Phenology of coastal upwelling in the California Current

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[1] Changes in the amplitude and phasing of seasonal events (phenology) can affect the functioning of marine ecosystems. Phenology plays a particularly critical role in eastern boundary ecosystems, which are driven largely by the seasonal cycle of coastal upwelling. Here we develop and describe a set of indicators that quantify the timing, evolution, intensity, and duration of coastal upwelling in the California Current large marine ecosystem (CCLME). There is significant interannual variability in upwelling characteristics during 1967–2007, with extended periods of high (1970s, 1998–2004) and low (1980–1995) seasonally-integrated upwelling and a trend towards a later and shorter upwelling season in the northern CCLME. El Niño years were characterized by delayed and weak upwelling in the central CCLME. Understanding the causes and ecosystem consequences of phenological changes in coastal upwelling is critical, as climate models project significant variability in the amplitude and phase of coastal upwelling under varying climate change scenarios. **Citation:** Bograd, S. J., I. Schroeder, N. Sarkar, X. Qiu, W. J. Sydeman, and F. B. Schwing (2009), Phenology of coastal upwelling in the California Current, *Geophys. Res. Lett.*, *36*, L01602, doi:10.1029/2008GL035933.

1. Introduction

[2] Many marine organisms have life histories adapted to seasonal events in the environment. Changes in the amplitude and phasing (i.e., phenology) of seasonally varying processes can therefore significantly affect the functioning of marine ecosystems, from primary producers to fish stocks to apex predators [*Cushing*, 1990; *Beare and McKenzie*, 1999; *Bograd et al.*, 2002; *Logerwell et al.*, 2003; *Abraham and Sydeman*, 2004]. Such phenological effects are potentially disruptive to trophic interactions, perhaps more so than those associated with interannual climate events and decadal climate shifts [*Stenseth et al.*, 2002; *Sydeman et al.*, 2006; *Barth et al.*, 2007]. Assessments of marine ecosystem response to climate change should consider potential changes in the seasonal cycle of the dominant physical processes that drive ecosystem structure and productivity [*Durant et al.*, 2007].

[3] The phenology of coastal upwelling plays a critical role in the California Current Large Marine Ecosystem (CCLME). The impact of anomalous seasonal cycles was particularly evident in 2005, when coastal upwelling was delayed in the northern CCLME [*Schwing et al.*, 2006], resulting in unusual coastal conditions [*Kosro et al.*, 2006; *Pierce et al.*, 2006] and ecosystem changes at multiple trophic levels from primary production [*Thomas and Brickley*, 2006] to zooplankton [*Mackas et al.*, 2006], to fish, birds, and mammals (*Brodeur et al.* [2006], *Sydeman et al.* [2006], and *Weise et al.* [2006], respectively). Long-term changes in the upwelling process may have been responsible for previous ecosystem shifts in the CCLME [*Schwing and Mendelssohn*, 1997].

[4] Here we develop simple indices to quantify variation in the timing of the onset of coastal upwelling in the California Current (i.e., the date of the "spring transition" to seasonal upwelling conditions), the temporal evolution and overall intensity of upwelling, and the duration of the upwelling season, as well as the spatial variations of these properties along the West Coast between Baja California and Vancouver Island. We also investigate interannual variability in the characteristics of coastal upwelling in the California Current over the period 1967–2007. Operational indicators of upwelling phenology could provide an early warning signal to resource managers of the probability of a disruption to the CCLME.

2. Data Sets and Index Definitions

[5] The coastal upwelling index (UI) [*Bakun*, 1973; *Schwing et al.*, 1996] has been a workhorse of fisheries oceanography for more than three decades, greatly contributing to our understanding of physical-biological coupling in eastern boundary current systems. The UI represents the magnitude of the offshore component of Ekman transport, which approximates the amount of water upwelled from the base of the Ekman layer. Positive values are the result of equatorward wind stress, whereas negative values imply downwelling, the onshore advection of surface waters accompanied by a downward displacement of water. Upwelling indices are computed from the 6-hourly, 1°-resolution sea level pressure fields obtained from the U.S. Navy Fleet Numerical Meteorology and Oceanography Center (FNMOC). Herein, we use the 41-year time series (1967–2007) of daily-averaged UI at six locations along the U.S. West Coast, from 33°N to 48°N, separated by 3° latitude, to develop within-season indicators of upwelling conditions.

[6] Since upwelling has a cumulative effect on ecosystem productivity and structure, we focus on the cumulative upwelling index (CUI); this index represents summation of the daily mean upwelling indices at each location starting on January 1st, and continuing to the end of the year [*Schwing et al.*, 2006; *Pierce et al.*, 2006]. Based on the CUI, we define within-season indices of the date of the

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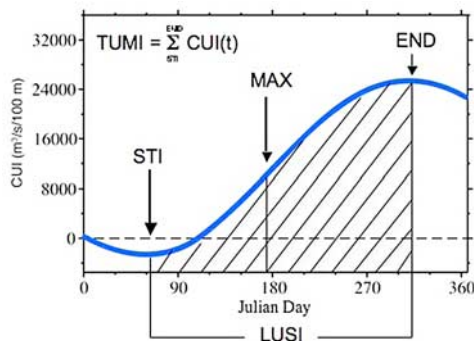
Figure 1. Climatological annual cycle of cumulative upwelling index (CUI; $m^3\ s^{-1}\ 100\ m^{-1}$) at 39°N in the California Current. Phenological upwelling indices are shown schematically: STI (spring transition index), LUSI (length of upwelling season index), and TUMI (total upwelling magnitude index). MAX (maximum slope of CUI curve) and END (annual maximum of CUI) give the dates of peak upwelling and end of upwelling season, respectively.

spring transition, intensity and evolution of upwelling, and duration of the upwelling season from the 41-year CUI series at each location as described below, and shown schematically in Figure 1:

[7] (1) Spring Transition Index (STI): The date (Julian Day) on which the CUI, integrated from January 1st, reaches its minimum value, i.e., the date after which positive UI (upwelling) prevails. Similarly, the end date of the upwelling season (END) is defined as the date on which the CUI reaches its maximum value. The date on which the rate of change of CUI is greatest (MAX) we define as the date of peak seasonal upwelling. The STI should be considered a systematic, though not definitive, estimate of the start of the upwelling season, as different parameters can yield different dates for the spring transition [e.g., *Kosro et al.*, 2006].

[8] (2) Length of Upwelling Season Index (LUSI): The total number of days between the observed start date (STI) and observed end date (date of maximum CUI) of the upwelling season.

[9] (3) Total Upwelling Magnitude Index (TUMI): The total CUI integrated from the observed spring transition date (STI) to the observed end date of the upwelling season. This is a measure of the intensity of coastal upwelling integrated over the entire length of the defined upwelling season.

[10] (4) Total Downwelling Magnitude Index (TDMI): The total CUI integrated from the observed end date of the

upwelling season (END) to the observed spring transition date (STI) the following year. This is a measure of the intensity of downwelling between subsequent upwelling seasons.

[11] Additional indices could be derived from the CUI. The evolution of CUI over the course of an upwelling season reflects intraseasonal variations in upwelling intensity, for example, and can be used to discriminate upwelling and relaxation events. Here we focus on indices characterizing interannual variability in the timing and integrated strength of upwelling in the CCLME, as these are likely to reflect the processes that impact when production begins (STI) and how the ecosystem evolves over the course of the upwelling season (TUMI, LUSI).

3. Interannual Variability in California Current Upwelling

[12] There is significant meridional and temporal variability in the characteristics of coastal upwelling in the California Current (Table 1 and Figure 2). The climatological upwelling season is nearly year-round (though weaker) off southern California, but gets progressively shorter with northward latitude (Table 1; the mean duration is 357 d at 33°N and 151 d at 48°N). There is significant variance in CUI over the 41-year record at all latitudes. From 42°N to 48°N, interannual variability in winter downwelling leads to a wide range of CUI values at the end of the calendar year. From 33°N to 36°N, variance in the date of maximum upwelling is high (σ = 198 d at 33°N), and the spread in CUI accumulates slowly over the year (Figure 2). The greatest intensity, and variance, in upwelling occurs off northern California (36°–42°N).

[13] Timing of the onset and duration of the upwelling season varied greatly from year to year, with particularly high variability at the latitudes of strongest upwelling in the CCLME (36°–42°N; Figure 3a). Variations in timing of the onset of upwelling may imply a "surplus" or "deficit" of upwelling relative to the climatological STI (Figure 2). At 42°N, for example, the CUI at the climatological spring transition date (JD 107) ranged from −19,066 $m^3\ s^{-1}$ 100m^{-1} (1983) to +1,866 $m^3\ s^{-1}$ 100m^{-1} (2007). In the northern CCLME, there is a significant trend (1.0 d y^{-1}; r = 0.42, p = 0.0061) towards a later spring transition, with an accompanying trend towards a shorter upwelling season at 48°N (−1.1 d y^{-1}; see Figures 3a and 3b). In the southern CCLME, there is a significant trend towards a longer upwelling season (0.34 d y^{-1}; r = 0.41, p = 0.0083).

[14] Decadal modulation of the integrated upwelling intensity was seen throughout the CCLME (Figure 3c), with periods of high TUMI (1970s, 1998–2004) inter-

Table 1. Climatological Mean and Standard Deviation of STI, END, LUSI, TUMI, and TDMI for Each Latitude Over the Period 1967–2007[a]

Latitude	STI (JD)	END (JD)	LUSI (d)	TUMI ($m^3\ s^{-1}\ 100m^{-1}$)	TDMI ($m^3\ s^{-1}\ 100m^{-1}$)
48°N	119 ± 29	269 ± 20	151 ± 37	3,156 ± 1,223	−17,774 ± 5,640
45°N	114 ± 26	283 ± 19	170 ± 33	6,378 ± 2,199	−17,514 ± 6,326
42°N	82 ± 29	304 ± 22	223 ± 37	19,126 ± 7,298	−13,155 ± 6,469
39°N	50 ± 34	331 ± 24	282 ± 45	29,386 ± 9,804	−3,977 ± 3,851
36°N	30 ± 28	348 ± 18	320 ± 37	27,779 ± 5,993	−548 ± 1,527
33°N	6 ± 7	361 ± 8	357 ± 10	26,929 ± 7,421	—

[a]JD, Julian Day (1 = 1 January); n = 41 years.

spersed with an extended period of generally low TUMI (1980–95) between 36°N and 42°N. These periods also correspond to periods of variable LUSI, with longer upwelling seasons in the first high-TUMI and the low-TUMI periods, and shorter upwelling seasons in the second high-

TUMI period. Thus, the recent period of high TUMI in the central CCLME can be attributed to anomalously strong upwelling intensity. In the 1970s, TUMI decreased meridionally from southern California to Washington, while the latter period of strong upwelling led to higher TUMI in northern California (39°–42°N). Total upwelling intensity (indexed by TUMI) has a significant linear trend at 33°N (decreasing) and 42°N (increasing). Downwelling intensity (indexed by TDMI) is also highly variable, although its meridional variation is due largely to the northward decline in the length of the upwelling season (Table 1).

[15] El Niño events appear to have an impact on CCLME upwelling phenology (Figure 3). At 36°–42°N, the upwelling season began late and was of anomalously short duration in the years affected by the strong El Niños of 1972, 1982–83, 1991–93 and 1997–98 (though not 1987; see Figures 3a and 3b). The decadal modulation of integrated upwelling intensity (TUMI) may be related to the frequency of El Niño events, with the period of low TUMI in the central CCLME encompassing several strong events (Figure 3c). The 1997–98 El Niño event was characterized by negative sea level pressure and cyclonic wind anomalies [Schwing et al., 2002], resulting in a weaker upwelling season and diminished productivity in the CCLME. El Niño events also impact winter downwelling, with the largest magnitude TDMI occurring in the northern CCLME during the strong 1997–98 event (not shown). Further analyses using historical observations and coupled ocean-atmosphere models are required to investigate the large-scale climate impacts on CCLME upwelling.

4. Discussion and Summary

[16] We have built upon the foundation of the historical upwelling index [Bakun, 1973], which has been applied effectively for years in coastal oceanography and fisheries research. The set of physical indicators developed here are the first to systematically address the critical issue of phenology in the CCLME, by quantifying the timing, evolution, intensity, and duration of coastal upwelling. We have documented significant interannual variability in upwelling characteristics, including long-term trends in the timing and duration of the upwelling season, decadal fluctuations in upwelling intensity, and delayed upwelling during El Niños, which may contribute to the diminished biological productivity seen at those times [Lenarz et al., 1995]. Indeed, the principal ecosystem effects of interannual to decadal climate variability in eastern boundary currents such as the CCLME could be driven by such phenological changes. It should be noted that upwelling in the CCLME can be driven by alongshore wind stress (as characterized by
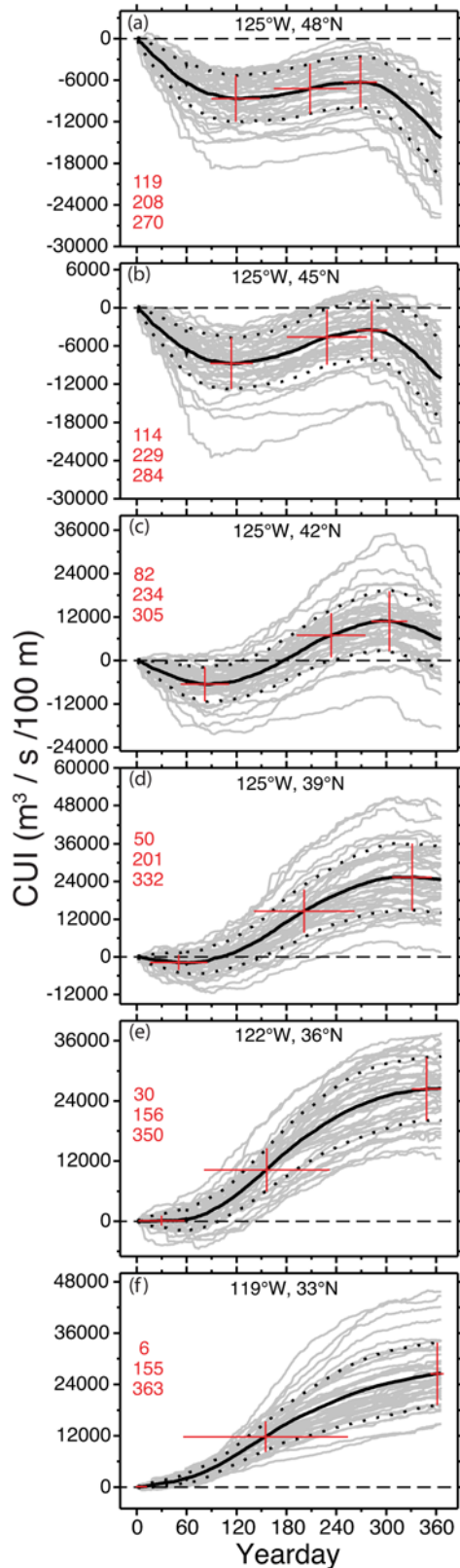
Figure 2. Cumulative upwelling index (CUI; $m^3 \ s^{-1} \ 100 \ m^{-1}$) for six locations in the California Current. Mean and standard deviation (black solid and dashed curves, respectively) and 1967–2007 (gray curves) are shown. Julian Days (red text) of climatological start (top) and end (bottom) of upwelling season and maximum upwelling (middle) are shown for each location. Standard error ellipses for CUI and Julian Day of start, end and maximum upwelling are shown in red.
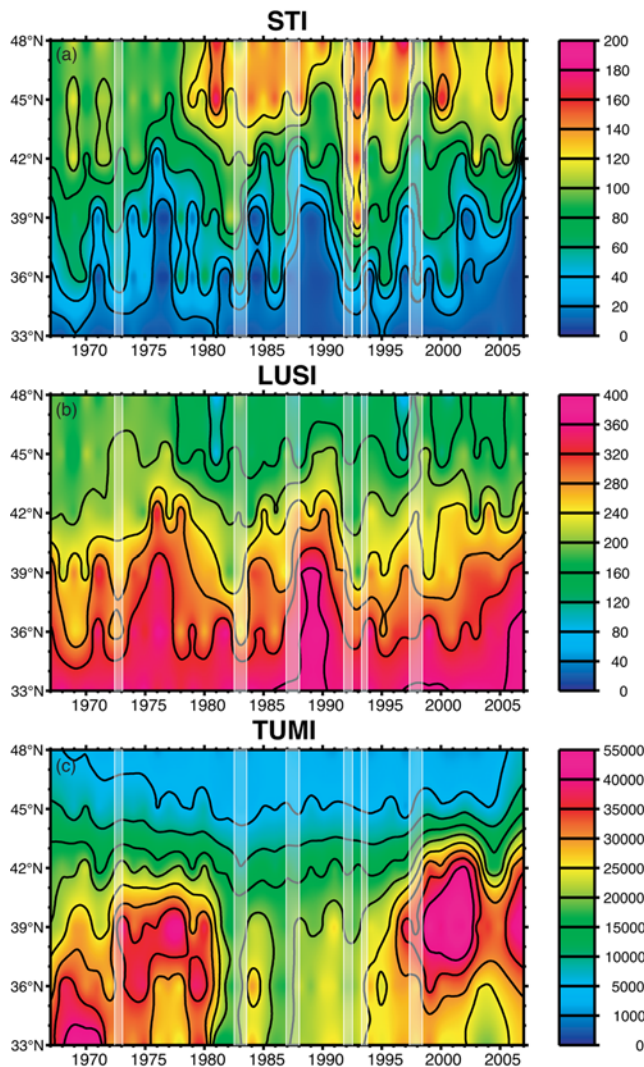
Figure 3. Time vs. latitude diagrams for (a) spring transition index (Julian day), (b) length of upwelling season index (days), and (c) total upwelling magnitude index (m^3 s^{-1} 100 m^{-1}). Periods of strong El Niños (defined by multivariate ENSO index >1.0) are marked.

the present indices) as well as offshore wind-stress curl, although interannual variations in these two processes do not appear to be tightly coupled in the southern CCLME [*Rykaczewski and Checkley*, 2008]. Other processes (e.g., coastal trapped waves) can also exert influences on the upwelling habitat of the CCLME.

[17] Marine organisms will, to varying degrees, show resilience to changes in the annual upwelling cycle. For primary producers (phytoplankton), the timing of the spring transition and nutrient input relative to solar insolation is likely to be critical to photosynthesis and productivity, particularly in the light-limited northern CCLME. At mid- to higher trophic levels, the phenology of upwelling may relate to matches and mismatches between the productivity and life cycles of predator and prey [*Sydeman et al.*, 2001; *Durant et al.*, 2007]. Many top predators time reproduction and/or migration to periods of maximum food abundance [*Cushing*, 1990]; however, there is no reason to assume that

changes in the phenology of upwelling would affect predators and prey species similarly. For species with limited plasticity in their life histories, any substantial changes in the timing, intensity or duration of upwelling could be disruptive to their foraging, reproductive, or migratory success if it impacts their trophic ecology. Indeed, under varying climate change scenarios, we expect greater mismatches in predator needs and prey availability, undoubtedly mediated in large part by the phenology of upwelling in the CCLME.

[18] Information on the phenology of upwelling is vital to managers tasked with assessing future changes in commercially important fish and protected species populations, and in the overall ecosystem health of the CCLME. A number of recent studies have discussed climate-driven phenological changes in marine and terrestrial ecosystems [e.g., *Edwards and Richardson*, 2004; *Stenseth and Mysterud*, 2002; *Stenseth et al.*, 2002]. *Logerwell et al.* [2003] and others have shown the importance of the spring transition to salmon fisheries in the northern CCLME. Groundfish productivity and recruitment may be similarly affected by variation in spring transition dates [*Miller and Sydeman*, 2004]. While statistics on the timing of upwelling, and total upwelling intensity, are indeed critical parameters to monitor, the event-based time scale (daily to weekly), not investigated per se in this study, is also of great significance [*Lasker*, 1978]. Eventually, examining the phenology of upwelling on multiple time scales will be needed to better resolve the coupling between upwelling and biology in the CCLME.

[19] Some studies employing global and regional climate models project significant variability in the timing and magnitude of coastal upwelling accompanying various climate change scenarios [*Snyder et al.*, 2003; *Diffenbaugh et al.*, 2004; *Diffenbaugh*, 2005], while others found little indication of anthropogenic climate change leading to systematic changes in CCLME coastal upwelling [*Mote and Mantua*, 2002]. The recent variations in the phenology of upwelling in the CCLME could be a harbinger of future changes that could disrupt predator-prey dynamics and reduce ecosystem services (fisheries) in the CCLME.

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