GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L22S03, doi:10.1029/2006GL027072, 2006

Physical versus biological spring transition: 2005

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Received 1 June 2006; revised 28 July 2006; accepted 2 August 2006; published 19 September 2006.

[1] In 2005, the onset of spring conditions in the physics of the coastal ocean (lowered sea level, spin-up of vertically-sheared equatorward coastal jet) came about 50 days later than average off Newport Oregon, on May 24. There was a further delay of 50 days before the subsurface upwelled water penetrated into the anomalously stratified surface layer, becoming most available for biological activity. The warm anomaly in sea surface temperature which provided the surface cap was observed at mid-shelf locations from Washington to central California, but it ended sooner south of Oregon. Biological impacts of these delays to several trophic levels have been reported.
Citation: Kosro, P. M., W. T. Peterson, B. M. Hickey, R. K. Shearman, and S. D. Price (2006), Physical versus biological spring transition: 2005, *Geophys. Res. Lett.*, *33*, L22S03, doi:10.1029/2006GL027072.

1. Introduction

[2] Over the continental shelf off Oregon, winter conditions are characterized by high coastal sea level, currents which are northward in the mean, barotropic and highly variable in time, and isopycnals which are level below the surface layer. Spring/summer conditions are characterized by low coastal sea level, currents which are southward at the surface and significantly sheared in the vertical, and isopycnals which slope upward toward the coast [*Huyer et al.*, 1978]. *Huyer et al.* [1979] pointed out that the transition from winter to spring conditions occurred rapidly, seemingly as the result of one coastal upwelling event driven by local winds, and that, once the transition has occurred, spring conditions were very persistent even through moderate reversals of the wind forcing. They named this phenomenon the “spring transition”. *Strub et al.* [1987] found that the transition event had large alongshore length scales (O(1000 km)) on the U.S. west coast between 37°N and 48°N. The spring transition in wind forcing off Oregon is not very sharp, with reversals to downwelling-favorable winds not uncommon in spring and summer [*Huyer et al.*, 1979; *Bane et al.*, 2005]; *Strub and James* [1988] show that it co-occurs with a shift in large-scale patterns of atmospheric pressure (*Lentz* [1987] shows that a sharp transition in wind-forcing does occur during the spring transition off northern California near 38°N). In discussing local vs. remote forcing, *Huyer et al.* [1979] use a volume budget to conclude that local winds are probably sufficient to produce the steric height change associated with the spring transition, while *Strub et al.* [1987] argue that remote effects, through coastal trapped wave dynamics, play an important role. *Huyer et al.* [1979], introduce the concept of cumulative Ekman transport in discussing the wind-forced initiation of the spring transition.

[3] During 1971–2005, the average date for the spring transition off Newport was April 4, with a standard deviation of 25 days (Figure 1). The transition dates were estimated by *Bilbao* [1999] from Empirical Orthogonal Function (EOF) modes of adjusted sea level height and large-scale winds during 1971–1998, and extended here using adjusted sea level and mid-shelf current shear off Newport, Oregon, through 2005, which produces similar results.

[4] The spring transition of 2005 was anomalous in the Pacific Northwest. Off Newport, it arrived on about May 24, later than normal by 50 days. In addition, although sea level dropped to its summer level on May 24, and the equatorward, vertically-sheared coastal jet developed at the same time, surface waters over the shelf remained anomalously warm and fresh for another seven weeks, until mid-July. There is evidence that these effects cascaded from the lower through the higher trophic levels including phytoplankton [*Thomas and Brickley*, 2006; *Hickey et al.*, 2006], zooplankton (D. L. Mackas et al., Zooplankton anomalies in the northern California Current system before and during the warm ocean conditions of 2005, submitted to *Geophysical Research Letters*, 2006; C. Newell and T. J. Cowles, Unusual gray whale *Eschrichtius robustus* feeding in the summer of 2005 off the central Oregon coast, submitted to *Geophysical Research Letters*, 2006), intertidal mussels and barnacles (J. A. Barth et al., The strange summer of 2005: Delayed coastal upwelling severely depresses the base of coastal ecosystems in the northern California Current, submitted to *Nature*, 2006) (hereinafter referred to as Barth et al., submitted manuscript, 2006), fish [*Brodeur et al.*, 2006] and birds (W. J. Sydeman et al., Planktivorous auklet *Ptychoramphus aleuticus* responses to the anomaly of 2005 in the California Current, submitted to *Geophysical Research Letters*, 2006).

[5] In the following, we will examine time series of sea level, wind forcing, mid-shelf currents, hydrography, and surface- and bottom-temperature to characterize the anomalous spring transition of 2005 off Newport, Oregon, and in surrounding waters.

2. 2005 Spring Transition in the Physical Fields

[6] The Newport Hydrographic Line, at 44° 39.1′N, was sampled for water properties at one- to two-month intervals during 1961–1971; regular sampling was renewed in 1997 at approximately quarterly intervals [*Smith et al.*, 2001;

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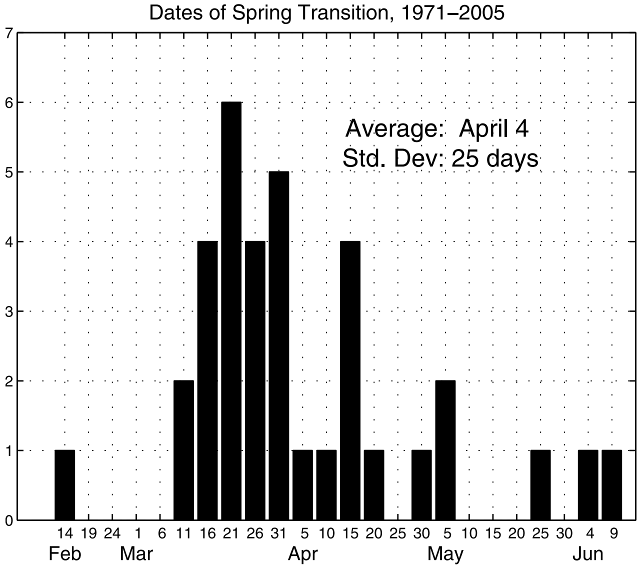

Figure 1. Histogram of spring transition dates, 1971–1998 [*Bilbao*, 1999] and 1999–2005.

Huyer et al., 2002; *Peterson et al.*, 2002; A. Huyer et al., The Newport line off Oregon—Studies in the north east Pacific, submitted to Progress in Oceanography, 2006] and is being maintained into the future. In addition to regular CTD sections, a Sontek moored Acoustic Doppler current Profiler (ADP) has been maintained at the 81m isobath since 1997 [*Kosro*, 2003], and surface current mapping has been conducted using standard-range (12 MHz) and long-range (5 MHz) SeaSonde HF systems, since 1997 and 2002 respectively. The National Oceanic and Atmospheric Administration (NOAA) measures coastal water level with a tide gauge at nearby Southbeach, Oregon (http://tidesandcurrents.noaa.gov), winds and near-surface (0.6m depth) temperature over the outer shelf are measured from NOAA National Data Buoy Center (NDBC) buoy 46050, and winds are measured at the coast from C-MAN station NWPO3 (http://www.ndbc.noaa.gov). Corrections to measured sea level for the effects of atmospheric pressure were made using model surface pressures from the NCEP reanalysis project, interpolated to tide gauge locations. In addition to measured winds, we also examined the "Upwelling Index" (UI), a model-based proxy for the regional winds (http://www.pfel.noaa.gov). Time-series of the cumulative offshore Ekman transport at the surface were computed as the time integral of UI.

[7] Figure 2 shows time-series of wind forcing and response off Newport.

2.1. Sea Level

[8] The most reliable indicator of past spring transitions has been the persistent drop in coastal sea level from the high winter state to the low, upwelling state, as warm, less-dense winter waters are replaced by cold, dense, upwelled waters over the shelf. In 2005, this persistent drop below the yearly average occurred on May 24, 2005 (Figure 2c, indicated by a vertical dashed line). Although there were short-lived events of lower sea-level earlier (early March, mid-April), and brief reversals to high sea level in June and early July, the May 24 event marked a step change in sea

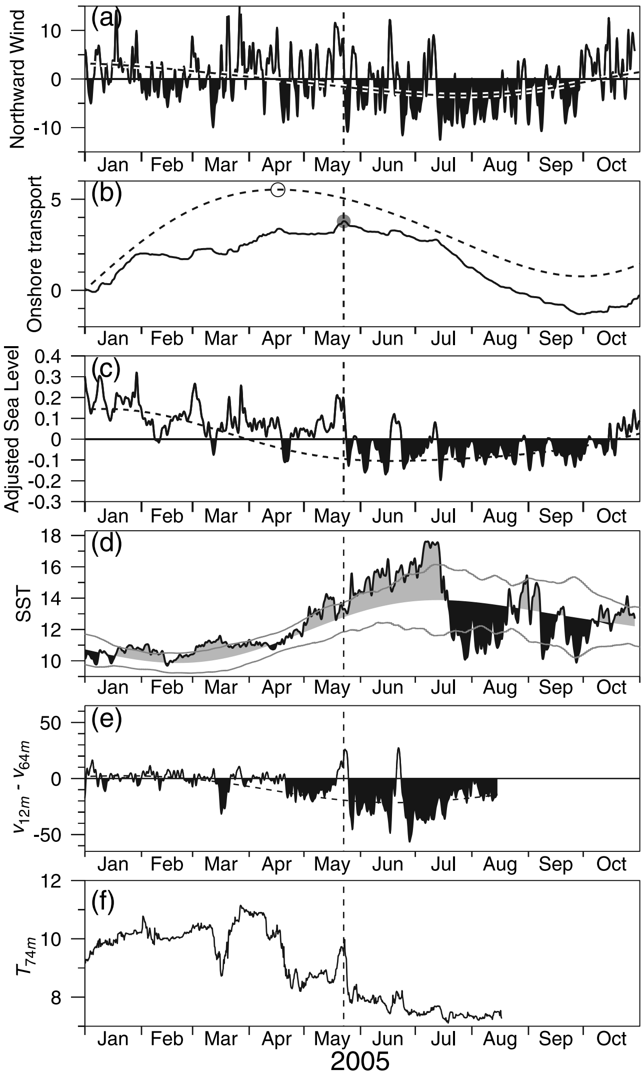

Figure 2. Time series of quantities indicative of the spring transition, for 2005 (solid lines) and long-term seasonal fits (dashed lines). (a) Northward wind velocity (m/s) at NDBC buoy 46050 located at the 130-m isobath near the NH line, (b) cumulative offshore surface Ekman transport, in 10^6 m^3 per meter of coastline, at 45°N, 125°W, from Upwelling Index; circles indicate transition to offshore transport (c) coastal sea level (meters) at Newport, adjusted for atmospheric pressure (filled for values below long-term mean) (d) sea surface temperature measured at NDBC buoy 46050, with deviation from long-term seasonal fit and the standard deviation (e) northward current difference (cm/s), top and bottom away from boundary layers, at 81 m isobath (NH10 mooring), and (f) temperature at the ADP, 74 m. For Figures 2a, 2c, and 2e, periods with southward wind, negative adjusted sea level, and southward shear, respectively, are highlighted. For Figure 2d, anomalously warm sea surface temperatures are highlighted in grey, anomalously cool periods are highlighted in black. The vertical dashed line indicates May 24, 2005, identified as the spring transition date based on coastal sea level, wind forcing, cumulative Ekman transport, and current shear.

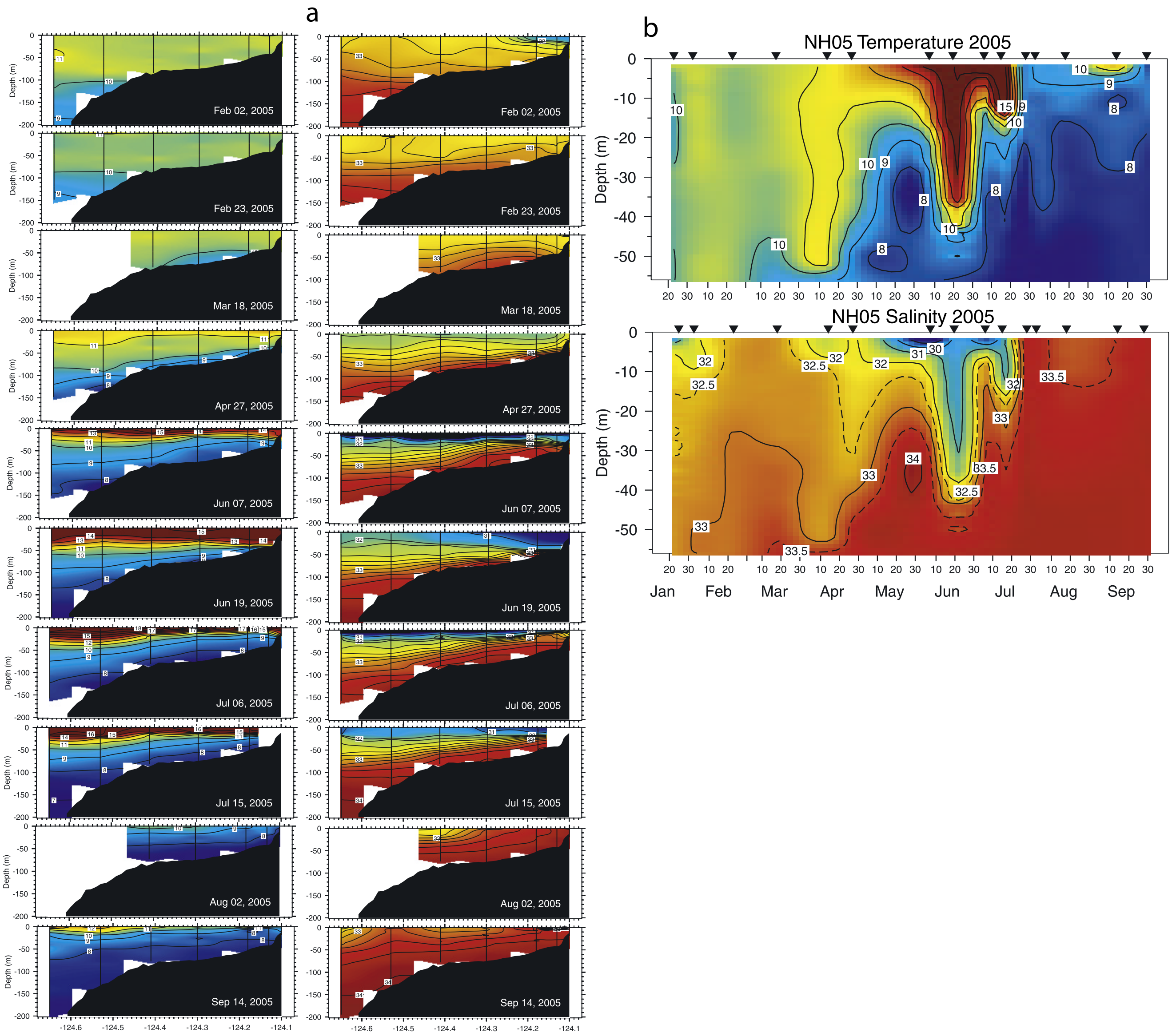

Figure 3. (a) Sections of temperature (left; °C; contour interval 1°C) and salinity (right; contours for S = 31 and for every 0.2 for $S \geq 32$) on the Newport Hydrographic Line during February through September, 2005. Data were collected from *R/V Elakha*, *R/V Wecoma* (Jun 19), *R/V Miller Freeman* (Jul 15). (b) Time-depth sections of temperature and salinity at NH-05, the most frequently sampled CTD station, located at 44° 39.1′N, 124° 10.6′W.

level on the monthly time scale. Coastal sea level for 2005 stood above its expected seasonal cycle from mid-March until May 24, aside from a brief event during mid-April.

2.2. Wind Forcing

[9] Frequent reversals of forcing are found in the local measured winds (Figure 2a) until at least May 24; even later, there are still strong wind reversals until mid-July. Moderate, but anomalously strong, upwelling events also occurred the preceding winter, during most of February and early in March 2005; this can be seen in both the local measured winds (Figure 2a) and in the anomalously low cumulative onshore Ekman transport during the first half of 2005, compared to the seasonal cycle (Figure 2b). On May 24, the low-frequency trend of the cumulative Ekman transport turns from onshore to offshore, giving another indication of the spring transition. In the first 50 days following the transition, from May 24 to July 13, the mean offshore Ekman transport was weak, at 0.23 m^2/s; during the subsequent 50 days, from July 13 to Sept 01, the mean offshore Ekman transport triples to 0.70 m^2/s (or 3.5 cm/s for an Ekman depth of 20m).

2.3. Currents/Upwelling

[10] The upwarping of density surfaces due to upwelling produces cross-shore gradients in density (and hence pressure), which are balanced geostrophically by a vertically-sheared current, more equatorward at the surface. The presence of low-frequency negative vertical shear in the time series of alongshore current is thus an indication of upwarped density surfaces. Measured currents over the 81 m isobath show sustained negative vertical shear from late May through most of the spring and summer, until mid-August, when the ADP was recovered (Figure 2e). This

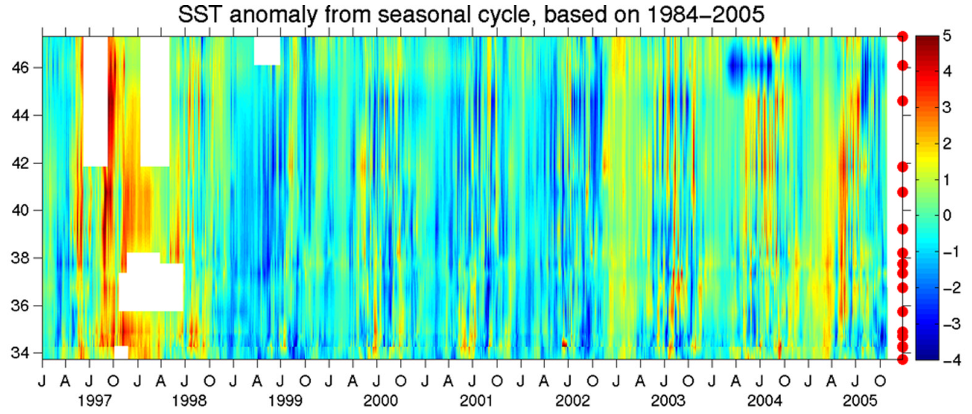

Figure 4. Latitude-time plot of sea surface temperature anomalies from the seasonal cycle at NDBC buoys over the shelf along the west coast (latitudes indicated by red dots).

provides further verification that the spring transition occurred, at the latest, in late May 2005.

2.4. Surface Temperature

[11] In contrast to the other fields examined, the near-surface temperature remained anomalously high even after May 24, 2005 (Figure 2d), with surface temperature anomalies exceeding 3.5°C by early July. On July 13, the low-pass filtered anomaly starts decreasing, becomes zero on July 17, and is −2°C by July 20. This mid-July timing is consistent with the surfacing of cold upwelled water seen in satellite imagery (P. T. Strub et al., Satellite estimates of SST, wind and surface transport anomalies during the spring-summer 2005 "warm event" in the northern California Current, manuscript in preparation, 2006) (hereinafter referred to as Strub et al., manuscript in preparation, 2006).

[12] Thus the vertically integrative data, including sea level and vertical shear in the currents, indicate that upwelling of cold deep water began no later than May 24, 2005. However, the surface waters over the outer shelf gave no indication of the presence of cold, upwelled water until nearly two months later, following the increase to strong offshore Ekman transport around July 13.

[13] The upwelling-driven advance of the cold, salty bottom water and evolution of the surface layer off Newport can be seen in the series of hydrographic sections along the NH line obtained during 2005 (Figure 3a), and in the time-series record of near-bottom temperatures at the 81m isobath (Figure 2f). In February, shelf waters are only weakly stratified in temperature, with no sign of cold upwelled waters at the bottom (Figure 3a, Figure 2f), despite persistent but weak upwelling favorable winds through much of February (Figure 2a). By March, an isolated pool of cold, saline bottom water has appeared on the shelf, presumably driven by the strong upwelling-favorable wind event of March 10–16, and then driven back somewhat by the weaker downwelling event of March 16–17. This small upwelling event was accompanied by vertical shear in the upwelling sense (Figure 2e). Strong downwelling winds through late March and early April forced the cold upwelled water to retreat, warming bottom temperatures at NH10 (Figure 2f) until the sustained upwelling event of April 17–23, which drove bottom temperatures down from 10.3°C to 8.3°C (Figure 2f). By April 27, the cool, salty upwelled water along the bottom had advanced nearly all the way shoreward, to within 5 km of the coast (Figure 3a). The average salinity in the upper 35m decreased by more than 0.5, from 32.86 to 32.30, reflecting the southward advection of Columbia River water. But the cool bottom temperatures had not yet broached the surface. Sustained downwelling winds from May 13 to May 23 force a small increase in bottom temperature (Figure 2f), but the upwelling wind event of May 24 results in sustained cold bottom temperatures which are not significantly warmed by the subsequent downwelling wind events of June or July. However, the cold water upwelled along the bottom of the shelf does not penetrate the increasingly warm and fresh surface layer cap in the sections of June 7, June 19, July 6 or July 15. Only after the onset of strong upwelling-favorable winds did the cold water enter the surface layer when, presumably, the work done by the winds was enough to raise the potential energy of the coastal waters sufficiently.

[14] The thickening trend of the nearshore bottom zone with upwelled waters can also be seen in Figure 3b, where the cold water first appears at NH-05 in the March 18 profile and the cold bottom layer finally surfaces in mid-July.

[15] The alongshore scale of the warm SST anomaly can be seen in measurements from the full array of mid-shelf meteorological buoys maintained by NDBC (Figure 4). Sea surface temperature from fifteen buoys over the continental shelf, at latitudes from 33.7°N to 47.3°N each were analyzed for their seasonal cycle and low-pass filtered anomalies were computed [e.g., *Kosro*, 2003]. A warm anomaly similar to that observed off Newport (44.6°N) during spring/summer 2005 is also apparent on the shelf at latitudes at least as far south as 36°N, beginning about the same time (late April), but ending sooner, after about a month (near May 21), than off Newport. These long coherence lengths for non-seasonal surface temperature anomalies are apparent for many other events in Figure 4, some of only a few days duration (July 2003), others lasting weeks to months (warm event of preceding spring/summer, 2004, between about 45°N and 39°N). The event of spring/summer 2005 is larger

in magnitude and longer in duration than events since the 1997–98 El Niño.

3. Discussion

[16] The nearly two month delay between the arrival of the (already late) spring transition in physical fields, by May 24, and the surfacing of the upwelled water (and evident start of the biological response) in mid-July, was unexpected. The trapping of upwelled waters below the anomalously warm, fresh (buoyant) surface layer made them less available for biological exploitation, and appears to have had significant consequences along the trophic cascade (see other papers in this volume). We are not aware of previous instances where such a long delay occurred between the spring transition to upwelling in physical fields and the arrival of the upwelled water at the surface.

[17] The step-wise development of upwelling in 2005 raises questions about the event-like nature of the spring transition. The sequence of hydrographic sections (Figure 3a) and the time-series of bottom-temperature at midshelf (Figure 2f) suggest that equatorward wind events well in advance of the spring transition, as early as mid-March, were injecting cold water onto the shelf near the bottom. Poleward, downwelling winds in later March and April were strong enough to sweep the cold bottom water away from the midshelf, but it was quickly re-established in late April. Thereafter, even strong downwelling wind periods were less effective (mid-May) or ineffective (late June, mid July) in warming the bottom temperatures at midshelf by submerging surface waters.

[18] A date of May 24 for the 2005 physical spring transition puts it about 50 days later than the average date of April 4; this is the third latest spring transition since 1971 [see also *Schwing et al.*, 2006]. However, an additional delay of 50 days, until mid-July, was imposed on the full biological response, due to the failure of the upwelled water to reach the surface over the shelf. For example, surface chlorophyll was below normal in this region in monthly averages for May and June, but near or above average for July both over the shelf [*Thomas and Brickley*, 2006] and at coastal sites (Barth et al., submitted manuscript, 2006); this timing corresponds to delivery of nutrients, associated with the upwelled waters, at the coast (Barth et al., submitted manuscript, 2006). This emphasizes that the timing of the transition in the physical fields (drop in coastal sea level; establishment of the equatorward coastal jet) can be distinct from the timing of the biological response, which depends critically on the delivery of nutrients to the euphotic zone.

[19] The surface temperature anomalies associated with this event were large (>3°C), long-lived (nearly 3 months off Newport, about one month south of 40°N) and extended over a large distance along the coast, from Oregon to Monterey, (O(1000 km)). Composite satellite images of sea surface temperature confirm their continuity along the coast in the Pacific Northwest (Strub et al., manuscript in preparation, 2006). These long alongshore scales for surface temperature anomalies are recognized for large events over the shelf such as El Niño [e.g., *Kosro*, 2002], and have been noted in monthly averages of shore temperatures [*McGowan et al.*, 1998]. S. D. Pierce et al. (Anomalously warm July 2005 in the northern California Current: Historical context and the significance of cumulative wind stress, submitted to *Geophysical Research Letters*, 2006) show that, off Newport, the anomalies in historical July shelf temperatures are significantly correlated with strength of the cumulative wind-driven cross-shore transport from the start of the upwelling season.

[20] During coastal upwelling, there are large changes of potential energy associated with the uplift and outcrop of isopycnals. The ultimate source of energy for this change is the work done by wind stress on the surface of the ocean. However, buoyancy fluxes, such as surface heat flux, evaporation, or river inputs, may also play a role. Surface heating can contribute significant changes to the potential energy of the water column through changes in the stratification increasing the amount of work required to raise a deep isopycnal to the surface [*Gill*, 1982].

[21] This creates an interesting competition between wind stress and surface heat flux during upwelling. As the surface layer warms, the amount of work required to raise deep isopycnals increases, delaying the outcrop of isopycnals at the surface and the delivery of nutrients to the surface layer, potentially having a profound effect on the ecosystems that rely on coastal upwelling.

[22] In 2005, shelf waters were significantly warmer and more strongly stratified than climatological averages for May, June and July, leading to increased potential energy in the water column. Mid-shelf currents seemed to respond to upwelling favorable winds in May and flow southward, but the outcrop of isopycnals at the surface did not occur until July. This delay is consistent both with the anomalously weak wind forcing, and with an increase in potential energy of the water column caused by surface heating and the additional work required to raise isopycnals. Although the observations are only suggestive, the interplay between surface heating, wind stress and upwelling dynamics clearly deserves closer study.

[23] **Acknowledgments.** We gratefully acknowledge the support provided by the National Science Foundation (grants 0000733, 237710 PMK; 0527168 RKS; 0239089 BMH) and the National Oceanic and Atmospheric Administration (NA03NES4400001 PMK; NA97FE0193, NA67RJ0151 WTP; AB133F05SE4205 SDP). Opinions expressed are those of the authors and not necessarily those of NSF or NOAA. SDP thanks Rebecca Thomas, Guy Fleischer and Jack Barth. This is GLOBEC contribution 313 and RISE contribution 7.

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