between 1990 and 2006, based on minimum annual temperature. Positive changes mean that warming conditions are favoring more warm-tolerant species ([www.arborday.org/media/map\\_change.cfm](http://www.arborday.org/media/map_change.cfm)).

Secondary effects of climate change could also influence spread and dispersal of invasive species (Sutherst, 2000). Climate change that leads to more rain and less snow at high elevations will alter seasonal periodicity in stream flow and possibly result in construction of more reservoirs to maintain adequate water reserves for human use (Fredrick and Gleick, 1999). Native fish communities are adapted to natural hydrologic regimes and changes in hydrology facilitate establishment of non-native fish species (Moyle and Marchetti, 2006; Johnson et al., 2008). Changes in the amount and distribution of precipitation could also alter fire regimes and increase the number of invasive species (D'Antonio, 2000). Melting of the polar ice cap will likely lead to shifts in shipping routes (Phillips, 2008) and changes in source and sink regions for introductions of exotic species via ballast water. Finally, climate warming will increase the pool of invasive species by facilitating the northward spread of aquaculture facilities and water gardens that are often the source of escaped invasive species that enter natural water bodies (Rahel and Olden, 2008).

Shifts in species ranges are an unavoidable and expected consequence of climate change in Oregon. The biogeography of native and invasive species in Oregon is not monitored systematically, so impacts of climate change on Oregon's plants and animals cannot yet be effectively assessed or managed. Oregon has the infrastructure in place to address invasive species issues (Oregon Invasive Species Council, 2010), but all programs are underfunded. Additional resources are required for the state to prepare for, and mitigate, the inevitable effects of climate change on invasive flora and fauna.

## **Case Study 7B: Climate Change, Ecological Resilience, and Natural Resource Management**

The ecological effects of climate change pose immense challenges for natural resource management because the biosphere is heading toward conditions that have not been experienced previously by modern humans in any particular region: the past no longer necessarily provides reliable insight for the future. As this report should make clear, even though substantial changes are occurring and will accelerate during this century, uncertainty is immense regarding specific changes and appropriate responses. In the context of rapid change and high uncertainty, an overarching goal to ensure that ecosystems do not change catastrophically is ecological resilience (Holling, 1986; Walker and Salt, 2006).

“Ecological resilience” is the capacity of an ecosystem to absorb disturbances without shifting to a drastically different state that is undesirable—and perhaps irreversible—from a human perspective (Holling, 1973; Gunderson, 2000). Therefore, fostering resilience is a fundamental principle for ensuring that the negative effects of climate change are minimized or otherwise slowed by management policy (Holling, 1986; Walker and Salt, 2006).

The management goal of “resilience” is different from that of “stability” in a way that has important ramifications for natural resource policy in response to climate change. Whereas the goal of resilience is an ecosystem that is allowed to vary naturally—sometimes substantially—yet without crossing a threshold into a fundamentally different and undesirable state, the goal of stability is an ecosystem that does not change or, following a disturbance, returns quickly to a specific state desired by humans (Holling, 1996). History has shown repeatedly that attempting to manage fish and wildlife for optimal population levels of specific target species or maximum sustainable yield of specific fishery species is impossible in the long run because ecosystems constantly change and cannot be held in a constant state by command-and-control approaches (Holling and Meffe, 1996). When thresholds are crossed due to human alterations of key nonliving and living processes, ecosystems jump rapidly between alternate stable states that human may view as deleterious. For example, old fire-suppression policies to keep western forests static resulted in the build-up of fuel until catastrophic wildfires killed far more trees and wildlife than if naturally small and more frequent fires had been allowed to burn (Stephens and Ruth, 2005). In the ocean, overexploitation of a single predatory species, the sea otter (now extinct in Oregon), resulted in the loss of kelp forests as sea urchins overgrazed kelp in the absence of their key mammalian predator (Estes and Duggins, 1995). In each case, the new state of the ecosystem was less useful to humans than the original state that dominated before the phase shift caused by trying to manage for static equilibrium. In short, all ecosystems naturally vary through time in adaptive cycles of generation, degeneration, and

regeneration (Holling, 1986). Allowing natural cycles to run their course tends to keep the system within a particular desirable regime in the long run (Folke et al., 2004).

It is important to realize that exactly what species and natural processes must be conserved to prevent the loss of resilience and sudden regime shifts typically are not predictable (Holling, 1986). This reality means that maintaining resilience requires ecosystem-based management that embodies precautionary and adaptive approaches to address unknown threats and consequences before they appear (Arkema et al., 2006). Precautionary policies do not harm ecosystem function. Adaptive management occurs when policies become hypotheses and management actions become experiments to test those hypotheses, providing feedback toward more effective approaches (Folke et al., 2005).

Experience in a variety of natural systems shows that two specific ecosystem-based policies are among the most effective at conferring ecological resilience (Walker and Salt, 2006).

(1) *Maintaining species diversity and functional redundancy*: Ecosystems in which all native species are in their unaltered abundances and size/age classes, including multiple species that share similar ecological functions, are more resilient than systems where key species groups have been overexploited or their habitats severely altered. For example, conservation of multiple species of top predator means that the loss of any one species due to climate change does not entirely remove this essential functional group (Elmqvist et al., 2003).

(2) *Allowing natural variability and modularity in processes at all scales of time and space*: Ecosystems where natural cycles and disturbances are allowed to run their course in a state of natural patchiness are more adaptable than those that have been artificially and uniformly boxed-in narrow states that are vulnerable to drastic change. For an example regarding space, habitat patches in different natural states of succession (defined by time since the last natural disturbance) enhance regional species diversity and provide opportunities for degraded patches to be recolonized by adjacent patches in different successional stages (Holling, 1986). For an example regarding time, big, old, fat, fertile, female fish (BOFFFFs) have longer spawning seasons and produce more eggs than younger females, and thus are more likely to spawn at times when their young find food-rich ocean water masses and are delivered by favorable currents to nursery habitats, both of which vary unpredictably from year to year (Berkeley et al., 2004).

In practice, these policies can be implemented by (1) networks of reserves where natural processes and connectivity between sites are fostered (Bengtsson et al., 2003; McLeod et al., 2009), and (2) active management that mimics natural cycles and disturbances (Folke et al., 2005). Resilient ecosystems on land and in the sea provide “stepping stones” where species can find refuge as they shift their geographic distributions due to climate change. For more complete introductions to ecological resilience, including examples of

ecosystem-based natural resource management, see Walker and Salt (2006) and Gunderson et al. (2010).

**Author Contributions:** Chapter organizer, editor, and summary & introduction author, ocean section lead and introduction author: Hixon. Land section lead and introduction author: Robinson. Freshwater section lead and introduction author: Gregory. *Insects and Relatives*: Miller. *Amphibians and Reptiles*: Garcia (amphibians), Robinson (reptiles). *Land Birds*: Haig. *Land Mammals*: Epps. *Freshwater Invertebrates*: Lytle. *Salmon and Other Freshwater Fishes*: Gregory, Noakes, Schreck. *Phytoplankton*: Letelier, White. *Zooplankton*: Batchelder, Peterson. *Seafloor Species*: Menge, Hixon (rocky intertidal zones), Rumrill (estuaries). *Marine Fishes and Fisheries*: Hixon, Peterson. *Seabirds*: Suryan. *Marine Mammals*: Baker, Rice. *Case Study 7A on Invasive Species*: Systema. *Case Study 7B on Ecological Resilience and Natural Resource Management*: Hixon.

**Acknowledgments:** Lead author Hixon is grateful to his many colleagues for generously participating in this important compilation and summary of scientific literature. All authors thank the seven peer reviewers for their constructive comments on the draft manuscript.

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## 8. Toward Assessing the Economic Impacts of Climate Change on Oregon

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### Summary and Knowledge Gaps

This chapter discusses the economic dimensions of measuring the impacts of climate change with a focus on selected sectors in Oregon. It presents a brief overview of the methodology for quantifying economic impacts of climate change, and summarizes recent assessments of climate change in Oregon and the Pacific Northwest. The regional assessments include:

- (1) the published impacts of climate change for similar sectors in California and Washington from their most recent climate change impact assessments;
- (2) the 2009 study by the Climate Leadership Initiative at the University of Oregon which provides an assessment of projected "potential" costs Oregonians might incur over the next several decades if we extend a business-as-usual (BAU) approach to climate change; and
- (3) specific studies on various aspects of change in the forestry and agricultural sectors in Oregon and neighboring states based on research at OSU that relate to quantifying the economic impacts.

Based on our review of existing research, it is not possible to provide a comprehensive economic assessment of the impacts of climate change in Oregon, since much of the needed modeling and analysis is incomplete. Projecting the economic impacts of climate change is an extensive undertaking for many reasons. Economic impacts require information on the physical changes in various resources and ecosystems, and models to predicting how human behavior and biological systems will respond to the physical changes. For example, predicting changes in water availability and timing as a result of a changing climate is part of the needed information, but this information needs to be supplemented with behavioral responses in order to quantify the economic dimensions of the change. Knowing physical and biological changes in the level of our natural capital does not translate directly into predicting how that change will impact Oregonians.

Quantifying the economic impacts on a sector-by-sector basis requires disaggregate models for predicting behavioral responses to change in climate variables as well as changes in economic variables (prices of inputs, products). Some studies have sidestepped the issue of behavioral response to these and projected economic impacts based on BAU scenarios. While these BAU scenarios provide useful information, they should be viewed as an upper bound on "costs" or impacts of climate change: these are the resulting impacts assuming that people do not adapt or respond to different economic or biophysical scenarios.

Oregon's economy, like the economies of many other states, is likely to be impacted by a changing climate and by public policies addressing projected climate changes. Policy makers must rely on science-based assessments of physical impacts, likely adaptation costs, and the economic costs and benefits of the climate policies themselves in making informed choices

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regarding policy design and implementation. As noted in other state-level reports (CA and WA reports), both the set of physical and economic assessments are in the early stages of development, and many scientific questions remain unanswered. Nevertheless, these assessments, as well as the material presented in the earlier chapters of this report, strongly suggest that climate change does pose potential risks to the western US and to Oregon in particular. The magnitude of the risks and economic impacts will depend on the rate that the physical impacts or changes to our natural capital occur, the resilience of our systems to accommodate these changes, as well as the ability and willingness of countries, states, and individuals to respond to a changing climate.

## 8.1 The Nature of the Challenge and the Implications for Policy Design

Taking a big picture perspective, climate change may be the hardest political problem the world has ever had to address. Climate change is referred to as a “wicked” problem: “...a prisoner’s dilemma, a free-rider problem, and the tragedy of the commons all rolled into one” (*Economist*, December 5, 2009). One challenge is defining the level of climate change that is socially efficient - a level of CO<sub>2</sub> emissions where the marginal social benefits of emission reduction is approximately equal to the marginal social cost of the policies or actions proposed. A second challenge is the difficulty of allocating the costs of collective action to remedy climate change spatially and temporally and insuring all emitters participate in the proposed policies. The global nature of climate change transcends any individual political entity, and achieving progress towards an effective and equitable solution requires consensus concerning a set of actions or reduction levels. The benefits of emission reduction policies can be offset by non-unilateral actions. Finally, the uncertainties in the benefits and costs and the long time frames complicate the process for setting efficient GHG emissions targets. Heal (2009) discusses the costs of climate change at a very aggregate level (worldwide) by examining costs of action and costs of inaction. Heal concludes there is a strong case for justifying immediate action on climate change, regardless of assumptions about discount rates or perceived levels of uncertainty, because of the risk for potentially irreversible damage to our natural capital, including agricultural and forest ecosystems. In his estimation, this risk is sufficiently high and of sufficient magnitude to merit public action to reduce the probabilities of irreversible changes to our natural capital.

The importance of how carbon policies are structured is evident in recent testimony on the House-passed climate bill (H.R. 2454) regarding the aggregate and distributional impacts on the agriculture sector. The bill is basically a cap and trade regime for GHG with opportunities for an offset market. The basic workings of these types of policies are discussed later in this paper. Under current proposed legislation, agriculture is not included in the “capped” sectors but the bottom line for the agricultural sector remains as uncertain since inputs and prices will be impacted. An analysis of HR2425 (USDA, 2009) suggests over the next 50 years energy costs could become almost 10 percent of the share of total production costs, up from about 1 percent currently, due to higher fuel and fertilizer costs. An offset market for carbon emissions, the selling of carbon credits generated primarily through terrestrial carbon sequestration, could minimize some adverse cost impacts on this sector. However, while agriculture could benefit from a “properly-structured cap and trade” program, not all sectors within agriculture will benefit equally. As economists frequently note, the magnitudes of the potential changes in carbon, as well as the transaction costs associated with monitoring and verifying the carbon amounts will differ spatially and as a result this specific type of policy will produce winners and losers among existing agricultural sectors. Much of the needed information on how farmers and ranchers will respond to the proposed climate/carbon legislation (i.e. how production costs and land use will change, and how carbon prices facilitate development of a market for carbon offsets) have yet to be completed on the spatial scale necessary for predicting how the agricultural sectors in Oregon may fare under a cap and trade or other Incentive based policies. There are projects in place at OSU and other regional institutions that are examining these

critical questions. The USDA through its NIFA competitive grants is supporting this research.

### 8.1.1 Aggregate Estimates

The Intergovernmental Panel on Climate Change (IPCC) (2007) and Stern (2006) reports have triggered a substantive effort in economic assessment and writings on climate change. In light of all recent research it is useful to briefly summarize the current estimates on benefits and costs of action to reduce GHG levels from an aggregate perspective.

The IPCC (2007) estimates the cost of maintaining CO<sub>2</sub> concentrations below 450 ppm as less than 3% of world GDP/yr by 2030. The Stern Review (2006) estimates the costs of maintaining concentrations in the 500-550 ppm range at approximately 1% of world GDP/yr. How do these numbers translate into dollars? If we assume the average cost per ton of CO<sub>2</sub> reduced is \$40 (based on the IPCC estimates of carbon dioxide Capture and Storage costs), then reducing emissions by 30 gigatons (to get us to a reasonable "target ppm") implies, according to Heal (2009), a total cost of \$1.2 trillion.

As noted above, quantifying the costs of climate change inaction is more controversial because it requires a connection between changes in climate and changes in human responses and ultimately human welfare. Many of the integrated assessment models (IAMs) suggest the costs of climate change would be close to 2% of world GDP. Stern (2006) on the other hand, suggests the costs of climate change could be between 5-20% of world GDP, depending upon the assumption made with respect to adaptation and technology changes.

### 8.1.2 Economic valuation of the physical changes to natural capital

Economic valuation of the changes in functioning ecosystems has been the subjects of significant research and controversy. Stated preference techniques are often used to measure nonuse values (Jaeger, 2005, Chapter 14). The question of valuation can be cast in terms of willingness to pay (WTP) for a change in the status quo (or in this case, a change in the unregulated progression of climate change) or willingness to accept (WTA) compensation for a decrease in available goods or services. Both WTP and WTA measures are contextual and depend upon income, prices, and current consumption levels of the items in question. A third means of assessing the value of changes to natural capital takes the replacement cost approach. Replacement costs are easier to estimate for damages to market goods and services, such as productive farmland where the damaged crop (reduced yields) has a quantifiable value. Estimating the value of damages to non-marketable goods and services such as an ecosystem adjacent to and overlapping farmlands however is more complex. In these non-market cases, the cost to restore the ecosystem can be used as a means of making society "whole" from damages rather than the WTP or WTA methods. This approach has been upheld in many legal instances regarding natural resource damage assessment (Kopp and Smith, 1993). The Exxon Valdez oil spill and the more recent BP oil well disaster in the Gulf of Mexico involve natural resource damage claims. As a result, both oil spills/leakages have focused national attention on the magnitude of damages that can occur from the release of crude oil and raised public awareness of damage assessment process as well as the difficulties in quantifying damages. Climate change also causes damage to ecosystems and natural environments, and replacement costs may serve as a basis for future valuation of the economic impacts to natural capital and



functioning ecosystems.

## 8.2 Climate change impacts for Washington and California

This section summarizes published impacts of climate change on selected sectors in Washington and California. The sources of this information are: (1) Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate (Climate Impacts Groups, 2009) and (2) Climate Action Team Biennial Report for California (Climate Action Team, 2009). Both Washington and California have invested significant resources into better understanding the impacts of projected climate changes and have had state-wide committees in place for about five years. Their proximity and similarities across key sectors provides a reasonable ground for extrapolating climate change impacts in the absence of completed Oregon specific climate change research. Other sections in this chapter present suggested future areas of research to more fully comprehend and quantify the economic dimensions of climate change in the state.

From these two reports the assumptions made with respect to climate change are primarily as follows.

- Increase in average annual temperatures of 0.5 °F per decade.
- Average annual precipitation not projected to change significantly, however more precipitation as winter rain is possible.
- An earlier snow pack melt reducing summer water availability.
- Increase in atmospheric CO<sub>2</sub> which in turn promotes plant growth.

### 8.2.1 Water Resources

*Washington.* In the Washington Climate Change Impacts Assessment, water resources in Washington were separated into regional hydrology, and water management in the Yakima River Basin and Puget Sound region. The climate change models suggest increasing temperatures will have a negative impact on snowpack, soil moisture, and stream-flow (hydrology) due to the low elevation at which snow accumulates. The models project that the April 1 snowpack, a common indicator of summer water supply, could decrease over 28% on average across the state by 2020, over 38% by 2040 and over 50% by 2080, from the historical 1916 to 2006 average. In addition, warmer temperatures are likely to increase winter stream flows while reducing spring and summer stream flows as more winter precipitation falls as rain. Overall annual runoff, however, is projected to increase by up to 2% by 2020, 2 to 3% by 2040 and 4 to 6% by 2080 due to increased winter precipitation. With regard to water management in the Yakima River Basin, current projections suggest junior water right holders may experience limited water availability as "water shorts" are projected to increase from 14% of the time to 32% by 2020, 36% by 2040, and 77% by 2080. "Water short" results in a loss of 25% of a junior water right holder's water right. The Puget Sound region will, in general, not be adversely affected, although, insuring summer seasonal stream flow for fish protection could limit summer hydroelectric power generation.

*California.* Climate change models predict reduced water availability as the region experiences dryer and warmer climatic conditions. Population growth in California is projected to double municipal water demand by the end of the century. Given the current challenges to water distribution in the region, the report assumes measures will be taken to develop appropriate water storage and distribution infrastructure to accommodate shifting precipitation patterns and thus minimize water shortages. However, these adaptations are projected to cost hundreds of millions of dollars, which realistically could be counted as a cost of climate change.

### **8.2.2. Energy Supply and Demand**

*Washington.* Changes in seasonal precipitation are projected to have substantial impact on hydroelectric power generation which accounts for more than 2/3 of the electrical energy production in the Pacific Northwest. It is projected that winter power production will increase up to 4% by 2040 compared to historical 1917 to 2006 levels, and about 10% by 2080 while summer power production is projected to decline by about 10%, 15%, and 20% by 2020, 2040, and 2080 respectively. This shift in power production is likely to increase power distribution challenges as projected population growth in the region will increase summer power demand for air conditioning.

*California.* Projected increases in temperature will increase demand for cooling during summer months, increasing consumer costs by several billion dollars over current levels by century's end. Hydroelectric power generation from high elevation reservoirs is projected to decline as seasonal precipitation patterns shift. However, there is tremendous uncertainty regarding the development of the power generation and distribution system.

### **8.2.3 Agriculture**

*Washington.* The Washington report focuses upon Eastern Washington crops of apples, potatoes and wheat. The climate models project minimal short-term impacts on these crops, however by the end of the century the region could experience crop yield reduction approaching 25%. This projection assumes that irrigation water is not limited although climate change models suggest shifting precipitation could impact water availability. Climate change may also have a significant impact on Washington's wine industry as increased temperatures could limit production of some wine-grape varieties. However, the regions' microclimates limit the usefulness of broad generalization of climate change impacts. A third element of Washington agriculture is livestock products. It is projected that increases in average annual temperature will negatively impact animal food consumption and therefore lower the rate of milk and meat production thus increasing per unit cost of production.

*California.* Climate change is projected to reduce water availability as well as increase temperature and increase atmospheric CO<sub>2</sub> levels. Research into the impacts of temperature and CO<sub>2</sub> (Costello et al., 2009) suggests the combined effect will be a net positive on crop yields. However, climate change models suggest water will be limited in the future due to shifting rainfall patterns. Research by Howitt et al. (2009) suggests approximately 25% of irrigated cropland could be idled by water restrictions. These economic impacts of climate change can be measured directly as loss in income to land owners and workers.

#### **8.2.4 Forests**

*Washington.* As with agricultural production, the significant impacts of climate change to forests result from projected reduction in summer precipitation and therefore water availability. In the case of forests, limited water increases the magnitude of fires. Forest fires are projected to double the average annual acreage burned reaching 0.8 million acres by 2020, 1.1 million acres by 2040 and 2.0 million acres by 2080. The reduction in water and increase in temperatures is also projected to increase disease and insect pest damage as host trees become more stressed toward the end of the century. Finally, as with other plant species, changing climatic conditions are projected to shift the distribution of commercially valuable tree species reducing the area suitable for timber production.

*California.* The impacts of climate change on California forests are mixed. The increase in temperature and CO<sub>2</sub> level are likely to enhance timber production, however if other producing regions experience similar beneficial growing conditions timber markets could be over supplied placing downward price pressure on the market. Climate change models also project an increase in disease and forest fires which increase forest management costs.

#### **8.2.5 Coastal Regions**

*Washington.* The projected increase in sea level along the Washington coast could shift beaches inland and potentially jeopardize coastal infrastructure such as ports in Seattle and Tacoma which are currently just above sea level. Climate change is also projected to negatively impact shellfish as ocean acidification, algal blooms, and lower dissolved oxygen levels are expected to reduce fish and shellfish populations.

*California.* The impacts of climate change on California's coast have many facets. First, the high density of population in close proximity to the coast increases risks to critical municipal infrastructure as well as private property. Protecting this infrastructure, or rebuilding it, would cost billions of dollars. Changing coastline conditions could also result in fewer tourists and visitors to the state's coastal recreation locations in turn reducing revenue by hundreds of millions of dollar by the end of the century.

### **8.3 Oregon: Review of impacts from the Climate Leadership Initiative 2009 report**

The assessments presented in this section are taken from the 2009 Climate Leadership Initiative (CLI) report (Climate Leadership Initiative, 2009). This study illustrates the potential costs Oregonians might incur in the near term (2020) and projected out to 2040 and 2080 under a business-as-usual (BAU) case where government does not step in with any policies to curb climate emissions, the climate projection are based on high emission scenarios predicted by the

IPCC report, and producers, consumers, and all Oregonians do not alter or change their behavior in the face of rising prices and restricted choices. Thus, from an economic perspective it is a “high end” assessment of the impacts because there are no price responses or changes in behavior. It abstracts from many responses but still provides valuable information and reflects a systematic effort to sort through impacts using existing data. Because of this systematic effort, the estimates might best be used in a relative, but still limited, sense.

While the CLI report has these limitations which are clearly noted by its authors, it does provide an initial benchmark to gauge impacts of lesser climate responses, impacts of adaptation of both environments and people, and impacts of policies to address adaptation and resource scarcity. This report provides only one piece of the picture: the potential, gross costs that might materialize in this state over the next several decades, if societies here and elsewhere fail to address climate change and by proceeding in a business as usual manner.”(p. iii). This study also recognizes two other ifs: if the projections on climate change by the IPCC are correct and if agents (consumers and producers) do not respond to changing market conditions (2nd paragraph, p. iii). The CLI report also acknowledges the omission of some sectors of the economy which may result in cost understatement.

Key components of the CLI framework (pp iii-vii) are:

- (1) Costs reflect costs produced by climate change itself (loss of income, etc.) and costs generated by some BAU activities contributing to climate change, such as continued use of greenhouse gas emitting energies, fossil fuels, and nitrogen fertilizers
- (2) Atmospheric concentrations used in the various scenarios of CO<sub>2</sub> are 400 ppm by 2020, 500 ppm by 2040, and 800 ppm by 2080.
- (3) Global temperature rises by more than 5C° (9F°) by 2080.
- (4) Higher temperatures increase incidence of heat-related health problems and ecosystem changes such as reduced stream flows.
- (5) BAU practices: continue to use fossil fuels to generate electricity, consume the same levels of energy (no demand response to higher prices), and continued use of 2010 technologies for production and services.

While these are admittedly unrealistic assumptions, one would need a model of technology development and adoption to predict energy patterns and energy technologies.

The major components of potential climate-change costs are as follows

- Health-related costs of about \$770 million per year.
- Reductions in salmon populations, valued at \$630 million per year.
- Reductions in recreational activities valued at about \$170 million.

In addition, continuing activities contributing to climate change would potentially cost

Oregonians almost \$1.3 billion per year in missed opportunities to implement energy efficiency programs and about \$33 million per year in health costs from the use of coal to generate electricity. According to the CLI report, climate change could cost an "average" Oregon household \$1,930 per year by 2020 (approximately 4% of income). Of this amount, \$830 relate to expenditures on energy, \$460 relate to health-related costs, and \$370 to the adverse effects of climate change on salmon populations. Extending this out to 2040 and 2080, the CLI report suggests the potential costs represent more than 5% and 7% of median household income respectively. The calculations for describing the BAU estimates of the cost of inaction are provided on pages 11-14 of the report (attached). Figure 2 in the CLI report describes some additional impacts of climate change not quantified in the 2009 report. A few cautionary points are again noted; below

- The CLI report recognizes the potential for mitigation and offsets some of the above costs in the near term by taking advantage of the potential economic benefits of climate change such as increased production of some crops or reduced expenditures on heating that might accompany moderate climate warming.
- The CLI report is useful in describing the potential consequences if such adjustments are not realized while projections and spatial distributions of climate change are realized.
- Further investigation through the Oregon Climate Change Research Institute (OCCRI) effort is required to determine the extent of these opportunities as well as other likely mitigation efforts, but the CLI report serves as one baseline to begin looking at the economic impacts of a BAU scenario.
- Since there are no behavioral responses, no technological innovations, and no price responses built into the CLI analysis, projections for 2020 (as opposed to the projections for 2040 and 2080) are probably the estimates that are least error-prone since they do not project out many decades and have perhaps the least amount of uncertainty regarding human behavioral and environmental changes.

## **8.4 Toward Addressing the Economic Impacts of Climate Change on Oregon's Agricultural Sector**

U.S. agriculture is one of the most important sectors of the economy and is highly dependent on climate; this is especially true in Oregon. Farms and ranches are the largest group of owners and managers of land impacting ecosystem services, such as greenhouse gas (GHG) mitigation, water quality and quantity regulation, and wildlife habitat and biodiversity conservation. In addition, U.S. agriculture is playing an increasingly important role in the energy sector through biofuels production. Consequently, the impacts of climate change on agriculture, the impact of policies designed to reduce GHG emissions, and agriculture's ability to adapt to and mitigate the impacts of climate change are critical issues for agricultural households, the general public and public policy decision makers. Discussions regarding climate change challenges for farmers and ranchers and assessing its impacts are bracketed by an understanding of two issues: 1) the types of carbon mitigation policies proposed and their likely impacts on agriculture, and 2) the findings from research on the adaptation of agriculture to climate change. Understanding mitigation and adaptation are essential; and understanding how "well" agriculture can both mitigate and adapt are fundamental to analyzing the potential impacts of climate change and

carbon policies. What we do know is there are tradeoffs between ease of adaptation and the costs of mitigation, and these tradeoffs will vary spatially and over time.

#### **8.4.1 Adaptation and Impact**

Since the first assessment of climate change was published by the Intergovernmental Panel on Climate Change (IPCC, 1990), substantial efforts have been directed toward understanding climate change impacts on agricultural systems (Antle, 2009, and Antle and Capalbo, 2010, for a more extensive discussion).

Agricultural adaptation can occur in many ways at the individual field level. Farmers make management decisions such as crop variety, tillage, fertilization, and pesticide application based on environmental conditions and policy incentives. Beyond the farm gate, many other decisions are made affecting the economic environment in which farms operate, including infrastructure investments, research and development, and public policy.

Impacts of climate change on agriculture can be quantified in physical and economic terms. Physical impacts can be measured in terms of changes in total production or productivity (e.g., crop yields or total factor productivity), and tracking the spatial and temporal distribution of these changes. In economic terms, impacts can be measured in many ways, including (a) changes in farm-level impacts, such as the gross value of production, cost of production, net value of production, and farm income and (b) changes in aggregate or market impacts, including the value of production, consumption, and trade.

Research suggests that in highly productive regions, such as the U.S. Corn Belt, the most profitable production systems may not change much as a result of a changing climate. However, in transitional areas, such as the zone between the Corn Belt and the Wheat Belt, substantial shifts may occur in crop and livestock mix, productivity, and profitability. Such changes may be positive if, for example, higher temperatures in the northern Great Plains were accompanied by increased precipitation, so that corn and soybeans could replace wheat and pasture presently dominate in the region. On the other hand, such changes could be negative if already marginal crop and pasture land in the southern Great Plains or southeast became warmer and drier. In addition to changes in temperature and precipitation, another key factor in agricultural productivity is the effect of elevated levels of atmospheric CO<sub>2</sub> on crop yields. Some studies suggest that higher levels of atmospheric CO<sub>2</sub> may increase the productivity of small-grain crops, hay, and pasture grasses by 50% or more in some areas. However, it should be noted these effects are likely to be constrained by other factors, such as water and soil nutrient availability. Climate change and elevated CO<sub>2</sub> may also shift pest populations and increase weed growth raising crop management costs. The potential adverse effects of increased pest pressures as a result of climate change are not well understood and needs further research.

According to a U.S. assessment study, the aggregate economic impacts of climate change on U.S. agriculture are estimated to be very small, on the order of a few billion dollars (compared to a total U.S. consumer and producer value of \$1.2 trillion). This positive outcome is due to consumer benefits that are greater than the negative impacts on producers. Impacts on producers differ regionally; for some impacts are positive and for others they are negative. The

overall producer impacts are estimated to range from  $-4\%$  to  $-13\%$  of producer returns, depending on which climate model is used.

The impact assessments cited above do not consider many of the potential impacts of climate change on the food transportation, processing, and distribution sectors. Only recently have some studies begun to assess impacts of proposed GHG mitigation policies on production agriculture, input production and distribution, output transport, and food processing and distribution systems. Recent experience with higher fossil fuel costs suggests these impacts may be more important for farmers and consumers than the impacts of climate on productivity. Thus, by largely ignoring possible impacts of mitigation policies, the impact assessments carried out thus far may have missed some of the most important long-term implications of climate change.

Many existing agriculture and food sector policies are likely to affect adaptation to climate change. However, climate change is generally not the focus of many of these policies and potentially provides contradictory signals to producers and consumers. Therefore, future climate change policy design should assess the outcomes of existing overlapping policies in order to craft a cohesive policy environment for all stakeholders while taking adaptation into consideration. (A complete discussion can be found in Antle, 2009).

Some examples of existing policies and their possible effects on climate change adaptation include the following:

- Agricultural subsidy and trade policies which reduce flexibility and have unintended consequences for global markets.
- Disaster assistance and production and income insurance policies. While providing some protection against climate variability and extreme events, these policies may also reduce the incentive for farmers and ranchers to take adaptive actions.
- Soil, water, and ecosystem conservation policies. These policies protect water quality and enhance ecosystem services such as wildlife habitat. However, they may also limit a producer's options when responding to climate change or extreme events by reducing the ability to adapt land use to changing conditions.
- Environmental and agricultural land use regulation. Regulations for locating confined animal production and the disposal of waste from these facilities are likely to affect the costs of adaptation.
- Tax policies affect agriculture in many ways, and could be used to facilitate adaptation. For example, favorable treatment of capital depreciation and investments needed to offset GHG emissions would reduce the financial burden of adaptation.
- Energy and GHG mitigation policies are likely to have many impacts on agriculture as a consumer and producer of energy. Development of new bio-energy production systems and GHG offset policies may benefit agriculture and facilitate adaptation. The increased cost of fossil fuels associated with GHG mitigation policies will likely adversely affect farmer income, however, they also provide an incentive for adaptation. In the 20th century, public sector investment has played a substantial role in the success of U.S. agriculture. This active investor involvement by the public sector raises a number of questions about appropriate policies in the context of climate change (Burney et al., 2010). A key question is whether agricultural markets can adequately respond to climate changes on their own or does climate change require an

expanded policy role.

Examples of areas for public policy activity may be:

- Estimation of adaptation costs and reassessment of impacts.
- Breeding climate-resilient crop and livestock varieties.
- Adaptation of confined livestock and poultry production to climate change and extremes, and development of sustainable livestock waste management technologies.
- Assessing the impact of climate change on insect pests, weeds and diseases and their management.
- Quantifying the effects of adaptation strategies on ecosystem services associated with agricultural lands.
- Provide information on long-term climate trends.
- Assessing implications of energy policies and GHG mitigation policies for agriculture and the food sector.

#### **8.4.2 Current Contributions of Agriculture to the Oregon Economy**

Total Oregon agricultural output in 2008 was valued at \$4,883 million up 2.2% from the 2006 to 2008 average of \$4,778 million (Oregon Department of Agriculture, 2009). Oregon's agriculture output is very diverse with crops making up 72.7%, livestock 21.1%, forest products 2.6% and fisheries 3.0% of the total. The top 5 commodities in 2008 were: nursery and greenhouse products (\$820 million), hay (\$613 million), grass seed (\$510 million), cattle and calves (\$427 million), and milk (\$412 million) (Oregon Department of Agriculture, 2009).

##### *8.4.2.1 Potential economic impacts of climate change on agriculture in Oregon*

Climate change predictions project a 0.5 °F increase per decade over the next several decades and no significant changes in precipitation levels in the Pacific Northwest, although winter season precipitation may shift from snow to rain.

Quantifying the impacts of climate change has two facets. First, it must be understood how projected increases in CO<sub>2</sub> and temperature impact agricultural production systems. Then the impact of increases in "unseasonal" weather anomalies must be applied to the quantification process. There is limited research on the impact of increased CO<sub>2</sub> and temperature on many of Oregon's agricultural products as most are specialty crop production systems.

Research performed by the states of California and Washington to assess climate change impacts on their agricultural sectors suggests projected increases in CO<sub>2</sub> and temperature, when combined, have a slight positive impact on agriculture production in the near term 2020 projection and a slightly negative impact in the longer term 2040 projection. In both cases the availability of water is the primary factor in climate impacts. In the Washington climate change assessment, if water was limited based upon reduced snowpack, agricultural losses would be greater, possibly in excess of \$100 million annually (Climate Impact Group, 2009). In the California climate change assessment, the assumed loss of irrigation water projects less land in production and therefore projected agriculture losses of \$1 to \$3 billion by the end of the century (Climate Action Team, 2009).

Oregon could experience losses similar to Washington if irrigation water is limited as a



significant portion of crops are irrigated during the dry summer growing season. However, additional research is required to more accurately estimate the impact of climate change on water availability for irrigation in Oregon. Quantifying the impact of the “unseasonal” weather anomalies is far more difficult as some variations are beneficial while others are detrimental. In addition, these anomalies are regional and do not have the same impacts across all producers. In recent years, Oregon farmers have experienced weather conditions that reduced output resulting in diminished returns as well as conditions causing excess production. Recently, the converse has been true as well for some agricultural market sectors. The net result of weather anomalies is likely increased production risks for specialty crop producers and therefore higher prices to consumers as agricultural markets become more volatile.

#### *8.4.2.2 Irrigation: limited water availability*

As with California and Washington, the impacts of climate change on Oregon agriculture are mainly expected to relate to water availability as projected temperature changes could result in shifting precipitation patterns across the state. West of the Cascade Mountains, across the Willamette Valley and through the coastal mountain range, Oregon currently experiences a wet winter season and dry summer season. East of the Cascade Mountains is a much drier climate. The Coastal region averages 60 to 90 inches of precipitation (Oregon Department of Agriculture, 2009). The Willamette Valley averages 35 to 70 inches of precipitation while regions east of the Cascade Mountains average 10 to 25 inches per year (Chapter 1).

Climate models suggest that as the region warms, winter snow precipitation will likely shift to higher elevations and snowpack will be diminished as more precipitation falls as rain. This transition is expected to have the greatest impact in eastern Oregon which relies heavily on snowpack for summer water. A reduction in water availability could significantly impact two important agricultural production regions: northeastern Oregon (Morrow and Umatilla counties) and east-southeastern Oregon (Baker, Harney, Klamath, Lake and Malheur counties). In 2008, Morrow and Umatilla counties agricultural production accounted \$750 million: 15.4% of Oregon’s agriculture sales and about 50% of Oregon’s grain production (Oregon Department of Agriculture, 2009). In 2008, Baker, Harney, Klamath, Lake and Malheur counties accounted for \$800 million in agricultural products; 16.4% of Oregon’s agriculture sales and about 50 percent of Oregon’s hay, forage, and cattle production (Oregon Department of Agriculture, 2009). These five counties also account for 50% of Oregon’s irrigation water use, 1.1 of the 2.2 trillion gallons or 1.2 million gallons per acre.

In east-southeastern Oregon, approximately 75% of farmers and ranchers, 3,057 of 4,085, have some irrigated land in production. On average, 18% of the agricultural land in the region is irrigated, well above the state average of 11%, and most, about 79%, use flood irrigation to water crops and pasture land. This contrasts with the northeastern region, Morrow and Umatilla counties, where almost 70% of irrigation water is applied with sprinklers.

In 2005, the east-southeastern Oregon region averaged 1.1 million gallons per acre, 50% more than the top producing agricultural counties in the Willamette Valley, Marion and Clackamas, which averaged 0.7 million gallons of water per acre (USGS, 2010; Oregon Department of Agriculture, 2007). Marion and Clackamas counties utilize sprinklers for all irrigation and they also benefit from higher precipitation levels, about 3 times the annual precipitation of many

counties in Eastern Oregon. Thus, shifting precipitation patterns that result in reduced water availability are likely to have a greater impact on agricultural producers in eastern Oregon than western Oregon.

A comparison of Oregon's irrigation use rate of about 2,900 gallons/day/acre to Washington, Idaho, and California shows California uses about the same amount of irrigation water (2,700 gallons/day/acre), Washington uses about 1/3 less (1,900 gallons/day/acre), and Idaho uses about 2/3 more (4,700 gallons/day/acre), water per acre than Oregon. Oregon's water use, in times of limitations, is complicated by the state's "use it or lose it" approach indicative of the Prior-Appropriation water rights system. The current system does not provide incentives for conservation or water sharing and instead encourages inefficient practices such as flood irrigation. Therefore, while climate change may reduce water availability, improved management practices and changes in water policy incentives could minimize negative impacts.

#### *8.4.2.2 Water resources and drought*

Climate change will have an effect on water resources, and on the frequency and intensity of drought. Adams and Peck (forthcoming) provide an examination of what is known about the effect of climate change on drought and how it relates to commercial agriculture and other water resource dependent sectors. The material in this section is taken from their draft (unpublished) report.

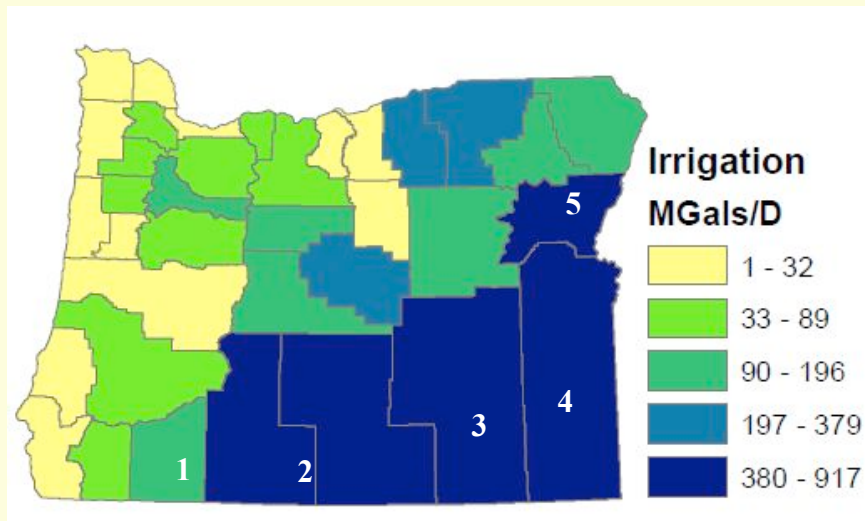
Global climate models (GCMs) predict annual-mean temperatures in the Pacific Northwest to rise by 3°F to 10°F over the next 100 years (Chapter 1). A changing climate will also produce numerous other climatic effects. Specifically, an ensemble of GCMs predicts a decrease in summer precipitation in Oregon in the next century (Chapter 1). Predictions for the central and eastern regions include an expected increase in winter precipitation for northern areas and a decrease in summer precipitation for southern areas. These projections reflect a range of potential effects of global climate change on water resources and agriculture including increased evaporation rates, increased global precipitation, increased proportions of precipitation received as rain, rather than snow, earlier and shorter runoff seasons, increased water temperatures, and decreased water quality. Precipitation patterns in the Northwest are also expected to become more variable, resulting in increased risk of extreme precipitation events, including droughts. More frequent and intense droughts arising from climate change would have serious management implications for water resource users (Adams and Peck, 2010). Water resource managers, agricultural producers, timber managers and policy makers can reduce the negative effects of drought through a number of strategies including revising water storage and release programs for reservoirs, adopting drought tolerant cropping practices, adjusting crop insurance programs, pre-positioning fire suppression equipment, and supporting water transfer opportunities. The ability to efficiently prepare for future drought conditions is currently limited, among other reasons, by imprecise long-term weather forecasts. Economic costs associated with drought could be further reduced with improvement in the ability to detect drought farther in advance, to more precisely forecast drought location and intensity, and to use such forecasts to refine basic drought management strategies. Increases in precipitation, given warmer atmospheric conditions, will not necessarily mean more available water. The associated higher evaporation rates are expected to result in less water availability for many regions. The greatest deficits are expected to occur in summer, leading to decreased soil moisture levels and

more frequent and severe agricultural drought. Simulation studies suggest precipitation must increase by at least 10% to balance evaporative losses resulting from a 7°F temperature increase.

Shifts in the timing of precipitation and runoff, specifically in snow-fed basins, are also likely to cause more frequent summer droughts. More precisely, rising temperatures are expected to increase the proportion of winter precipitation received as rain, with a declining proportion arriving in the form of snow. Investigations show that these changes are already taking place in the western U.S. and in Oregon (Nolin and Daly, 2006). It is also expected that snow pack levels will form later in the winter, accumulate in much smaller quantities, and melt earlier in the season, leading to reduced summer flows.

Changes in snow pack and runoff are of economic concern to water managers in a number of settings: hydropower generation, irrigated agriculture (as noted above), urban water supply, flood protection and recreational fishing. In agriculture for example, if the runoff season occurs primarily in winter and early spring, rather than late spring and summer, water availability for summer-irrigated crops will decline causing water shortages to occur earlier in the growing season, particularly in watersheds which lack large reservoirs. Timing of runoff will affect the value of hydropower potential in some basins if peak water run-off occurs during non-peak electricity demand. Shifts in runoff, precipitation, and evaporation patterns may also intensify interstate and international water allocation conflicts. Additionally, reductions in surface water supplies may increase reliance on groundwater for agricultural production, a response to prolonged drought already observed in many coastal areas including those in the West. Drought results in substantial economic losses in agriculture and energy sectors and has profound effects on local communities. More frequent or intense drought implies increased costs to society, unless agricultural producers, water users and others are able to adapt. More accurate, precise and timely forecasts can reduce the risk for decision makers and decrease economic losses due to drought. Current drought management tools can also be reassessed and revised. For example, drought insurance programs may need to revise coverage conditions and premiums to reflect a changed climate. Adoption of more drought accommodating practices and enterprise mixes could also reduce losses during extreme weather events. Reservoir capacity, timing of water releases, and safety will need to be reconsidered and possibly altered. Voluntary water transfers, with or without climate change, will become an increasingly important tool. Municipalities drawing on water supplies vulnerable to drought, pollution, and saltwater intrusion may need to consider new protection programs and supplemental water sources. Improved confidence in regional forecasts of climate change impacts is, however, of primary importance in helping managers understand risk levels, identify management priorities, and define realistic adaptations.

## Case Study 1: Oregon irrigation



**Figure 8.1** 2005 Total irrigation water withdrawals by county with top irrigation water use counties: Klamath(1), Lake(2), Harney(3), Malheur(4), and Baker(5) noted. (U.S.

In 2005 there were, on average, 7.174 billion gallons per day drawn from Oregon surface and ground water sources, 79% of the water was used for irrigating agricultural crops (U.S. Geological Survey, 2010). Over half of the irrigation water draws occurred in the south eastern region made up of Klamath, Lake, Harney, Malheur, and Baker counties (Figure 8.1). Climate models project increasing temperatures and shifting rain fall patterns toward the middle and end of the century. These climatic changes could have a significant impact on water availability in these high use counties as they rely heavily on melting snow pack to provide summer water. The projected warmer temperatures could result in more rain in late winter and early spring accelerating the melting process. On average, 18% of the agriculture land in these counties is irrigated, however, 34% of the agriculture land in Klamath is irrigated while 10% of agricultural land in Harney is irrigated (U.S. Department of Agriculture, 2009). Most of the irrigation water in this region, about 80%, is applied by flooding the field or pasture rather than with sprinkler or micro-irrigation systems. Flood irrigation is the least targeted means of applying water to crops. If irrigation water becomes limited as a result of climate change, growers will need to invest in the more efficient sprinkler or micro-irrigation systems to keep the farm as productive as when water was less scarce. These more efficient systems can cost thousands of dollars per acre to install.

U.S. Geological Survey. 2010. Oregon water use program 2005 water use compilation irrigation totals. Access 05/28/2010 [http://or.water.usgs.gov/projs\\_dir/or007/or007.html](http://or.water.usgs.gov/projs_dir/or007/or007.html)

U.S. Department of Agriculture. 2009. 2007 Census of Agriculture: United States Summary and State Data. Vol 1. Geographic area series. Part 51. National Agricultural Statistical Service, Washington D.C. Accessed 06/22/2010 - [http://www.agcensus.usda.gov/Publications/2007/Full\\_Report/index.asp](http://www.agcensus.usda.gov/Publications/2007/Full_Report/index.asp)

## **Case Study 2: Oregon winegrapes**

Oregon's wine producers have experienced significant growth in terms of acres planted and wine revenue in recent years. In 2008, farm-gate value of Oregon's wine grapes acceded \$71 million up from \$26 million in 2005. Vineyard acreage has increased from 14,100 acres in 2005 to 19,300 acres in 2008 (Oregon Department of Agriculture, 2009; Oregon Department of Agriculture, 2007). Vineyard establishment is a long-term investment with the potential life of the vineyard in excess of 50 years and establishment costs approaching \$20,000 per acre (Julian et al., 2008). Pinot noir and Pinot gris are the dominant wine grapes produced in Oregon accounting for 58% and 14% of acreage and 64% and 12 % of wine grape value, respectively. Given the expected long life of vineyards and high costs to establish and maintain, the projected temperature increases associated with climate change could have significant impact on Oregon's wine industry. Pinot noir and Pinot gris are both cooler climate grape varieties, although Pinot noir is more heat tolerant, preferring average growing season temperatures in the high 50s°F to low 60s°F to develop optimal wine making characteristics (Jones, 2006). Therefore, if temperatures increase as projected, vineyards at lower elevations may no longer have the appropriate microclimate for premium wine production. This would force growers to choose between producing lower quality grapes, on average, or starting over with a wine grape better suited for the vineyards location.

### Case study 3: Environmental policy implications on water use

In 2001, drought conditions in the Klamath River basin, which includes parts of Klamath county Oregon, caused Endangered Species Act (ESA)-related restrictions of irrigation water withdraws costing farmers tens of millions of dollars. The dire economic consequences were caused by an unusual set of circumstances: low water inflows, high ESA in-stream flow and lake level requirements, and limited irrigation from groundwater sources along with the lack of effective water allocation mechanisms such as water markets. It is unlikely that similar coinciding conditions will occur in the future due to easing of ESA requirements and increased groundwater pumping capacity. However, Boehlert and Jaeger suggest that it is possible that the economic impacts of the drought could have been avoided had market driven water allocation policies been in place (Boehlert and Jaeger, in Press).

Boehlert, B. B. and W. K. Jaeger. In Press. Past and Future Water Conflicts in the Upper Klamath Basin: An Economic Appraisal. Water Resources Research.

## 8.5 Impacts of Climate Change to Oregon's Forest Sector

### 8.5.1 Current Contribution of Forests to the Oregon Economy

There are 30 million acres of forests in Oregon, covering 48% of the state's 63 million acre landmass (Figure 8.2). The federal government owns 60% of Oregon's forestland, 35% is privately owned, and 3% is owned by the state.

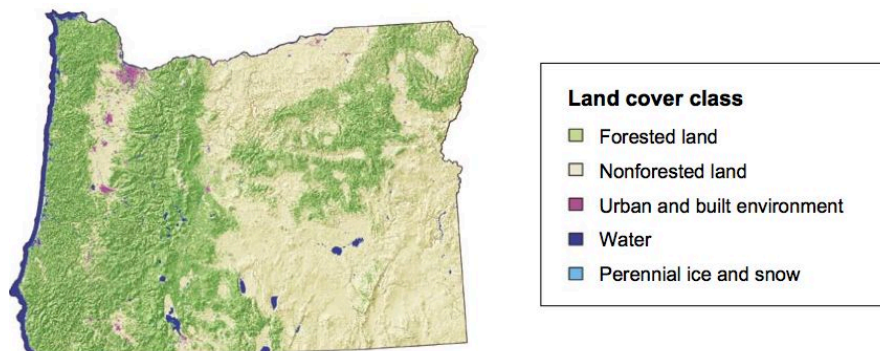


Figure 8.2 Forest land in Oregon. Campbell et al., 2004.

The moist Westside Oregon forests, where growth rates are highest, are dominated by young stands, whereas the dry Eastside forests have older, slower-growing stands. Most of the state's valuable saw-timber is located in the moist Westside forests, particularly under federal ownership. About 80% of the timber harvested in 2008 came from private lands, mainly on the Westside. Another 8% came from the state-owned timberlands on the Westside.

State-owned forests provide \$51 million to Oregon Counties, and \$9.2 million to the common school fund. Federal lands, with 60% of the forestland base, only produce about 9% of harvested volume. Oregon’s timber production has declined from a high of 8.7 billion board feet in 1986 to 3.4 billion board feet in 2008, largely as a result of decreasing harvests on publicly-owned national forest lands (Oregon Department of Forestry, 2009).

The forestry and logging sector directly employed 7,024 workers in 2008; the sawmill sector employed 7,472 workers in 2008 (Oregon Employment Department, 2009). Both of these figures declined in 2009 because of the housing slump and economic downturn, with 5,681 employed in forestry and logging, and 6,237 in sawmills. Oregon’s forests provide additional employment in administrative, governmental, firefighting, recreation, and scientific research positions.

**Table 8.1 2004 Contribution of forests to Oregon GDP, in \$billions, and employment.**

Wood product manufacturing	\$2.90
Paper manufacturing	\$0.90
Forestry, fishing, and related activities	\$1.70
<b>Employment in wood products</b>	<b>32,000</b>

Source: Climate Leadership Initiative, 2009

Forest management costs include the price of policy and legal enforcement, and the costs of firefighting. The Oregon Department of Forestry provides fire control on 15.8 million acres of public and privately owned forests. In 2008, there were 1,088 fires that burned 7,581 acres; in 2009, there were 990 fires on 7,040 acres. The state spends an average of \$9.5 million on wildfire suppression every year (Oregon Department of Forestry, 2010). Two-thirds of these fires were human caused.

### 8.5.2 Economic Impact of Climate Change on Forests in Oregon

In describing the economic impacts of climate change to forests, Sohngen and Sedjo (2005) distinguish between: 1) flow effects, which are changes to annual tree growth; and 2) stock effects, or losses to current timber stands, such as from storm damage and forest fires. According to Kirilenko and Sedjo (2007), losses to stock from extreme weather events and insect infestations may surpass the flow effects of climate change, but at present, very few models incorporate stock effects.

Flow and stock effects will impact the timber industry and could impact emerging industries centered on carbon sequestration or biomass. Rates of growth influence timber management decisions and timber supply for harvest, with consequences for both forest landowners and timber producers. Stock effects can impact the timber industry by decreasing the supply of timber, and can also increase forest management costs, such as firefighting costs. Stock effects like storm damage can temporarily increase timber supply by providing a pulse of timber after the event (Box 1). We have listed relevant flow and stock effects below, and the potential

impacts to Oregon's forest economy.

#### **Case Study 4: *The mountain pine beetle, climate change, and timber availability***

In British Columbia, Canada, an unprecedented mountain pine beetle (MPB) outbreak has resulted in dramatic changes to the forest sector. The MPB epidemic is thought to be connected to a warming climate, and if so, illustrates the sometimes non-linear, unexpected, and devastating consequences of climate change. Measured in terms of visual tree mortality, the outbreak increased from 400,000 acres in 1999 to over 17 million acres in 2004 (Patriquin et al., 2007). The MPB is shifting the region's forests from carbon sinks to carbon sources, as productivity (NPP) is reduced, and respiration increased (Kurz et al., 2008). The management response has been to dramatically increase the harvest in the region, in some places to 60% greater than pre-infestation levels, referred to as the "uplift" (Patriquin et al., 2007). Long-term timber supply will be reduced because of dramatic die-backs, and so "the uplift in the timber harvest will result in a period of economic boom followed by an economic downturn due to timber shortages in the longer term" (Patriquin et al., 2007: 939). The range of the mountain pine beetle is also likely to increase in the future with further warming.

##### *8.5.2.1. Impact on forest growth rates*

Boisvenue and Running (2006) analyzed field and satellite-based data from 49 studies over the last 55 years and find the majority of research papers report a positive forest growth trend in areas where water is not the limiting factor for growth. For Oregon, this means forest growth rates are likely to increase on moist westside forests, where most private timberland in the state is located. These projected growth increases are due to temperature and precipitation increases, longer growing seasons, and increased CO<sub>2</sub> concentrations.

In Oregon's eastside forests, growth effects as a result of increased CO<sub>2</sub> are uncertain. In California, Battles et al. (2007) find Ponderosa pine growth rates may decline in mixed-conifer forests of the Sierra Nevada, though later models developed by the same team find Ponderosa pine growth rates may actually increase (Climate Action Team, 2009).

Latta et al. (2010) find yields in Oregon's forests are very likely to increase with rising mean temperatures. The authors developed a model that combines changes in productivity under several different climate scenarios from the fourth IPCC report. They find timber yields (potential mean annual increment) rise with predicted temperature increase. Their model also suggests higher rates of yield increase in eastern Oregon than in western Oregon. Much of the increase in yield is predicted in higher elevation forests (>3000 ft. elevations), which currently have lower growth rates and are dominated by federal ownership (Latta et al., 2010). Lower-elevation forests, which currently account for 83% of harvests, may realize less benefit from climate change (Latta et al., 2010).



#### *8.5.2.2. Emerging markets in the green economy*

Emerging and speculative markets may provide new employment opportunities and increasing forest revenues for private landowners. Two such markets are the biomass and carbon sequestration markets. However, policies establishing reliable biomass and carbon offset markets in Oregon need to be developed in order to realize their benefits. These benefits include the development of technology and expertise that can be exported to other economies.

##### *Emerging biomass market*

Oregon Forest Resources Institute (2006) identifies a number of opportunities for biomass creation from Oregon's forests, although currently there is little market incentive. In southwestern and eastern Oregon, management to reduce fire risk and restore forest health would produce small-diameter trees as a by-product, but handling small-diameter trees is expensive and current infrastructure is limited (Oregon Forest Resources Institute, 2006). A biomass market has been successfully developed in a number of places, including Sweden, where biomass is now the leading source for energy generation, after lawmakers prioritized fossil fuel independence. As a result, Swedish wood fiber prices have increased, and there are incentives for additional alternative energy research and investments (Global bioenergy industry news, 2010.). Although the biomass market is still nascent in Oregon, similar policy incentives would likely create a viable market for small-diameter wood, and facilitate restoration in the wildfire-prone forests. Small-scale and pilot projects have begun in several communities of central and eastern Oregon, including Warm Springs, Prineville, Wallowa, Sisters, and Lakeview. Policies may be pursued to encourage market development, such as a Renewable Portfolio Standard to require a minimum amount of electricity generation from biomass (Oregon Forest Resources Institute, 2006). In addition, biomass may become more competitive relative to fossil fuels due to future increases in fossil fuel taxes, subsidies for biomass production, and production mandates.

##### *Emerging carbon market*

Carbon markets are currently underdeveloped in the U.S. The Kyoto Protocol did not create favorable conditions for forest sequestration projects in carbon markets, as it focused on reducing emissions rather than creating carbon sinks. Still, the global carbon market was worth over \$10 billion in 2005; and though the U.S. has not yet created a national regulatory system, regional, state, and voluntary markets are being developed (von Hagen and Burnett, 2006). Oregon may have a competitive advantage in carbon markets because of the very high carbon sequestration capacity of its forests, and potential additional carbon sequestration in old-growth forests "would be worth billions of dollars" (Smithwick et al., 2002: 1315). Economic benefits could be realized through the establishment of a state cap-and-trade system, or a regional carbon market; but investment is necessary in infrastructure, including institutional structures, regulations, and knowledge necessary to develop a market (von Hagen and Burnett, 2006).

Participation in a carbon market requires a landowner to forego or delay timber harvests. Fletcher et al. (2009) find that at present prices few landowners in Massachusetts would participate in a carbon-offset market and that landowners favor markets with no penalty for withdrawal from the carbon program. Van Kooten et al. (2009) conducted a meta-analysis of 68

studies and find the cost of creating carbon offsets through forest conservation activities, like delaying harvest, is about \$33 per ton of CO<sub>2</sub>, higher than their baseline for agroforestry projects. Similarly, Beach et al. (2009) analyze impacts of alternative GHG mitigation policies for forestry and agriculture, including bio-energy production. They find there is significant mitigation potential, but the price must exceed \$15 per ton of CO<sub>2</sub> to be cost effective. In a study focused on western Oregon, Im et al. (in press) find a carbon price of \$19 per ton would incentivize sufficient numbers of landowners to maintain early 2000s forest carbon flux levels.

These studies suggest few landowners will participate in forest carbon preserving management strategies until carbon offset prices increase significantly from current levels. The creation of a legitimate forest carbon offset market backed by a mandatory emissions cap and trade program could impact timberland owners' revenues as the price of carbon offsets would be expected to rise significantly. The current Chicago climate exchange, which is voluntary, has low carbon prices, less than \$1 per ton in 2009 (Ristea and Maness, 2009).

Creating a strong forest carbon offset market could fundamentally change the economics of timber growing. An offset market would create a financial incentive for longer rotations and thereby larger logs. Older, larger trees have a high conservation value because of their relative rarity, especially on private lands; in addition, larger logs could then contribute to higher value wood products and a stronger local processing economy.

#### *8.5.2.3. Timber stagnation and death: Insect and disease interactions*

Predicted timber yield increases as a result of climate change may be offset by insect and disease interactions. As an example, Swiss Needle Cast (fungus *Phaeocryptus gaeumannii*) is endemic to the Pacific Northwest. *P. gaeumannii's* detrimental effects on tree growth have become apparent in the last 30 years as it increased in extent to over 400,000 acres of affected trees (Black et al., 2010). Swiss Needle Cast leads to loss of needles, resulting in growth reduction in Douglas-fir trees, the most important commercial timber species in Oregon. Increasing severity and extent of Swiss Needle Cast is linked to climate change (Black et al., 2010). In 76 long-term plots located in undisturbed, old forests, van Mantgen et al. (2009) find that regional warming in the North American west has contributed to increasing levels of bark beetle caused tree mortality. In Oregon, increasing bark beetle mortality will likely impact pine species in dry eastside forests, where current infestations can cause economic losses and costs related to management and increased wildfire risk.

Root diseases such as *Armillaria*, common across Oregon, can cause tree mortality, leading to increased fuels and wildfire risks. Tree stress, caused by drought or insects, increases the spread of the *Armillaria*, and climate change will likely increase both incidence and extent of root diseases, at least in dry eastside forests (Klopfenstein et al., 2009).

#### *8.5.2.4. Increasing wildfire: Stock effects and costs*

If precipitation increases continue to occur mainly in spring and early summer (Mote, 2003), then forest fires may increase in both severity and extent. Large fire seasons in drier forests tend to occur when there has been a wet spring (increasing fuel load), followed by a dry summer (Westerling et al., 2006). Temperature increases would exacerbate this effect. Also, decreased precipitation rates in winter will reduce snowpack (Boisvenue and Running, 2006), which could

negatively impact growth rates in the drier forests east of the Cascades, and potentially increase the incidence of fires. The impact of fires on commercial timberlands in western Oregon may be mitigated by the fact these forests are highly accessible, which facilitates early detection and firefighting. The most likely scenario is that climate change will increase firefighting costs and property damage associated with fires within the wildland/urban interface in proximity to federal forestlands. In California, spatial scenarios for climate-related changes in wildfire probability and population growth were analyzed for changing patterns of damage under climate change scenarios (Bryant and Westerling, 2008). The authors forecast little change until later this century, and “a substantial portion of the increased economic loss is driven by the assumed increase in exposed value due to population growth and development in fire-prone areas” (Climate Action Team, 2009: 2.12).

Under business-as-usual assumptions, there could be 50% more wildfire acreage by 2020 and 100% more wildfire acreage by 2040 in Oregon (Climate Leadership Initiative, 2009). Multiplying these wildfire increases by projected losses to timber values at \$1000/acre, timber losses could be \$109 million in 2020 and \$223 million in 2040 (Climate Leadership Initiative, 2009). Currently, the Oregon Department of Forestry’s annual wildfire costs are approximately \$9.5 million, with about \$50 million spent in very bad fire years, such as 2002. Using linear projections based on a business-as-usual approach, Climate Leadership Initiative (2009) finds that firefighting costs in Oregon could increase to \$97 million in 2020, \$200 million in 2040, and \$444 million in 2080.

#### *8.5.2.5. Non-timber market effects*

Climate change will impact Oregon’s forest-based recreation economy. At a national level, Loomis and Crespi (1999) estimate the impacts of climate change (assuming a doubling of CO<sub>2</sub>, with increases of 4.5 °F and 7% precipitation) to forest-based recreation, such as camping and hiking, at about \$658 million by 2060. They estimate that snow-based industries such as skiing could have losses of over \$4.2 billion in 2060 (Loomis and Crespi, 1999). Starbuck et al. (2004) have modeled recreation behavior in New Mexico’s national forests and find that forest closures cause economic loss to local economies because of decreasing forest recreation. Similar research has not been conducted in Oregon, but revenue losses may be expected because of increased wildfires and decreased snowpack.

Non-timber forest products such as mushrooms, berries, and floral greens, will also be impacted by climate change. However, economic changes will be difficult to gauge as there is little research about non-timber forest products. In 1989, the forest-based floral greens market had \$128.5 million in sales in Washington, Oregon, and southern British Columbia, with the bulk of these sales in Washington (Schlosser et al., 1991). In 1992, the total contribution of wild edible mushrooms to Oregon’s economy was about \$25 million (Schlosser and Blatner, 1995).

#### *8.5.2.6. Interaction between effects*

Economic impacts of climate change are ambiguous, in part because of management and market adaptation: “adaptation in U.S. timber and wood-product markets will offset some of the potential negative effects of climate change” (Irland et al., 2001: 754). If timber growth rates

increase across the globe, this could have differential impacts for timber producers, timberland owners, and wood consumers. Generally, “increased forest growth leads to increased log supply, reductions in prices, and timber producer welfare (profits) declines, whereas consumer welfare (prices) increases” (Joyce, 2007: 470). Sohngen et al. (2001) find that while productivity gains benefit producers, wood prices globally would decline, resulting in net losses to producers in the Pacific Northwest. Consumers, however, would benefit from falling wood product prices (Sohngen et al., 2001). This could be offset by future increases in demand for woody biomass. Sohngen and Mendelsohn (1998) conducted an analysis combining climatological, biogeographical, biogeochemistry, and economic models with intertemporal adaptation. Their paper departs from previous steady-state analyses and other dynamic analyses that do not factor timber supply changes resulting from ecosystem changes; the authors incorporate biophysical disturbances, such as massive die-backs and gradual changes in tree growth and species distribution, as well as human and market responses (Sohngen and Mendelsohn, 1998). Sohngen and Mendelsohn’s dynamic analysis allows for market adaptation and adjustment to be factored into economic projections. Their findings are that all model combinations produce positive economic benefits for U.S. timber producers overall, particularly because of expected salvage from dieback and projected timber species shifts, as faster-growing softwoods become suitable for northern latitudes.

Irland et al. (2001) utilizes the Forest and Agricultural Sector Optimization Model (FASOM) (Adams et al., 1996) to project economic effects of climate change in timber markets, including forest management adaptations. FASOM is a dynamic model simulating timber inventory changes, consumer and manufacturer adjustments, shifts between agricultural and forest land uses, and landowner adjustments of forest management. Public land harvests and wood product imports are treated as exogenous variables. Irland et al. (2001) does not include stock or flow effects of insects, diseases, invasive species, or fires. Their 120- year projection finds generally positive results for wood product manufacturers due to increased timber supply and decreasing log prices. This echoes other research, with benefits to consumers and losses to timber growers due to overall lower prices.

Haynes et al. (2007) models large-scale impacts from fires and bark beetle outbreaks at historical levels and patterns, and does not incorporate many human responses (salvage, changed genetic stock) or ecological responses (species shifts), but does create a dynamic model having implications relevant to the Pacific Northwest. Their analysis finds that with a 6 °F change across the U.S., and a slightly higher temperature increase in the western U.S., 2050 softwood saw-timber prices would fall by 18% in the Pacific Northwest West (Haynes et al., 2007).

In California, Hannah et al. (2009), combine predicted shifts in species range with changing timber yield predictions, and find that climate change will result in a decline in harvested timber value of between 4.9% and 8.5%, depending on climate scenario. There is wide variability under the A2 climate scenario, with possibilities of slight timber revenue increase or substantial revenue decrease. Under the B1 scenario, timber revenue will likely increase.

Within forestry, projected climate change impacts include the following.

- Rising timber yields overall, but possible large-scale losses because of wildfire, insects, and disease.

- Declining timber prices because of increased supply.
- Possible new markets for low value timber, such as biomass and carbon sequestration markets.
- Rising management costs associated with wildfire suppression and other disturbances.
- Impacts on Oregon's non-timber forest economy, including projected losses for forest recreation.

Multiple knowledge gaps influence current economic research regarding climate change. In order to facilitate forest management and adaptation, a great deal of additional research is necessary. In general, research is currently somewhat impeded because climate, ecological, and management models are often scaled differently: "the spatial resolution of these current [climate] models is much larger than the spatial scale of forest management or of current ecological models" (Joyce, 2007: 480). In the future, existing models will need to be integrated at appropriate spatial scales, and large-scale models may be scaled down to Oregon. Second, existing models may be combined in novel ways to predict economic impacts to forests. For example, combining models incorporating the effects of Swiss Needle Cast with models assessing the effects of increased CO<sub>2</sub> on timber yield may project net effects on forest productivity. Such combinations are technically feasible, but have not yet been undertaken (Darius Adams, personal communication, May 2010). Future models could include the effects of increased vegetative competition, forest fires, insect and disease infestations, and damage from extreme weather events. While some studies have begun, these efforts (e.g., Sohngen and Mendelsohn, 1998), the effects of overlapping variables have not been integrated with projected impacts to Oregon's forest economy. Third, there are unknown impacts of species shifts across the landscape, "restrict[ing] the application of these models for management recommendations on planting of new species" (Joyce, 2007: 482). For example, the commercial range of Douglas-fir may shift with climate change, allowing for Douglas-fir planting at higher altitudes, which are dominated by federal ownership. Additionally, under a warming climate, timberland owners may have the option of planting fast-growing non-native species, such as loblolly pine, currently a common species in the U.S. South. Fourth, current models do not incorporate the effects of suburbanization and urbanization, which will undoubtedly impact Oregon's forest economy as population in the region grows. Some forestlands will be converted to non-forest residential purposes, regional consumer demands will increase, and wildfire risks and suppression costs will increase, especially at the wild land-urban interface. Current research is underway to include these urbanization effects (Darius Adams, personal communication, May 2010). Fifth, none of the developed models includes the potential impact of increased species listings under the Endangered Species Act. As species are listed as threatened or endangered, mitigation and regulation costs and no-harvest zones for habitat conservation will increase (Climate Leadership Initiative, 2009). An economic precedent is found in Oregon in the development of the Northwest Forest Plan in response to the ESA listing of the Northern spotted owl, which resulted in steep declines in harvest levels from public forests, temporary increases in stumpage prices on private forests, and long-term effects to community capacity and timber infrastructure in many parts of the state (Buttolph et al., 2006). Sixth, because with climate change forest fires will likely increase in both extent and severity, economic research focusing on the prevention and suppression of fires would help prioritize management decisions. In order to better predict forest fire costs, research needs to extend across ownerships, both public and private. Current political boundaries have little relevance for wildfire

suppression, though preventative measures, including funding and mandates for fuel breaks, thinning, and access, differ among ownerships. As with a number of other aspects of climate change, Oregon needs to look to other regions and countries for lessons on effective management and mitigation regarding climate change. For example, Australia has a “stay or go” policy in which residents are trained to fight wildfires threatening their homes, and to make informed decisions about staying with or leaving their homes in the face of a wildfire (Stephens et al., 2009). Seventh, research regarding the creation of carbon sequestration and biomass markets should continue, with particular emphasis on the many legislative and policy steps necessary to incentivize viable markets. For carbon markets, concerns about forest carbon permanence, leakage (displacement of timber harvests to other regions), and the tradeoffs between maintaining older stands with high stocks of carbon versus reforesting stands with younger, more vigorous trees, all need to be further explored in Oregon. Carbon market development should be considered in the context of regional and global markets, which will impact Oregon’s success. The U.S., E.U., and Australia each approach carbon market development differently, and studies need to address their various benefits and drawbacks. These include tradeoffs between different commitment periods, as long commitment periods lead to more stable investments, while short commitment periods may allow for market adjustments in response to scientific and other developments (Fankhauser and Hepburn, 2010a). There are also tradeoffs between taxation, cap-and-trade markets, and concerns over regional cost and policy differences as markets are linked globally (Fankhauser and Hepburn, 2010b).

Biomass market research is somewhat more developed; in 2005, Oregon’s governor created an interagency group (The Oregon Biomass Coordinating Group) to explore the development of new biomass energy markets as part of the statewide Renewable Energy Action Plan. Research should continue to focus on both landowner incentives and infrastructure development.

It is evident there are a number of uncertainties regarding the effects of climate change on Oregon’s forest economy. We currently do not have the tools necessary to answer the many research questions posed by the effects of a changing climate. More research is necessary to determine how to maximize the potential benefits of climate change for Oregon’s forest economy including potential competitive advantage in carbon markets, and the ability to export innovations. More research is also necessary to avoid damaging effects of climate change in Oregon’s forest economy, such as escalating costs of wildfire management and suppression. With climate change comes a great deal of uncertainty affecting investment possibilities, policy implementation, and timberland management. The forest sector in Oregon will face challenges and opportunities under a changing climate; what is necessary is to identify and capitalize upon opportunities, while preparing for and mitigating challenges.

## **8.6 Summary and Future Research**

We know that climate change will have multiple, and sometimes conflicting, impacts on Oregon’s economy. A full understanding of the economic impacts, measured as economic valuations of the potential physical impacts, is uncertain and continues to evolve. This

evolution is due to both improvements in the estimates of physical impacts and improvements in the economic science of measuring and valuing changes.

This chapter highlights some of the recent literature on economic impacts noting research needs and data. Like the conclusions from similar analyses in California and Washington, climate change will impose substantial costs to Oregonians, but these costs may be substantially reduced if global GHG emissions and thus climate changes (precipitation and temperature variability) are lessened through GHG mitigation policies and adaptation. Climate change mitigation and adaptation costs are being discussed at both federal and state levels. It is recognized that the feasibility and costs of these two options will vary by sector and region and are interdependent.

Despite the potential impacts of climate change on agricultural and food systems the resulting need to anticipate and adapt, climate change policy remains highly contentious. Climate change projections are uncertain, particularly at the spatial and temporal resolution relevant to agricultural systems. However, that should not deter investments in research to quantify the costs and benefits of alternative adaptive options and develop systems that are climate resilient.

The uncertainty of climate change raises many economic and policy questions regarding adaptation in agricultural and food systems. For example:

- What is the economic value of specific adaptations, such as systems and varieties more resilient to climate extremes?
- Can farmers, ranchers, and the food system beyond the farm gate successfully adapt to climate change with private investment or is there an increased role for public investment in research and development, and in the provision of public information?
- How would the array of public policies related to agriculture and the food system (climate mitigation, food safety, environmental, farm subsidies, trade, and energy, etc.) affect or be affected by adaptation to climate change?
- Should climate considerations be incorporated into other policies or can other policy objectives be met with climate change policies?

In 2010, the U.S. government announced major new research initiatives on climate change impacts and adaptation. Similar initiatives are being undertaken in other countries, and also under the auspices of the Consultative Group for International Agricultural Research. The Obama administration is undertaking an inter-agency review of adaptation options for the federal government. Thus, it appears to be an opportune time to evaluate mitigation and adaptation to climate change and climate policy implications, and to consider how to improve our ability to address these important questions as we move forward with an innovative climate change, agriculture, and energy research agenda.

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## **9. Human Dimensions of Climate Change: Public Knowledge, Attitudes, and Barriers to Change; Impacts on Cultural and Built Environment; and Potential Public Health Impacts**

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### **Summary and Knowledge Gaps**

To date very little research has been conducted explicitly with Oregon citizens regarding their understanding or attitudes about climate change. In this chapter we discuss results of four recent studies (all completed within the last 18 months) in the context of a behavioral change model that suggests that while individuals and groups need to know something about climate change to make appropriate behavioral changes—to either mitigate greenhouse gas emissions or adapt to changing climate—they also need to believe changing their behavior is important and worthwhile, and any barriers to behavioral change must be identified and addressed.

Two of the studies examine how different groups (private and public sector professionals along the Oregon coast and County Health Department professionals) understand climate change and how it affects their professional responsibilities and obligations. In general, the studies find a widespread acceptance of changing climate, although rural County Health professionals are less likely than urban professionals to accept climate change. And, in both contexts all respondents believe they have the capacity and expertise to address the most pressing impacts of climate change if barriers are removed including funding, policy changes, and management support. The other two studies surveyed members of the general public to characterize attitudes toward climate change, finding that many respondents identified climate change as an important issue facing individuals, organizations, and government agencies. The national American Values Survey also suggests a substantial portion of the population (36% nationally) is currently involved in activities directed at mitigating or adapting to climate change. While Oregonians participated in this national survey, we are unable to isolate the Oregon responses; however, a follow-up focus group was conducted in Oregon to validate the national responses. We should use the results of this survey carefully, although it does support findings of research focused only on Oregonians.

These initial and small-scale studies suggest that Oregonians know something about climate change and many are likely to perceive it as a problem although they may not know all the scientific details. There are cognitive and perceptual barriers needing to be addressed if we expect individuals or groups to change behaviors for either mitigating or adapting to climate

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change, although there appears to be general acceptance of, and desire for, government policies to direct such behavioral change.

Recent projects conducted by the Climate Leadership Initiative (CLI) examined the impacts of climate change on cultural and tribal resources, and the built environment more generally. While a lack of understanding and awareness persists about Oregon tribes' vulnerability and capacity to adapt to current and projected climate change, dependency on natural resources, confinement to small portions of reservation land, and existing stressors will likely increase their vulnerability to climate change impacts (CLI and NCCSP 2010).

Projected climate changes in precipitation rates and temperatures are likely to threaten the integrity of the built environment, including buildings, roads, highways and railroads, water and sewage systems, and energy facilities throughout Oregon (CLI 2008, 2010). Direct costs will result from flood events and anticipated increases in wildfire intensity and frequency due to climate change, while indirect costs are likely to be many times larger and will result from more rapid depreciation of property from higher temperatures, more intense storms and other climate stressors (CLI and NCCSP 2008). The full extent of impacts on cultural and built environments remains to be assessed in Oregon.

Finally, climate change is likely to have an impact on public health issues in Oregon including the spread of communicable diseases as well as an increase in water-, food-, and air-borne infections. Predicted average increases in summer temperatures will make heat waves a greater likelihood, causing heat-related morbidity and mortality, especially among vulnerable populations, such as the elderly, low income populations, pregnant women and those who work in outdoor occupations. Indeed, an increase in injuries and cases of carbon monoxide poisoning (from using gas-powered generators) has been reported as a result of the recent winter storms and subsequent flooding in Oregon. Increasing temperatures in Oregon could raise the threat of vector-borne diseases and emerging infections. Respiratory insults, especially among persons with pre-existing lung health problems would be exacerbated by exposure to smoke from forest fires, as well as from the projected increases in air pollution levels in our region. Air pollution and increases in pollen counts (and a prolonged pollen producing season) may increase cases of allergies, asthma, and other respiratory conditions among susceptible populations.

Additional research is needed to set baselines in order to monitor changes over time to understand more fully: (1) how a wide range of Oregonians who are likely to be affected by climate change due to the place they live, the job they hold, or the organization they work for, experience climate change impacts; (2) the acceptability of specific policy and behavioral changes to a wide range of Oregonians; and (3) the barriers faced by individuals, groups, and organizations, including state agencies, as they start to respond to the observed impacts of climate change in Oregon. While the studies reported in this chapter focus primarily on individual understanding and response to climate change, we have no current research regarding organizational or institutional capacity for carrying out any policy or operational changes required to adapt to a changing climate in Oregon. The Oregon Public Health Department has an ongoing tracking and monitoring program for most of the infectious and communicable diseases likely to be affected by climate change. The best means of fending off

any changes for the worse due to climate change are similar to those already in place: ensuring that changes in disease patterns can be detected, investigating as needed, and mounting an appropriate public health response as soon as possible.

## **9.1 Introduction**

This chapter examines recent research exploring what is known about how Oregonians perceive the issue of climate change and reviews a small number of projects that have attempted to assess and characterize the climate change impacts on cultural and built environments, including tribal resources. Finally, we briefly describe the mechanisms and potential effects of climate change on public health. References and additional resources are included at the end of the chapter.

To date, only a limited amount of social science research has focused on understanding public views of climate change in Oregon; and, of the four recent studies discussed briefly below, one is a national study from which we are unable to extract Oregon-specific results although it does shed some light on general knowledge and perceptions of climate change among the public. There has been extensive research in social science, however, in understanding what motivates behavioral change. A simplification of one such model, the theory of planned behavior (Ajzen, 1991), proposes that in addition to knowledge about a specific phenomena, individuals' values, as well as perceived and real barriers, all contribute to any decision to take action. This suggests that effective climate policies aimed at changing behaviors need to be based not only on climate knowledge, but also address the range of attitudes and values people hold about climate change, and any real and perceived constraints on their behavior.

## **9.2 Public Knowledge and Perceptions of Climate Change**

### **9.2.1 Oregon Coast Professionals**

In a study conducted in 2008 by Oregon Sea Grant (Borberg et al., 2009), 300 Oregon coast professionals from both the private (e.g., fishing, tourism including hotel and charter services) and public (e.g., local government, watershed councils) sectors were surveyed using an internet-based questionnaire. The findings suggest these respondents are highly concerned about a range of climate change effects, and feel responsible for mitigating and adapting to impacts. They also report that they generally feel that they do not have enough information about climate change to do their jobs effectively (see Table 9.1). Respondents were also asked a series of questions about who is responsible for taking both mitigating and adaptive action in response to climate change. As displayed in Table 9.2, three-quarters or more of the respondents believe that both individuals and government agencies need to take action on climate change issues. There is a generally wide-spread sense of both individual and collective agency—that we can and should do something to mitigate climate changing activities and adapt to climate changes as they occur. However, climate change information needs were found to be high, with coastal professionals having low amounts of information on topics that they consider important for the performance of their job (Table 9.1). In addition, this study provides some insight into



perceived or actual barriers to taking action to adapt to climate change. In general, respondents agreed that they would be willing to take action to respond to climate change if they had information that applied directly to their responsibilities, new funding, and a sense of local urgency.

**Table 9.1: Importance of Climate Change Issues to Oregon Coastal Professionals**

<b>Important Issue (n)</b>	<b>Climate Change Topic</b>	<b>Enough Information (n)</b>
84% (179)	Changes in flood elevation, shoreline erosion, and beach width	7% (138)
79% (168)	Effects of sea level rise on existing shoreline protective structures	7% (148)
78% (166)	Climate change effects on community infrastructure: water systems, sewer, streets, bridges, and public buildings	4% (161)
78% (165)	Changes in ocean conditions that may affect Oregon’s marine ecosystems, ocean productivity, or marine species composition	7% (132)
77% (163)	Updates on latest climate change scientific data and how the Oregon coast may be affected	5% (141)
76% (162)	Changes in rainfall, which may increase landfall	7% (147)
76% (164)	Climate change effects on coastal weather	7% (127)
74% (157)	Changes in frequency and intensity of storms and the potential effect on building design standards	5% (150)
74% (160)	Sea level rise predictions	14% (111)
71% (151)	Location-specific effects of climate change	4% (163)
68% (151)	Projected economic costs and benefits of climate change	4% (164)
66% (144)	Climate change impacts on energy resources	5% (155)
66% (139)	Changes in rainfall, which might alter ocean or bay salinity and other aspects of estuarine habitat	5% (154)
65% (137)	Changes in climate, which may introduce new diseases and pests to the area	3% (172)

Source: Borberg et al., 2009.

This study is limited by its convenience sample that is not representative of any population. We can use the results to deepen our understanding of public perceptions but cannot use the results to make predictions of other populations’ perceptions or understanding.

**Table 9.2: Individual and Government Responsibility for Climate Change Response in Oregon**

Statement	Agree or Strongly Agree (n)
It's important for individuals to prepare for the effects of climate change that are predicted to occur in Oregon by reducing local vulnerability.	80% (210)
It's important for individuals to take immediate steps to reduce the apparent causes of global climate change.	78% (209)
It's important for governments to prepare for the effects of climate change that are predicted to occur in Oregon by reducing local vulnerability.	77% (205)
It's important for governments to take immediate steps to reduce the apparent causes of global climate change.	75% (200)

Source: Borberg et al., 2009.

### 9.2.2 General Public

In a second study conducted by OSU and other researchers (Pierce et al., 2010), a random sample mail survey of more than 1500 Oregon households asked respondents about the role of renewable energy in the face of climate change. However, in one question respondents also revealed general attitudes about climate change (see Table 3). As shown below, about one-quarter of the respondents do not perceive climate change as a serious problem (and do not see the need for new renewable energy policies) although almost two-thirds (63.5%) perceive climate change as a moderate or serious problem requiring policy changes regarding renewable energy. While this study is mostly concerned about respondents' knowledge of renewable energy sources, it does reveal something about their general attitudes toward climate change as at least a moderate problem to be addressed through new policy efforts.

This study supports the idea that increasing awareness and knowledge of complex issues can lead to enhanced public support for policy efforts to mitigate climate change (as through the use of renewal energy technology in this study). And, because the individual and collective activities of citizens contribute to climate change, it's important to continue exploring the strength of the link between policy-relevant knowledge and support for specific policy decisions. In addition, strong support of the New Environmental Paradigm (NEP)—a cultural rather than knowledge variable—also contributes to preferences for policy actions. Van Liere and Dunlap's NEP indicator (see Dunlap et al., 2007) contained a subset of five of the twelve items found in the original inventory and has been found to generate results virtually identical to those of the twelve-item version. The items are as follows: (1) The balance of nature is very delicate and easily upset by human activities; (2) There are no limits to growth for nations like the United States; (3) Plants and animals do not exist primarily for human use; (4) Modifying the environment for human use seldom causes serious problems; (5) Humankind was created to rule over the rest of nature. A Likert-type response format was provided for each item, taking the following format: "strongly agree," "agree," "neutral," "disagree," and "strongly disagree." A pro-NEP position consists of agreement on the first three items, and disagreement on the last

two items.

These findings suggest that while it is important for citizens to understand climate change (and related policy activities), understanding and addressing citizens' values is critical to the development of public support for such policy actions. Again, this study does not provide information about any perceived barriers to changing individual behaviors, but there does seem to be a general acceptance among respondents that government policy is needed to move forward on both mitigation and adaptation efforts as represented by preferences for renewable energy policies.

**Table 9.3: General Attitudes of Oregon Citizens Regarding Climate Change and Renewable Energy**

Recently there has been much discussion about climate change and global warming due to years of human use of fossil fuels such as petroleum and coal. Some have called for the development of renewable energy sources—such as wind, solar, wave and geothermal—to reduce our reliance on fossil fuels. In general, which of the following views best describes your opinion in this area?	
Statement	% respondents agreeing
1. Do not know	1.6%
2. Climate change is not a problem; existing energy policies should be maintained.	25.6%
3. Climate change is a minor problem; only minor energy policy changes are needed to encourage the development of renewable energy sources.	9.4%
4. Climate change is a moderate problem; moderate energy policy changes are needed to encourage the development of renewable energy sources.	30.3%
5. Climate change is a serious problem; significant energy policy changes are needed to encourage the development of renewable energy sources.	33.2%
	N=1,480

Source: Pierce et al., 2010.

### 9.2.3 County Health Departments

The Climate Leadership Initiative (CLI) at the University of Oregon recently partnered with The Oregon Coalition of Local Health Officials, Environmental Health Committee to conduct a survey of public health care provider attitudes, practices, and preparedness for the health effects of climate change (Vynne and Doppelt, 2009). They received responses from 25 of 35 County Health Departments in Oregon. While 88% of respondents described climate change as a serious

or very serious problem, only about 40% of rural county representatives reported climate change as a serious problem. When asked whether their department is doing anything to change procedures or policies to reduce contributions to climate change, 53% reported changes in their department, primarily recycling programs (100%), energy conservation (46%), and purchasing practices (46%).

Only about 16% of respondents report that their department was doing anything to address potential health effects related to climate change although more than half of the departments report discussions have begun about potential human health effects. Among the more common concerns about human health impacts are vector-borne diseases, drought, forest fires, water quality, and health care service disruptions during climate-related emergencies (e.g., floods, fires, etc.).

Respondents were asked directly why they weren't planning for climate change and they reported that climate change related impacts were not a priority and other concerns are more critical; there is a general lack of awareness and/or interest by County Commissioners, clients, management, and staff; counties haven't seen impacts of climate change; and, not surprising, most (87%) report a lack of funding to address these types of concerns. This study also suggests County Health Departments' perceptions of their own capacity (generally low) to respond to impacts of climate change (see Table 9.4). More surprising, is the general lack of faith that the Oregon State Department of Health and Human Services or the federal government has the knowledge, expertise, and capacity to address these concerns.

**Table 9.4: Oregon County Health Department Representative Perceptions of Capacity for Dealing with Human Health Impacts of Climate Change** (Source: Vynne and Doppelt, 2009.)

	Strongly Agree	Agree	Disagree	Strongly Disagree	Don't know
My health department has the <b>knowledge and expertise</b> needed to develop strategies for dealing with potential public health impacts of climate change in my region.	13%	47%	41%	0	0
My health department has the <b>capacity</b> needed to develop strategies for dealing with potential public health impacts of climate change in my region	50%	38%	13%	0	0
The health care <i>delivery system</i> in my county has the <b>knowledge and expertise</b> ...	22%	34%	25%	0	19%
The health care <i>delivery system</i> in my county has the <b>capacity</b> ...	34%	44%	6%	0	16%
The Oregon Health Department has the <b>knowledge and expertise</b> ...	3%	9%	41%	3%	44%
The Oregon Health Department has the <b>capacity</b> ...	3%	32%	16%	3%	45%

The <i>federal government</i> has the <b>knowledge and expertise</b> ...	3%	13%	41%	13%	31%
The <i>federal government</i> has the <b>capacity</b> ...	6%	19%	22%	9%	44%

This study suggests to some extent how a specific set of Oregon professionals—County Health Care managers—frame climate change as a potentially serious problem for their constituents (and themselves). County Health Care managers report a limited set of climate-related health impacts that they consider potential future issues although they are not now perceived as such due to a set of real (and perceived) barriers that include funding, interest and attention by others, and a full plate of issues they already are not staffed to deal with. While County Health Departments view themselves with the capacity, knowledge, and expertise to handle future health impacts of climate change, they don’t receive much support from state or federal agencies.

#### 9.2.4 American Values Survey

Finally, the Climate Leadership Initiative (CLI) at the University of Oregon participated in collecting and analyzing national data for the American Values Survey (AVS) through the Social Capital Project (SCP) with a special emphasis on Pacific Northwest applications (Pike et al., 2008). More than 2000 adults participated in the project, answering a series of 800 questions about climate change and other topics. The national findings were validated through focus groups in Oregon and elsewhere. The AVS segments the respondents into ten distinct groups depending on how they think about the environment and their attitude toward its protection (see Table 5). The SCP “mapped” the presence of the different attitude segments in different communities in Oregon (and Washington). For more information and graphics visit the Social Capital Project website at [www.thesocialcapitalproject.org/The-Social-Capital-Project](http://www.thesocialcapitalproject.org/The-Social-Capital-Project).

In addition to characterizing the worldviews and perspectives of respondents, the AVS also characterized several interconnected perceptual barriers to changing behavior: (1) a sense that individual behavior is unlikely to make much of a difference; (2) it’s expensive to be “green”; (3) the complexity of climate change makes it difficult to determine direct cause and effect relationships; and (4) the magnitude of the problems is overwhelming so attention is turned to more local and tractable concerns.

If Oregonians are anything like the general population described in the AVS, about 36% of the population is likely to be engaged in or willing to be engaged in environmental activities. And, another proportion who consider “global warming” to be an important issue may also be mobilized through effective outreach. This study also identifies several perceptual barriers citizens have to changing individual behaviors and/or becoming engaged in collective activities although it doesn’t address other types of barriers (e.g., infrastructure, institutional practices, etc.).

**Table 9.5: Importance of “Global Warming” to Populations with Different World Views**

Segment	Percentage of Respondents	Percent ranking “Global Warming” as one of the most important issues
<b>Greenest Americans:</b> Everything is connected, and our daily actions have an impact on the environment.	9%	68%
<b>Idealists:</b> Green lifestyles are part of a new way of being.	3%	51%
<b>Caretakers:</b> Healthy families need a healthy environment.	24%	44%
<b>Traditionalists:</b> Religion and morality dictate actions in a world where humans are superior to nature.	20%	22%
<b>Driven Independents:</b> Protecting the earth is fine as long as it doesn’t get in the way of success	7%	29%
<b>Murky Middles:</b> Indifferent to most everything, including the environment.	17%	34%
<b>Fatalists:</b> Getting material and status needs met on a daily basis trumps worries about the planet.	5%	46%
<b>Materialists:</b> Little can be done to protect the environment, so why not get a piece of the pie.	7%	25%
<b>Cruel Worlders:</b> Resentment and isolation leave no room for environmental concerns.	6%	29%
<b>Ungreens:</b> Environmental degradation and pollution are inevitable parts of America’s prosperity.	3%	13%

Source: Pike et al., 2008.

### 9.3 Impacts on Cultural and Built Environments

In several recent projects, the Climate Leadership Initiative (CLI) and partners (e.g., CLI 2010; CLI and NCCSP 2007, 2009, 2010) looked at the impact of climate change on a range of factors including cultural resources for Oregon tribes and the built environment. A brief summary of their findings is provided below and can also be reviewed on their website at <http://>

### 9.3.1 Projected Impacts of Climate Change on Tribal and Cultural Resources

While a lack of understanding and awareness persists about Oregon tribes' vulnerability to climate change and their capacity to adapt to current and projected climate change (MacKendrick 2009), dependency on natural resources, confinement to small portions of reservation land, and existing stressors will likely increase their vulnerability to climate change impacts (Houser et al., 2001; Tsosie, 2007; Nilsson, 2008; CLI and NCCSP, 2010). Climate change may lead to loss of native species and fundamental shifts in ecosystems that have guided and formed the culture of many tribal communities, linking future generations and their ancestors (CLI and NCCSP, 2010). In addition, the loss of culturally important species and ecosystems is likely to lead to economic and functionality losses. For example, seasonal cues such as blooming plants and eel runs may no longer indicate when to collect important resources (CLI and NCCSP, 2010); forest species composition may shift and reduce tribal timber yields; fishing and oyster harvests may continue declining (MacKendrick, 2009); and species important for subsistence and culture could be entirely lost such as salmon, lamprey, trout, suckers, wocus (aquatic plant), shellfish, acorns, deer, elk, bear grass, Oregon blackberry and salmonberry (MacKendrick, 2009; CLI and NCCSP, 2010). Increases in wildfires and smoke could negatively affect the health of tribal members by causing increased respiratory disease and the need for greater access to hospitals and resources for care. Oregon's coastal tribes risk land inundation and loss from sea-level rise, increased wave height and intensity, and beach erosion (MacKendrick, 2009). Additional coastal impacts could damage burial sites, tribal infrastructure, and reduce income generation from tribal business enterprises (MacKendrick, 2009; CLI and NCCSP, 2010).

As many tribes work to rebuild their communities, governments, and cultures following decades of uncertain federal Indian policy, there is concern among tribes that climate change may negatively impact the ability to restore communities as well as the ability of the federal government to oblige by treaty agreements such as water allocation (USGCRP, 2003; Houser et al., 2001; MacKendrick, 2009; CLI and NCCSP, 2010).

In addition to impacts to Oregon's tribes, many areas and species of cultural importance to all Oregonians are likely to be impacted. For instance, glacier and snow pack loss from two important Oregon icons, Mount Hood and Crater Lake National Park, will change forest and species composition in those regions. Annually, Mount Hood attracts four million visitors (New World Encyclopedia, 2010) while Crater Lake National Park attracts 500,000 visitors (NPS, 2010). While no specific studies have been done on the impacts of climate change to Oregon's historical architecture and landmarks, assessments from King County, Washington, and Europe demonstrate that extreme events (heat, precipitation, wind), flooding, fire, snow pack melt, pest infestations, and sea-level rise are likely to have negative impacts on buildings and landmarks of historical and cultural importance (Snover et al., 2007; Sabbioni et al., 2006) and are discussed in more detail in the next section.

### 9.3.2 Projected Impacts of Climate Change on the Built Environment

Projected climate change impacts are likely to threaten the integrity of the built environment, including buildings, roads, highways and railroads, water and sewage systems, and energy facilities throughout Oregon (CLI, 2008, 2010). Projected increases in long-term, annual, and seasonal variability in precipitation and snow pack loss is likely to result in less dependable fresh water supplies, presenting a significant challenge for water managers and water infrastructure. Demand for dams, reservoirs, and wells is likely to intensify in response to declining groundwater and increasing seasonal flow variability as well as increase the pressure on the already limited off-stream water storage, particularly in the summer (CLI and NCCSP 2008, 2010). Increased runoff, intense storm events, and increased sedimentation may overwhelm drinking water and wastewater treatment facilities, which could lead to increased municipal water pollution and higher treatment costs. Many drinking water systems in Oregon, especially parts of Portland, are old and already degraded; failing pipes caused by more extreme flooding could lead to mixing of municipal water and sewage (CLI, 2010). The availability of fresh water is critical for agriculture and municipal purposes in much of Oregon and many areas of the state are already over-appropriated (CLI and NCCSP, 2008, 2009, 2010).

Electricity demand may increase with rising population; growing demand for home cooling, refrigeration, water (which requires energy to transport); and ever increasing production and purchasing of small electronics. At the same time, efficiency and reliability of power transmission and delivery is likely to decline as power lines are stressed by higher ambient temperatures, increased risk from wildfires, and reduced reliability of hydroelectric power with reduced stream-flow and increased sediment from wildfires, particularly along the Columbia and McKenzie Rivers (CLI and NCCSP 2008, 2009, 2010; CLI, 2010). As a result, more brownouts and blackouts are possible. Expansion of biomass-based energy production may also be limited due to loss of supply from forests and agriculture from increased wildfire (CLI and NCCSP, 2009).

Rail service may become more competitive and experience an increase in demand as fuel prices rise (CLI and NCCSP, 2010). In addition, both rural and urban areas in the Pacific Northwest are likely to receive an increase in population of people who are displaced due to climate-related events—a trend that is likely to accelerate the demand for local and regional mass transit, including rail, as well as increase congestion and deterioration of road systems. Severe flooding caused by storm and rain events as well as increased forest fires are likely to impact roads and impair movement of persons and equipment during storm emergencies. The most susceptible roads will be those bordering the coast, rivers and streams, running through valley bottomlands, and those in the vicinity of unstable slopes (e.g. highway s101, 6, 26, and 30 (CLI, 2010)). Maintenance of rural county roads may suffer as funding priorities shift to meet changing demands on local governments and the needs of growing urban areas (CLI and NCCSP, 2008). Air transport may also be affected by increased storms and smoke intrusion from wildfires (CLI and NCCSP, 2008). In addition, many bridges, culverts, and bike paths throughout the state will be more susceptible to flooding (CLI, 2010).

Infrastructure in floodplains and the urban/wildland interface may be lost to flooding and forest fire as a high number of homes are built in forested areas next to public lands



(Headwaters Economics, 2007). Direct costs will result from flood events and anticipated increases in wildfire intensity and frequency due to climate change, while indirect costs are likely to be many times larger resulting from more rapid depreciation of property from higher temperatures, more intense storms and other climate stresses (CLI and NCCSP, 2008).

## 9.4 Mechanisms and Potential Effects of Changes in Climate on Human Health in Oregon

Climate change poses risks for increased injuries, illnesses and deaths from both direct and indirect effects (Ebi et al, 2008). Incidents of extreme weather (such as floods, droughts, severe storms, heat waves and fires) can directly affect human health as well as cause serious environmental and economic impacts. Indirect impacts can occur when climate change alters or disrupts natural systems. This can give rise to the spread or emergence of vector-, water-, and food-borne diseases in areas where they either have not existed, or where their presence may have been limited.

Predicted average increases in summer temperatures will make heat waves a greater likelihood, causing heat-related morbidity and mortality, especially among vulnerable populations, such as the elderly, low income populations, pregnant women and those who work in outdoor occupations. An increase in injuries and cases of carbon monoxide poisoning (from using gas-powered generators) has been reported as a result of recent winter storms and subsequent flooding in Oregon. Increasing temperatures in Oregon could raise the threat of vector-borne diseases and emerging infections. Respiratory insults, especially among persons with pre-existing lung health problems would be exacerbated by exposure to smoke from wild land and forest fires, as well as from the projected increases in air pollution levels in our region. Air pollution and increases in pollen counts (and a prolonged pollen producing season) may increase cases of allergies, asthma and other respiratory conditions among susceptible populations.

This section of the chapter reviews the latest research and efforts in Oregon to address public health issues related to climate change. There are many additional diseases that may be climate change sensitive and affect Oregon residents, such as malaria, Chagas disease, and tuberculosis among others. At this time, there is no research that describes what those impacts are likely to be in Oregon. Increased surveillance for changes in the patterns and distribution of the diseases described in this chapter will yield additional data over time. A summary of public health issues, prepared by the CLI, is also available online (<http://climlead.uoregon.edu/node/168>).

### 9.4.1. Communicable Diseases

Many vector-borne pathogens are sensitive to temperature. West Nile virus (WNV) infection, for example, already exhibits strong seasonality with peak transmission in late summer in the Northwest; longer summers with higher temperatures may substantially increase the incidence of WNV fever and encephalitis in Oregonians. Oysters harvested in Oregon, Washington, and British Columbia during summer months have caused outbreaks of *V. parahaemolyticus* infection (Wechsler et al., 1998); but in 2004, an outbreak aboard a cruise ship implicated oysters

harvested from Prince William Sound, Alaska—1,000 km north of the pathogen’s previously recognized northern outpost (McLaughlin et al., 2005). Warming waters in the Pacific Northwest could lead to higher concentrations of *Vibrio spp.* in shellfish beds and more prolonged periods of summer risk. The predicted increasing rain in the Northwest, with flooding effects multiplied by rain-on-snow events in the Cascades, may lead to the washing of *Cryptosporidium parvum*, a protozoan agent of diarrhea in cattle, along with other animal intestinal indwellers, into drinking water reservoirs (National Research Council, 2001).

The fungus *Cryptococcus neoformans* lives in dead or rotting trees and is a notorious cause of meningitis in patients with organ transplants or AIDS; but one variety has shown a particular ability to infect even healthy hosts (Speed and Dunt, 1995). This variety, known as *gattii*, was thought to have been restricted to tropical and subtropical areas; however, the pathogen emerged on the east coast of Vancouver Island, British Columbia, in 1999, and environmental sampling in a provincial park uncovered an ecological berth among several tree species there including Douglas fir. A novel genotype of *C. gattii*, VGIIc, has recently emerged in Oregon (Brynes et al., 2010) and infections appear to be more virulent and have a more complicated clinical course than the more common *C. neoformans*. Researchers hypothesize the establishment of *C. gattii* in this area may have been due to climatic changes (Kidd et al., 2004).

We cannot predict what the net health effect of climate change will be to Oregon. Given the dynamic interplay among disease reservoirs, vectors, human hosts, and the environment, we can predict that communicable disease patterns will change. The best means of fending off any changes for the worse are similar to those for addressing emerging infectious diseases: ensuring that we can detect changes in disease patterns, investigate as needed and mount an appropriate public health response. To that end, Oregon Public Health Division (OPHD) has made a number of diseases reportable under Oregon Revised Statutes (ORS).

- Chapter 433 (433.001-035) (<http://www.leg.state.or.us/ors/433.html>), Oregon Administrative Rules (OARS).
- Chapter 333, Division 18 - Health Services ([http://arcweb.sos.state.or.us/rules/OARs\\_300/OAR\\_333/333\\_018.html](http://arcweb.sos.state.or.us/rules/OARs_300/OAR_333/333_018.html)).
- OAR Division 19 - Investigation and control of diseases (<http://www.oregon.gov/DHS/ph/acd/oars/div19.shtml>)

#### **9.4.2 Waterborne Diseases**

Climate directly impacts the incidence of waterborne disease through effects on water temperature and precipitation frequency and intensity (Portier et al., 2010). Waterborne disease are caused by a number of pathogenic microorganisms, biotoxins, and toxic contaminants found in water we use for drinking and food preparation, cleaning, irrigation, recreation, business, and even for cooling.

The range of infectious microorganisms causing waterborne disease include parasites responsible for cryptosporidiosis and giardiasis, bacteria causing legionellosis and cholera, viruses causing viral gastroenteritis, amoebas causing dysentery and amoebic meningoencephalitis, and algae causing neurotoxicity. The effects of climate change are anticipated to increase the frequency and range of waterborne diseases with rising temperatures

and more incidents of flooding as well as from the effects of other severe weather incidents. Oregon Public Health Dept. tracks cases of most waterborne diseases mentioned above as part of required disease reporting by health care providers and hospitals. Algae blooms in coastal marine and fresh water systems are monitored, and alerts are issued to advise people of risks and to reduce exposures.

### **9.4.3 Cardiovascular Disease and Stroke**

Cardiovascular disease is the leading cause of death in the United States, and stroke is the third leading cause of death (CDC, 2009). Many Oregonians are living with some form of these diseases (including high blood pressure, coronary artery disease, heart attack, and abnormal electrical activity in the heart—cardiac dysrhythmias). The range of climate and weather changes can have both a direct or indirect effect on cardiovascular diseases (Portier et al., 2010).

There is evidence that climate and weather conditions have an exacerbating effect on cardiovascular disease and stroke (Portier et al., 2010). Under future climate projections for Oregon, heat and air pollution levels are likely to increase, and thus they may be expected to increase rates of cardiovascular morbidity and mortality. Likewise, decreases in extreme cold temperatures may reduce the risk of cardiovascular morbidity and mortality.

There are gaps in our understanding of the impacts of climate change on cardiovascular disease and additional research is needed to better measure the relationship between climate conditions and impacts on heart disease and stroke. While we can infer that increased ambient temperatures and more frequent episodes of extreme weather associated with climate change will likely have an adverse impact on those who already have cardiovascular disease, we need to focus public health attention on improved surveillance for these diseases to better measure changes in both outcomes of existing disease and the onset of new illness. We especially need to design research and tracking efforts to better understand the possible synergistic effect of long term temperature change, weather variability and stresses associated with displacement and interruptions of medical care due to severe climate change episodes on cardiovascular disease onset and outcomes.

### **9.4.4 Asthma, Respiratory Allergies, and Airway Diseases**

Allergic diseases include asthma, hay fever, rhinitis and atopic dermatitis and all are considered climate-sensitive diseases because a number of environmental factors are known to trigger exacerbations or episodes of illness (Portier et al., 2010). Temperature increases related to climate change are expected to result in earlier flower blooming and a longer season for flower and pollen production. Increased carbon dioxide (CO<sub>2</sub>) concentrations are expected to affect plant photosynthesis and metabolism, which would increase pollen production through broader plant distribution and extending the duration of pollen production. Rising temperature and CO<sub>2</sub> levels may make some aeroallergens more allergenic. Plants like poison oak appear to thrive with increased CO<sub>2</sub> levels, and may produce more potent irritant and allergenic oils. Taken together, these factors will likely mean that people with allergies will be exposed to greater pollen levels for a longer blooming season. It is unclear whether more people will become sensitized to pollens as a result of increased exposures. About 5% of the population has

symptoms of allergic reaction when exposed to airborne mold spores.

We know most about people in Oregon who suffer from asthma—a chronic lung disease that causes shortness of breath, coughing, and wheezing, but information about the number and characteristics of people who suffer from allergies and atopic dermatitis is more difficult to assess because these are not reportable conditions in Oregon. Oregon has a higher burden of asthma than the overall U.S. population: 9.9% of Oregon adults and 8.3% of children have asthma. More than 355,000 Oregonians have asthma (Garland, 2009). Asthma symptoms can develop when a person is exposed to triggers such as tobacco smoke, animal fur or feathers, cockroaches, mold or mildew, dust mite feces, and pollen. OPHD tracks hospitalizations for asthma exacerbations and asthma deaths, using hospital discharge and Vital Records data.

We will need to build improved mechanisms for tracking environmental triggers for asthma and respiratory allergies in order to assess whether there is a measurable increase in the frequency and severity of disease exacerbations and an increase in the overall burden among those susceptible. We will also need to work with partners to do research on whether there are changes in the composition and levels of air pollutants and aeroallergens over time.

#### **9.4.5 Food-Borne Disease and Nutrition**

Food insecurity and under-nutrition are already a concern for a segment of the Oregon population (Nord et al., 2009). The Intergovernmental Panel on Climate Change Working Group and the U.S. Climate Change Science Program report a likely increase in the spread of multiple food borne pathogens and pests due to climate change (IPCC, 2007; Ebi et al., 2008). Drought, flooding, and other extreme weather incidents can also disrupt the transportation and distribution systems of food during times of crisis. Food borne illness is an ongoing problem in Oregon and the U.S., as indicated in the Communicable Diseases section above.

Oregon PHD is one of nine states that participate in the Food Borne Diseases Active Surveillance Network (FoodNet) program to track food borne illness using surveys of physicians and laboratories, case-control studies, and active case finding of the following pathogens.

- *Campylobacter*
- *Cryptosporidium*
- *Cyclospora*
- *E. coli O157*
- *Listeria*
- *Salmonella*
- *Shigella*
- *Vibrio*
- *YersiniaFT*

Health care providers are required to report any known or suspected common-source outbreaks. OPHD receives hundreds of case reports of food borne illnesses each year, as defined under Oregon Statute and Rule. OPHD tracks the number of cases by condition and actively investigates outbreaks of multiple cases of food borne illness to identify the source and

mechanism of spread in order to stop the outbreak. OPHD's active surveillance and response system is carried out in collaboration with the Portland Health Department and local health departments—and has enabled rapid identification to help stop food-borne outbreaks of both local and national significance. OPHD tracks changes over time to observe patterns of these illnesses by organism. These skills will continue to be applied in preparation for the potential contribution to food-borne illness cases from climate change factors.

#### **9.4.6 Weather-related Morbidity and Mortality**

Oregon and the Pacific Northwest experience a variety of extreme weather incidents ranging from severe winter storms and floods to drought and dust storms, often resulting in morbidity and mortality among people living in the impacted regions. Climate change is expected to increase the frequency and intensity of some weather incidents (Portier et al., 2010). The health impacts from extreme weather-related episodes can include both direct impacts such as death, injury, and mental health effects, and indirect impacts such as population displacement, drinking water contamination and waterborne disease outbreaks.

Populations at risk from severe weather incidents include people in most areas of Oregon. For example, flooding threatens people living in valley communities, and dust storms and drought are not uncommon in parts of rural eastern Oregon. Heavy precipitation episodes and flooding can compromise drinking water supplies, disrupt human systems, and displace people living in low-lying areas. Drought, like that currently experienced in the Klamath Basin, can adversely impact agricultural productivity, threaten the livelihoods and economic well-being of affected communities and increase food prices for others. Coastal and nearby inland communities are regularly impacted by severe winter storms. Sea-level rise combined with storm surge incidents are a special threat along the Oregon coast. Climate change related sea-level rise is expected to magnify the threat from storm surges that often accompanies severe weather incidents in coastal areas (CCSP et al., 2008).

#### **9.4.7 Needs for Improved Adaptation Planning and Preparedness**

State and local level public health agencies currently track individual and public health impacts associated with many natural disasters and disease outbreaks happening in their jurisdictions. This is accomplished through the Public Health Emergency Preparedness (PHEP) program. Laboratories and clinicians are required to report a number of conditions associated with communicable diseases, contamination of food and water, and illnesses spread by insect vectors. Public health agencies also have the capacity and methods to detect, investigate and respond to a number of chronic conditions and injuries affecting adults and children in Oregon.

Oregon public health agencies do not, however, currently have rapid access to medical information from emergency departments and hospitals that would be needed during emergency situations. Nor does public health currently mandate reporting the range of conditions likely to be seen during natural disasters that may be associated with climate change. These data are needed to improve our ability to accurately and rapidly understand human health impacts from these incidents; to recommend appropriate response and adaptations to emergency situations associated with extreme weather and climate incidents; to develop

culturally appropriate messages that can guide and empower communities to become more resilient; and to evaluate effectiveness of adaptation measures.

State and local public health agencies have made gains in understanding the capabilities needed to expand our tracking, prevention, response and planning efforts to include illness and injury outcomes resulting from weather and climate conditions previously not considered as part of the primary responsibility of public health services. OPHD is working with local health departments to conduct and refine public health hazard vulnerability analyses that will help identify and prioritize risks that communities face.

### **9.3 Summary and Conclusions**

The studies and projects discussed above present different lenses for examining public understanding and reactions to climate change. Although these studies and projects use different approaches, measures, and methods, commonalities are revealed; it is likely many Oregonians perceive climate change as a problem although they may not know the scientific details. There are cognitive and perceptual barriers that need to be addressed if we expect individuals or groups to change behaviors for either mitigating or adapting to climate change, although there appears to be general acceptance of and desire for government efforts that will direct such behavioral change. It may be possible to use existing state assessment and monitoring programs to monitor climate change impacts on cultural resources, built environments, and public health.

We need additional research to set baselines in order to monitor changes over time to understand more fully: (1) how a wide range of Oregonians who are likely to be affected by climate change due to the place they live, the job they hold, or the organization they work for experience climate change impacts; (2) the acceptability of specific policy and behavioral changes to a wide range of Oregonians; and (3) the barriers faced by individuals, groups, and organizations, including state agencies, as they start to respond to the observed impacts of climate change in Oregon.

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