GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L22S04, doi:10.1029/2006GL027149, 2006

Anomalously warm July 2005 in the northern California Current: Historical context and the significance of cumulative wind stress

Stephen D. Pierce,[1] John A. Barth,[1] Rebecca E. Thomas,[2] and Guy W. Fleischer[2]

Received 7 June 2006; revised 8 August 2006; accepted 31 August 2006; published 6 October 2006.

[1] In the northern California Current, the onset of the 2005 upwelling season was five weeks later than usual, and well-established upwelling with a cold surface signature did not occur until about seven weeks after this. As part of the joint US-Canada Pacific hake survey, from 14–16 July 2005 we occupied the Newport Hydrographic line at 44.65°N, from the Oregon coast to 83 km offshore. Instead of the cold surface layer expected in July, we observed anomalously warm water. For example, 10-m temperature at the shelf station NH-5 was the warmest ever recorded in July at this location: 6.2°C above average, with observations back to 1961. We explore the pivotal role played by cumulative (time-integrated) wind forcing in the development of upwelling, in both 2005 and previous years. We find that 80% of July surface layer (0–30 m) interannual temperature variance can be explained by cumulative upwelling index from the spring transition. **Citation:** Pierce, S. D., J. A. Barth, R. E. Thomas, and G. W. Fleischer (2006), Anomalously warm July 2005 in the northern California Current: Historical context and the significance of cumulative wind stress, *Geophys. Res. Lett.*, *33*, L22S04, doi:10.1029/2006GL027149.

1. Introduction

[2] The northern California Current system has a strong seasonal cycle in water properties, circulation, and the upwelling of nutrients that support phytoplankton growth and hence the coastal ecosystem. Winter conditions are characterized by variable winds with strong poleward storm events, variable and mostly poleward currents, and weak cross-shore density gradients. Every year in the spring, equatorward upwelling-favorable winds become more common, relatively cold, saline, and nutrient-rich waters are brought up to shallower depths near the coast, and equatorward currents associated with strong horizontal density gradients develop [*Huyer et al.*, 1979]. The timing of this rapid spring transition varies each year, and at 45°N usually occurs between mid-March and mid-May, with a climatological mean of 17 April [*Schwing et al.*, 2006].

[3] In 2005 the spring transition was unusually late: by inspection of buoy wind records it was 24 May 2005, about five weeks later than average and beyond the one standard deviation range of the last 20 years. Just as significantly, even after this late transition, upwelling-favorable winds were unusually weak and interrupted by strong northward events until mid-July [*Kosro et al.*, 2006]. Even though stronger-than-average upwelling-favorable winds began in mid-July and persisted through September, the weak start to the upwelling season had a variety of biological effects, e.g., low early-season nutrients and chlorophyll [*Hickey et al.*, 2006; J. A. Barth et al., Delayed upwelling alters coastal ocean ecosystems in the northern California Current, submitted to *Nature*, 2006, hereinafter referred to as Barth et al., submitted manuscript, 2006], low satellite surface chlorophyll [*Thomas and Brickley*, 2006], low Oregon mussel recruitment for May–August 2005 (Barth et al., submitted manuscript, 2006), breeding failure of a planktivorous bird, the Cassin's auklet [*Sydeman et al.*, 2006], and unusual gray whale feeding and poor body condition (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). The delayed onset of typical upwelling appears to have had considerable ecosystem effects.

[4] *Schwing et al.* [2006] address how anomalous 2005 was in the context of historical large-scale wind patterns for the entire U.S. west coast, while Barth et al. (submitted manuscript, 2006) include discussion of how early-season weak upwelling-favorable winds in 2005 were associated with a southward shift of the position of the Jet Stream. *Hickey et al.* [2006] track the delayed development of physical upwelling off the Washington coast with a series of hydrographic lines. *Kosro et al.* [2006] present time-series measurements and a February to September sequence of hydrographic shelf lines to document the evolution of the 2005 season off Oregon: they note how as late as 15 July, cold upwelled water had still not penetrated a warm and fresh surface layer cap.

[5] Here we describe the warm mid-July state of the 2005 coastal ocean on the Newport Hydrographic (NH) line, and we compare this to available historical July NH lines. Noting the unusually weak upwelling-favorable winds early in the 2005 season that lead up to the strange July, we address the question of how this wind forcing compares to other years. We focus on the important relationship between cumulative (i.e., integrated over time) alongshore wind forcing and the state of the hydrography in July.

2. Data and Methods

[6] High-quality hydrographic sampling off central Oregon began in 1961, with regular temperature and salinity observations along the NH line (44.65°N) continuing through 1971 [*Smith et al.*, 2001]. Here we use the most frequently visited standard stations NH-5, NH-15, NH-25, NH-35, and NH-45 (names denote nautical miles from shore) extending from midshelf to midslope (Figure 1). Between 1971 and 1997, relatively few NH lines exist. From 1997–2004, the

[1] College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, Oregon, USA.

[2] Northwest Fisheries Science Center, NOAA Fisheries Service, Seattle, Washington, USA.

0094-8276/06/2006GL027149$05.00

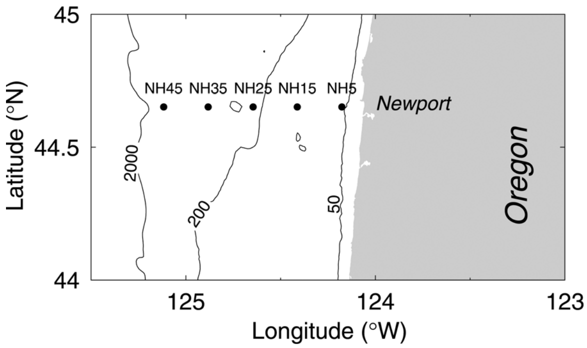

Figure 1. The Newport Hydrographic (NH) line standard stations used in this study. The 50, 200, and 2000 m isobaths are shown.

GLOBEC (Global Ocean Ecosystems Dynamics) program supported regular NH sampling again (data available at http://ltop.coas.oregonstate.edu) [e.g., *Huyer et al.*, 2005]. In July 2005 an NH line was occupied by the NOAA ship *Miller Freeman*, a portion of a larger series of physical oceanographic data collected routinely as part of the 2005 joint US-Canada acoustic Pacific hake survey. This fisheries and oceanographic survey is part of an established time series which spans the continental slope and shelf areas of the West Coast of the US and Canada [e.g., *Fleischer et al.*, 2005]. NH lines in the month of July from all the different programs are available for the following years: 1961–1968, 1983, 1997, 1999–2003, and 2005. Temperature anomalies (e.g., Figure 3b in section 4) are formed by subtracting the 1962–1968 July mean, for consistency with previous studies, [e.g., *Smith et al.*, 2001].

[7] We use daily upwelling indices, proportional to alongshore wind stress derived from US Navy Fleet Numerical Meteorology and Oceanography Center sea level pressure fields [*Schwing et al.*, 1996] at 45°N, 42°N, and 39°N (available at http://www.pfeg.noaa.gov). While these are relatively smoothed versions of the actual wind stress calculated from directly observed winds, they offer the advantage of a longer historical series, extending back to 1967.

[8] Cumulative upwelling (CU_{45N}, CU_{42N}, or CU_{39N}) is determined by integration over time of daily upwelling index, from the spring transition date for each year and location. The spring transition date is found using the following method: begin integrating upwelling index from 1 January, then after 1 February note the day that the minimum value is achieved (e.g., for 2005 case: Figure 2a, dot and vertical dashed line).

[9] In section 7, we estimate available potential energy (APE) per unit volume using the classic definition [e.g., *Huang*, 1998]: $APE = g \int\int(\rho - \rho_r)dxdz / \int\int dxdz$, where: g is acceleration due to gravity, $\rho = \rho$ (x, z) is observed density in the hydrographic line, and $\rho_r = \rho(z)$ is a reference column of density. We choose a local reference ρ_r (July 1962–68 mean profile at offshore station NH-165, 306 km from the coast), appropriate for defining the APE available to drive local currents.

3. Spring Transition Date and Cumulative Forcing

[10] The 2005 spring transition date at CU_{45N} was the 4th-latest amongst the 39-year set beginning in 1967 (Figure 2b), 38 days later than the mean date. We also note an apparent difference in statistical properties of the spring transition date, before and after 1977: interannual variability increases. This shift matches well with the 1977 shift in Pacific Decadal Oscillation (PDO) climate index [*Mantua et al.*, 1997], although there is not a strong relationship between PDO and cumulative upwelling [*Schwing et al.*, 2006]. The unusually late 2005 spring transition is one part of the explanation for the low CU_{45N} eventually achieved by mid-July (Figure 2c, bold curve). In addition, note the relative weakness in the early-season upwelling index (bold curve does not rise as quickly as most years). The dips in the 2005 curve in mid-June and mid-July are the result of strong northward wind events (Barth et al., submitted manuscript, 2006).

4. Newport Hydrographic Line in July

[11] Each available July NH temperature line shows some signs of classic upwelling, with isotherms generally rising towards shore, as expected for this time of year (Figure 3a). We also note a large degree of interannual variability, most clearly seen in temperature anomaly (Figure 3b). The year 1968 is coldest overall, with a −0.3°C line-average anomaly, while 2002 is also fairly cold but in a different way: this is an interesting example of a "subarctic intrusion" year, where

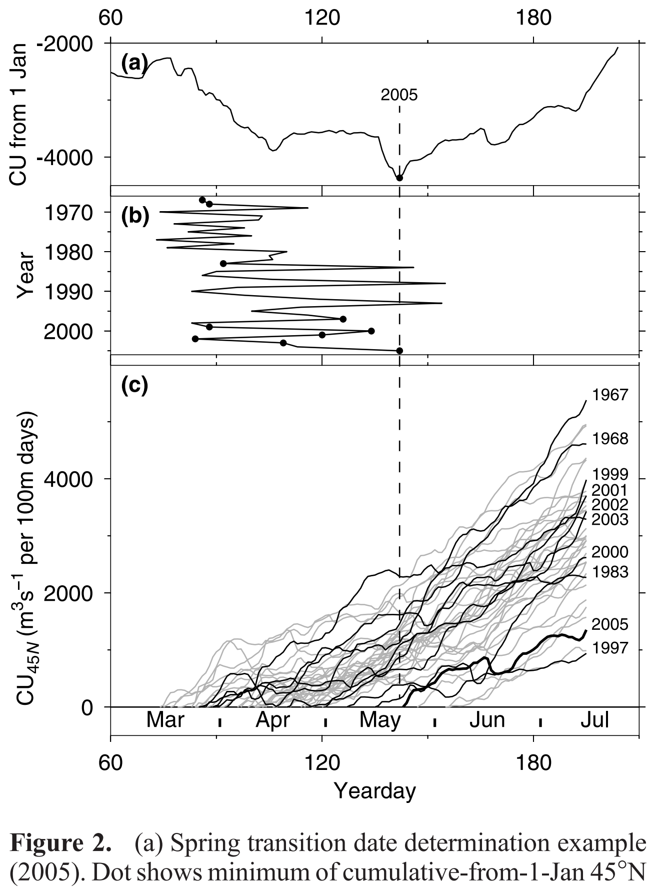

Figure 2. (a) Spring transition date determination example (2005). Dot shows minimum of cumulative-from-1-Jan 45°N upwelling index. (b) Spring transition dates for all years (1967–2005). Dots mark years where a July NH line is available. (c) Cumulative upwelling (CU_{45N}), from the spring transition date to July 15 (gray curves). Black curves are July NH line years, labeled at right side of the plot (2005 is a thicker line).

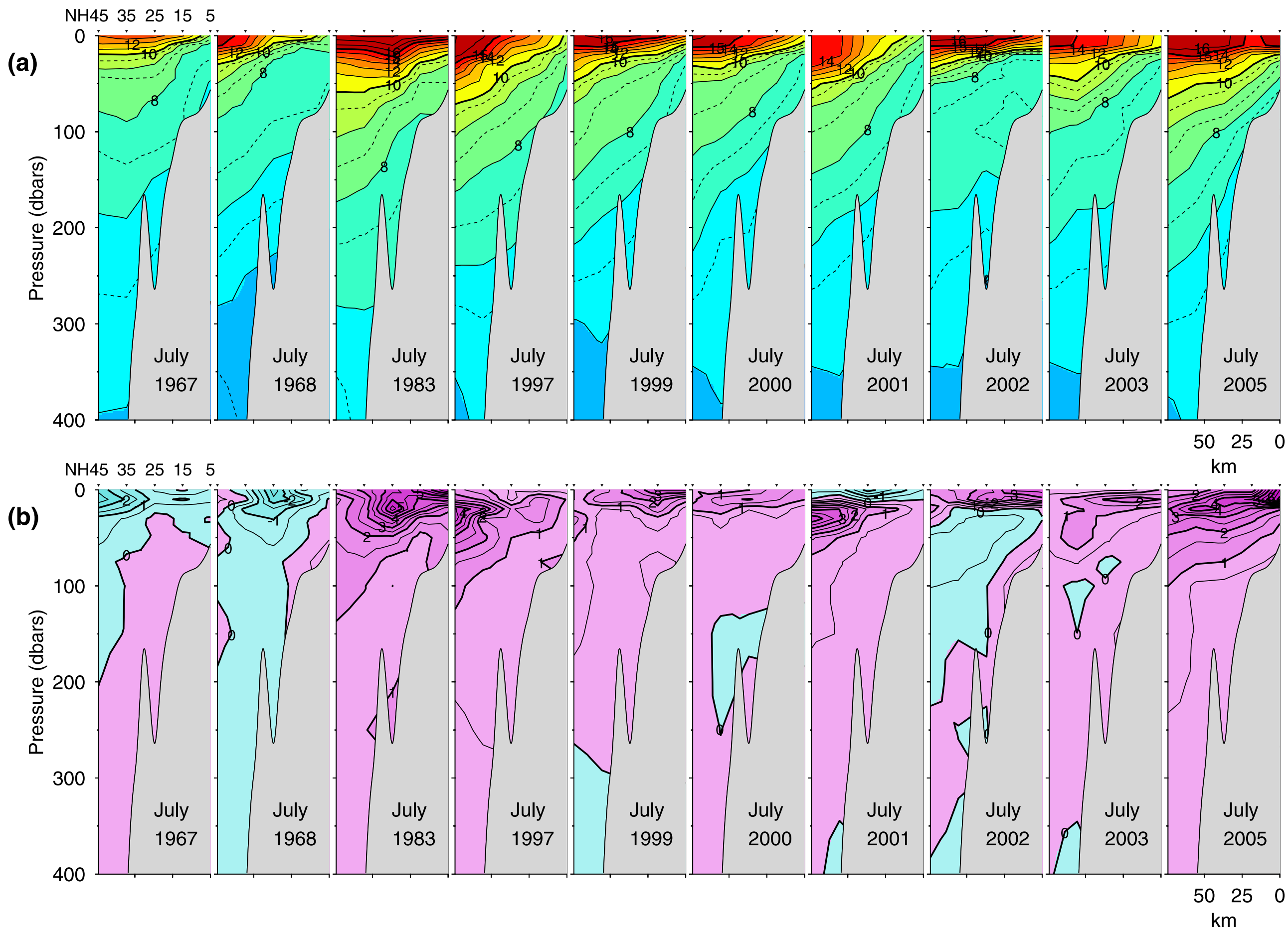

Figure 3. (a) July temperature (°C) sections along the NH line, for available years $\geq$ 1967. (b) Temperature anomaly sections formed by subtraction of the July 1962–1968 mean.

fresher, colder, and nutrient-rich water is advected from the north [*Huyer*, 2003, and references therein]. The years 1983, 1997, and 2005 stand out as notably warm: the line-average temperature anomalies of these three are all >0.8°C. Most interannual variability in temperature anomaly in the California Current has been associated with an El Nino signal, which can travel here either through the ocean or indirectly through the atmosphere [*Chavez et al.*, 2002]. In fact, two out of three of our warmest Julys, 1983 and 1997, are definite examples of an El Nino effect [*Lynn*, 1983; *Huyer et al.*, 2002]. The MEI (Multivariate ENSO Index) [*Wolter and Timlin*, 1998] for June/July 1983 and 1997 had relatively high values of 1.8 and 2.6 respectively (MEI available at http://www.cdc.noaa.gov).

[12] The July 2005 case is particularly anomalous in being warm and yet not an El Nino year (June/July MEI was 0.4). Based on the average temperature of the upper 30 m across each line, 2005 had the warmest July surface layer ever observed (including the six pre-1967 lines not shown in Figure 3).

5. Temperature Anomaly

[13] We consider the interannual variability of NH line July surface layer (0–30 m) temperature anomaly and its relationship to wind stress cumulative from the spring transition. Following the transition every year, alongshore wind stress begins to transfer energy to the upwelling system, forcing Ekman transport and generally lifting colder water to the surface as the season progresses. Cooler (warmer) surface layer temperature on a given date should be associated with larger (smaller) cumulative upwelling index up to that date.

[14] Indeed, we find a surprisingly strong linear relationship between the two, with an r^2 of 0.80, significant at 95% (Figure 4a). We conservatively assume a reduced N* = 5 to account for the possibility of some serial correlation amongst our 10 data points: the r^2 remains significant. Also note that, even with only 10 points, the samples include a wide range of CU_{45N} values, based on the full 39-year set (Figure 2c, gray background curves), including the 39-year minimum and maximum (note that Figure 2c shows all CU_{45N} ending on July 15, while Figure 4a and other regression results use CU_{45N} cumulative to the particular date of NH line occupation that year).

[15] If we consider similar CU_{45N} regressions, but this time against temperature anomaly series at individual stations and standard depths, we note a strong area close to the surface, thinning and diminishing at the inshore end of the line (Figure 4b). This is consistent with the upwelling system over the inner shelf being tied more closely with recent wind history, rather than integrated winds back to the spring transition date: *Austin and Barth* [2002] found that the

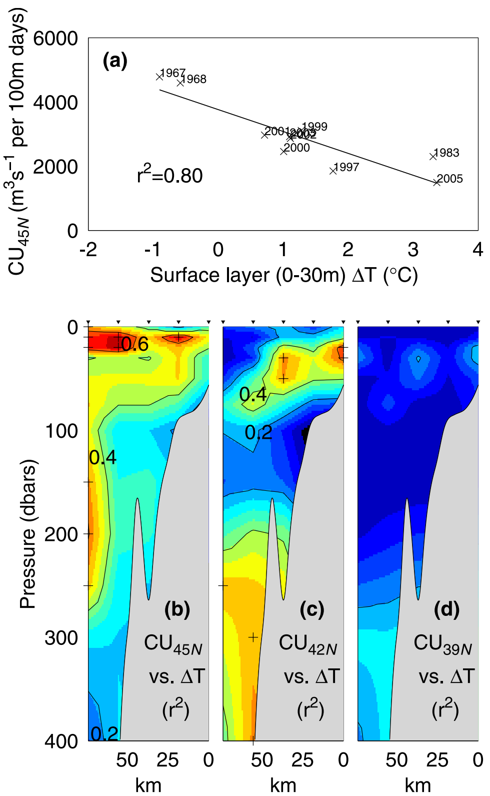

Figure 4. (a) Regression of surface layer (0–30 m) temperature anomaly against CU_{45N}. The r^2 = 0.80 is significant (95%). Regression results of the temperature anomaly series at each station and standard depth against (b) CU_{45N}, (c) CU_{42N}, and (d) CU_{39N}. Significant (95%) r^2 values are marked with plus signs.

position of upwelled isopycnals over the inner shelf is best related to an 8-day trailing running mean of wind history.

[16] Similar regression analyses of CU_{42N} and CU_{39N} against our 44.65°N line data reveal generally lower values (Figures 4c and 4d). Interestingly, though, we see a subsurface region of higher r^2 hugging the slope from 200–400 m, stronger in CU_{42N} but also present in CU_{39N}. Temperature anomalies at these depths are much better explained by CU_{42N} than by the local CU_{45N}. This suggests that remote forcing and subsequent wave propagation help determine subsurface July NH temperatures. *Hickey et al.* [2006] also found evidence for this type of remote forcing in their study of a sequence of 2005 hydrographic lines off Washington, and the phenomenon is described by coastal-trapped wave theory [*Allen*, 1976]. Wind stress at 42°N tends to be different than at 45°N as well, not only stronger but with different timing [*Huyer et al.*, 2005], so the remote forcing from the south affects NH line development differently.

6. Depth of the 7° Isotherm

[17] Our July 2005 hydrographic data were collected during the NOAA acoustic survey of Pacific hake, and isotherm depth is of particular interest for the role it may play in hake ecology. Trawl data have shown that adult Pacific hake are generally found in the 4–9°C range, with a large percentage near 7°C [e.g., *Fleischer et al.*, 2005]. At the offshore end of the NH line over the midslope, the 7°C isotherm in July 2005 was at 246 m, more than 3 standard deviations deeper than the 1962–68 mean of 188 m, and anomalously deep for a year with no El Nino effect: only the strong El Nino case of 1983 was deeper.

[18] To explore interannual variability of isotherm depth, we regress against CU_{45N} and find r^2 = 0.54 (Figure 5a). If we create a multiple regression model with CU_{42N} as an additional variable, however, the r^2 jumps up to 0.72 (Figure 5b). This is consistent with Figures 4b and 4c, where the relevant 180–280 m depth region at NH-45 has fairly high r^2 for both CU_{45N} and CU_{42N}: remote forcing from the south plays a role in the 7°C isotherm depth.

[19] From the 2005 Pacific hake survey, we also note an intriguing though anecdotal result regarding the effect of the unusual evolution of the 2005 upwelling season on hake. On 12 July 2005, prior to the onset of well-established upwelling, Pacific hake were observed in a tight aggregation just seaward of the shelf break at 43.44°N, at a mean depth of 326 m. When this same transect was repeated on 20 August 2005, in the midst of the stronger-than-average upwelling that was by then well-established, hake were found to have moved to a shallower mean depth of 231 m, in a mesopelagic layer which extended several kilometers offshore. This shift of mean hake depth was perhaps driven by thermal and related hydrographic preferences.

7. Available Potential Energy

[20] Wind stress cumulative from the spring transition lifts up isopycnals and thus increases the APE in the density distribution. This energy is then available for conversion into the kinetic energy of currents in the upwelling system. The APE of an observed line of density in the California Current is a good metric for summarizing the development of the upwelling system. The July 2005 line-mean APE was

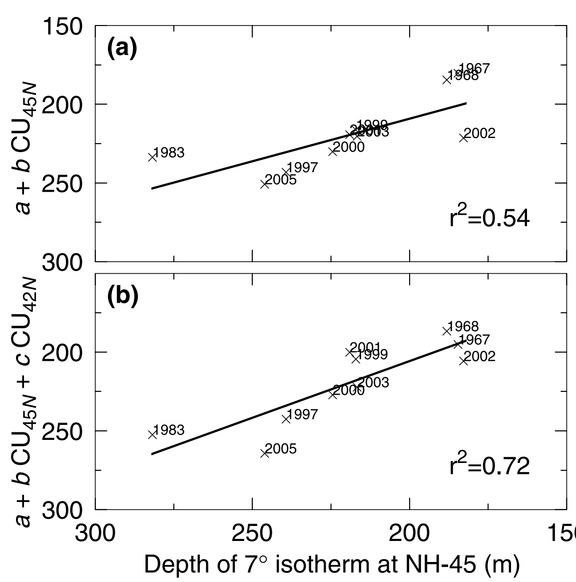

Figure 5. (a) Single-variable regression model $a + bCU_{45N}$ for depth of the 7° isotherm at NH-45. (b) Two-variable regression model $a + bCU_{45N} + cCU_{42N}$ (significant at 95%).

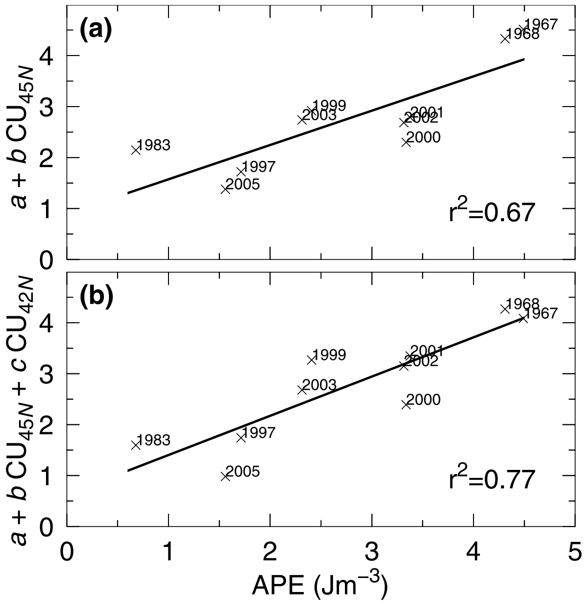

Figure 6. (a) Single-variable regression model $a + bCU_{45N}$ for NH line mean available potential energy (APE) per unit volume. (b) Two-variable regression model $a + bCU_{45N} + cCU_{42N}$ (significant at 95%).

1.6 Jm^{-3}, more than 2 standard deviations less than the 1962–68 mean of 4.0. Only the 1983 El Nino year had smaller July APE. Once again, the interannual variability in this metric can be well-explained by relation to the wind forcing. We find $r^2 = 0.67$ in the regression against CU_{45N} (Figure 6a), and a significant increase to $r^2 = 0.77$ when we add CU_{42N} to the model (Figure 6b). We are estimating APE using a reference July mean density profile from an offshore station (NH-165). The interannual variability at the reference station (available at http://ltop.coas.oregonstate.edu) leads to an uncertainty of 0.9 Jm^{-3} (95%): this a priori uncertainty is consistent with the regression residuals (1.0 Jm^{-3} in the Figure 6b case).

8. Discussion

[21] In one sense the results here are not surprising, since energy input into the upwelling system by wind forcing ought to be related to the available potential energy contained in the tilt of density surfaces, from fundamental physical principles [e.g., *Cushman-Roisin*, 1994]. What we find noteworthy is the remarkable strength of this relationship, which can then be used to predict mid-summer hydrographic conditions off central Oregon. Across a wide range of historical conditions, 77% of interannual variability of the upwelling system at the Newport Hydrographic line in July can be linearly explained by cumulative upwelling indices.

[22] Apparently, important sources of interannual variability such as El Nino primarily affect the northern California Current system indirectly through the atmosphere. The NH line may be particularly well behaved in this regard since it is in a region of relatively simple bottom topography, not affected as much by flow-topography interactions compared to locations to the south in the "lee" of Heceta Bank [*Barth and Wheeler*, 2005, and references therein]. Also, the effects of wind stress curl, which we do not consider here, tend to be small at the NH line, but significant at other locations such as south of Cape Blanco [*Huyer et al.*, 2005]. Even so, examination of time-integrated wind indices from spring transition date would seem to be an excellent starting point towards understanding the physical development of coastal upwelling anywhere.

[23] **Acknowledgments.** Thanks to R.L. Smith, A. Huyer, and J. Fleischbein for encouragement and cheerful sharing of historical NH line data. Thanks also to P. Ressler and the *Miller Freeman's* crew and scientific parties during the 2005 hake survey. S.D.P. supported under award AB133F05SE4205 from the National Oceanic and Atmospheric Administration, NOAA U.S. Dept. of Commerce. The statements, findings, conclusions, and recommendations are those of the authors and do not necessarily reflect the views of the NOAA or the U.S. Dept. of Commerce. Additional support provided by the National Science Foundation (grant OCE-0435619). This is contribution 319 of the U.S. GLOBEC program.

References

Allen, J. S. (1976), Some aspects of the forced wave response of stratified coastal regions, *J. Phys. Oceanogr.*, *6*, 113–119.

Austin, J. A., and J. A. Barth (2002), Variation in the position of the upwelling front on the Oregon shelf, *J. Geophys. Res.*, *107*(C11), 3180, doi:10.1029/2001JC000858.

Barth, J. A., and P. A. Wheeler (2005), Introduction to special section: Coastal advances in shelf transport, *J. Geophys. Res.*, *110*, C10S01, doi:10.1029/2005JC003124.

Chavez, F. P., C. A. Collins, A. Huyer, and D. L. Mackas (2002), El Niño along the west coast of North America, *Prog. Oceanogr.*, *54*, 1–5.

Cushman-Roisin, B. (1994), *Introduction to Geophysical Fluid Dynamics*, 320 pp., Prentice-Hall, Upper Saddle River, N. J.

Fleischer, G. W., K. D. Cooke, P. H. Ressler, R. E. Thomas, S. K. de Blois, L. C. Hufnagle, A. R. Kronlund, J. A. Holmes, and C. D. Wilson (2005), The 2003 integrated acoustic and trawl survey of Pacific hake, Merluccius productus, in U.S. and Canadian waters off the Pacific coast, *NOAA Tech. Memo. NMFS-NWFSC-65*, 45 pp., NOAA, Washington, D. C.

Hickey, B., A. MacFadyen, W. Cochlan, R. Kudela, K. Bruland, and C. Trick (2006), Evolution of chemical, biological, and physical water properties in the northern California Current in 2005: Remote or local wind forcing?, *Geophys. Res. Lett.*, *33*, L22S02, doi:10.1029/2006GL026782.

Huang, R. X. (1998), Mixing and available potential energy in a Boussinesq ocean, *J. Phys. Oceanogr.*, *28*, 669–678.

Huyer, A. (2003), Preface to special section on enhanced subarctic influence in the California Current, 2002, *Geophys. Res. Lett.*, *30*(15), 8019, doi:10.1029/2003GL017724.

Huyer, A., E. J. C. Sobey, and R. L. Smith (1979), The spring transition in currents over the Oregon continental shelf, *J. Geophys. Res.*, *84*, 6995–7011.

Huyer, A., R. L. Smith, and J. Fleischbein (2002), The coastal ocean off Oregon and northern California during the 1997–98 El Niño, *Prog. Oceanogr.*, *54*, 311–341.

Huyer, A., J. H. Fleischbein, J. Keister, P. M. Kosro, N. Perlin, R. L. Smith, and P. A. Wheeler (2005), Two coastal upwelling domains in the northern California Current system, *J. Mar. Res.*, *63*, 901–929.

Kosro, P. M., W. T. Peterson, B. M. Hickey, R. K. Shearman, and S. D. Pierce (2006), Physical versus biological spring transition: 2005, *Geophys. Res. Lett.*, *33*, L22S03, doi:10.1029/2006GL027072.

Lynn, R. J. (1983), The 1982–83 warm episode in the California Current, *Geophys. Res. Lett.*, *10*, 1093–1095.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis (1997), A Pacific interdecadal climate oscillation with impacts on salmon production, *Bull. Am. Meteorol. Soc.*, *78*, 1069–1079.

Schwing, F. B., M. O'Farrell, J. M. Steger, and K. Baltz (1996), Coastal upwelling indices, west coast of North America, 1946–1995, *NOAA Tech. Memo. NOAA-TM-NMFS-SWFSC-231*, 144 pp., NOAA, La Jolla, Calif.

Schwing, F. B., N. A. Bond, S. J. Bograd, T. Mitchell, M. A. Alexander, and N. Mantua (2006), Delayed coastal upwelling along the U.S. West Coast in 2005: A historical perspective, *Geophys. Res. Lett.*, *33*, L22S01, doi:10.1029/2006GL026911.

Smith, R. L., A. Huyer, and J. Fleischbein (2001), The coastal ocean off Oregon from 1961 to 2000: Is there evidence of climate change or only of Los Niños?, *Prog. Oceanogr.*, *49*, 63–93.

Sydeman, W. J., R. W. Bradley, P. Warzybok, C. L. Abraham, J. Jahncke, K. D. Hyrenback, V. Kousy, J. M. Hipfner, and M. D. Ohman (2006), Planktiverous auklet Ptychoramphus aleuticus responses to the anomaly of 2005 in the California Current, *Geophys. Res. Lett.*, doi:10.1029/2006GL026736, in press.

Thomas, A. C., and P. Brickley (2006), Satellite measurements of chlorophyll distribution during spring 2005 in the California Current, *Geophys. Res. Lett.*, *33*, L22S05, doi:10.1029/2006GL026588.

Wolter, K., and M. S. Timlin (1998), Measuring the strength of ENSO—How does 1997–98 rank?, *Weather*, *53*, 315–324.

J. A. Barth and S. D. Pierce, College of Oceanic and Atmospheric Sciences, Oregon State University, 104 COAS Admin Bldg, Corvallis, OR 97331-5503, USA. (spierce@coas.oregonstate.edu)

G. W. Fleischer and R. E. Thomas, Northwest Fisheries Science Center, NOAA Fisheries Service, 2725 Montlake Boulevard East, Seattle, WA 98112, USA.