07-07
Project Title: The Phenology of Coastal Upwelling in the California Current

Principal Investigators:
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Goals:
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 will need to consider potential changes in the seasonal cycle of the dominant physical processes that drive ecosystem structure and productivity (Hunt et al., 2002; Durant et al., 2007).

The objective of this project was to 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 investigated 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.

Approach:
We developed indices that build upon and expand the utility of the historical Upwelling Index (UI; Bakun, 1973). Since upwelling has a cumulative effect on ecosystem productivity and structure, we derived the cumulative upwelling index (CUI), based on integrating the mean daily upwelling index from January 1st to the end of the year. We used the 41-year time series (1967-2007) of daily UI at six locations along the U.S. West Coast, from 33°N to 48°N, separated by 3° latitude, to develop several indicators characterizing the phase and amplitude of California Current upwelling.

Work Completed:
Based on the CUI, we defined within-season indices of the date of the 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.

(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.

(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.

(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.

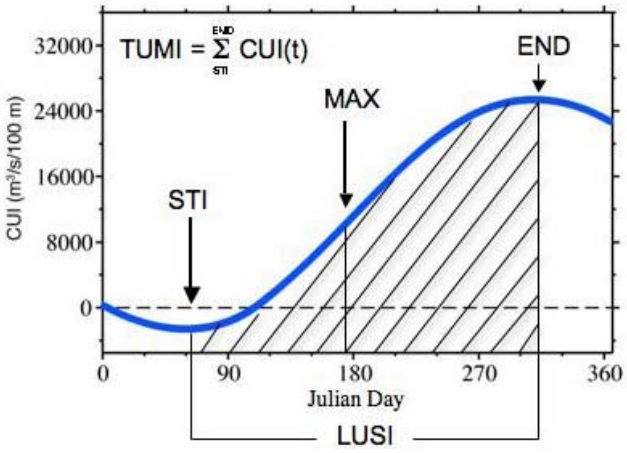

Figure 1: Climatological annual cycle of CUI, showing derived phenological indices.

(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.

We have used this set of indicators to describe meridional and temporal variability in the characteristics of coastal upwelling in the California Current (Figure 2). These indices reveal extended periods of strong (1970s, 1998-2004) and weak upwelling (1980-1995) 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. These results are described in Bograd et al. (2008).

Finally, we have related these intra-seasonal and interannual variations in upwelling to responses at several trophic levels, focusing on the reproductive success of one planktivorous (Cassin's auklet) and one pisciverous (common murre) seabird species that breed on the Farallon Islands. The dates of egg laying for both species are highly correlated with indices of coastal upwelling, with a lag of 2-3 months. This implies that a pre-conditioning of the system by early (late winter) upwelling events yields an earlier

mean egg-laying date, and hence higher reproductive success. These results are described in Schroeder et al. (2008).

Applications:
The set of physical indicators developed here are the first to address the critical issue of phenology in the California Current, and will contribute to our understanding of climate-ecosystem interactions in the CCLME. Although still largely in research-development-validation mode, these indices are being correlated with a variety of long-term biological time series. These indices will become part of subsequent Integrated Ecosystem Assessments (IEAs) of the California Current Ecosystem, and will be made available to NMFS scientists and managers for implementation into stock-specific and ecosystem-based assessment models.

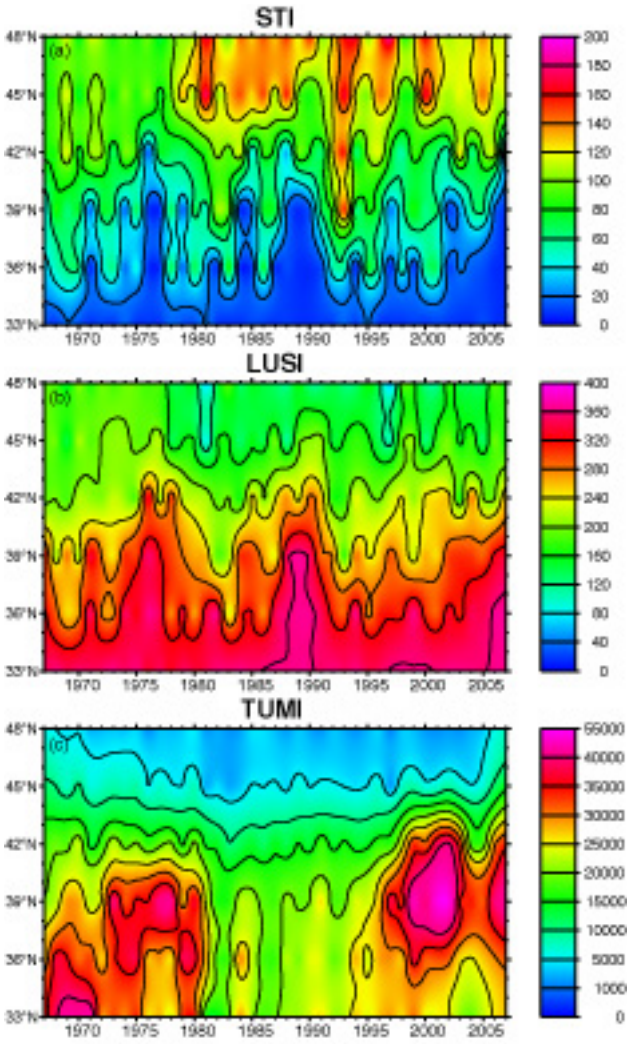

Figure 2: Time vs. latitude diagrams for (a) spring transition index (Julian day), (b) length of upwelling season index (days), and (c) total upwelling magnitude index (m^3 s^{-1} 100 m^{-1}).

Publications/Presentations:

Bograd, S.J., I. Schroeder, N. Sarkar, X. Qiu, W.J. Sydeman, and F.B. Schwing, 2008. The phenology of coastal upwelling in the California Current, *Geophysical Research Letters*, submitted.

Schroeder, I., W.J. Sydeman, S.J. Bograd, N. Sarkar, and F.B. Schwing, 2008. Phenological indicators of seabird reproductive success in the California Current, *Marine Ecology Progress Series*, submitted.

Bograd, S.J., The phenology of coastal upwelling in the California Current. PICES 16th Annual Meeting, Victoria, BC, October 2007.

Bograd, S.J., The phenology of coastal upwelling in the California Current. IEP Annual Workshop, Pacific Grove, CA, February 2008.

Schroeder, I., Phenological indicators of seabird reproductive success in the California Current. FATE Annual Science Meeting, August 2008.

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