09-03

Project Title: Beyond the Spring Transition: Winter Pre-Conditioning of Ecosystem Dynamics and Implications for Sentinel Species and Fisheries

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Background

In this study, we integrate time series of rockfish growth and seabird reproductive success to investigate the impacts of climate on California Current Ecosystem structure and function. Of particular interest is that role of climate variability during the winter months. Preliminary research showed the rockfish growth and seabird reproductive success strongly covary, and that this covariance could be explained by their shared sensitivities to wintertime ocean conditions, especially upwelling between January and March. Years with favorable wintertime upwelling were characterized by robust rockfish growth, early seabird lay date, and high seabird fledgling success. Though upwelling is generally considered a spring and summertime phenomenon, wintertime climate may be much more important for ecosystem productivity than previously appreciated, as independently corroborated by these diverse and uniquely long biological time series.

Goals

This project has several objectives, both scientific and operational:

1) To extend the existing splitnose rockfish chronology (1948-1995) through the 2000s to more fully overlap with seabird reproductive success in that the covariance among biological and physical time series may be better explored.
2) To derive leading biological indicators of the health and productivity of the CCE from historical seabird and rockfish datasets.
3) To develop a mechanistic understanding of the role of winter pre-conditioning in setting overall ecosystem productivity in the California Current.
4) To incorporate derived climate-growth relationships into a stock assessment of splitnose rockfish.
5) To use derived biological indicators to understand and forecast chinook salmon return rates, following the Sydeman-Roth-Mills model.
6) To provide input to the California Current Integrated Ecosystem Assessment.

Work Completed:

<u>GOALS 1 and 2:</u>

The original splitnose growth-increment chronology (see (Black et al. 2005, Black 2009)) spanned 1948-1995. Over the past year we have extended the chronology to span 1936-2006; a 71-year time series unprecedented in length and resolution for the California Current Ecosystem. In summary, splitnose rockfish otoliths collected between 2006 and 2008 were obtained from the NOAA Southwest Fisheries Science Center in Santa Cruz, CA. At the Hatfield Marine Science Center, otoliths were embedded, thin sectioned and polished to reveal the annual increments, which were best viewed with reflected light. Samples were visually crossdated to ensure that all annual growth increments were assigned the correct calendar year. After visual crossdating, the dorsal half of the otolith was then photographed and the annual increment widths measured continuously from the margin to as close to the focus as possible using the program ImagePro Plus v. 6.0. Each otolith measurement time series (from an individual fish) was then fit with a negative exponential function and divided by the values predicted, thereby removing age-related growth declines and standardizing each time series to a mean of one. These detrended time series were averaged to form the master chronology in which each value represented sample-wide growth for a given calendar year. A value greater than one represented above-average growth while a value below one represented below-average growth. A total of 72 otoliths was used to develop the splitnose rockfish master chronology, and the length of the final chronology was 1936-2006, the time period in which minimum sample depth was greater than six, the number necessary to sustain and adequate signal to noise ratio (Figure 1).

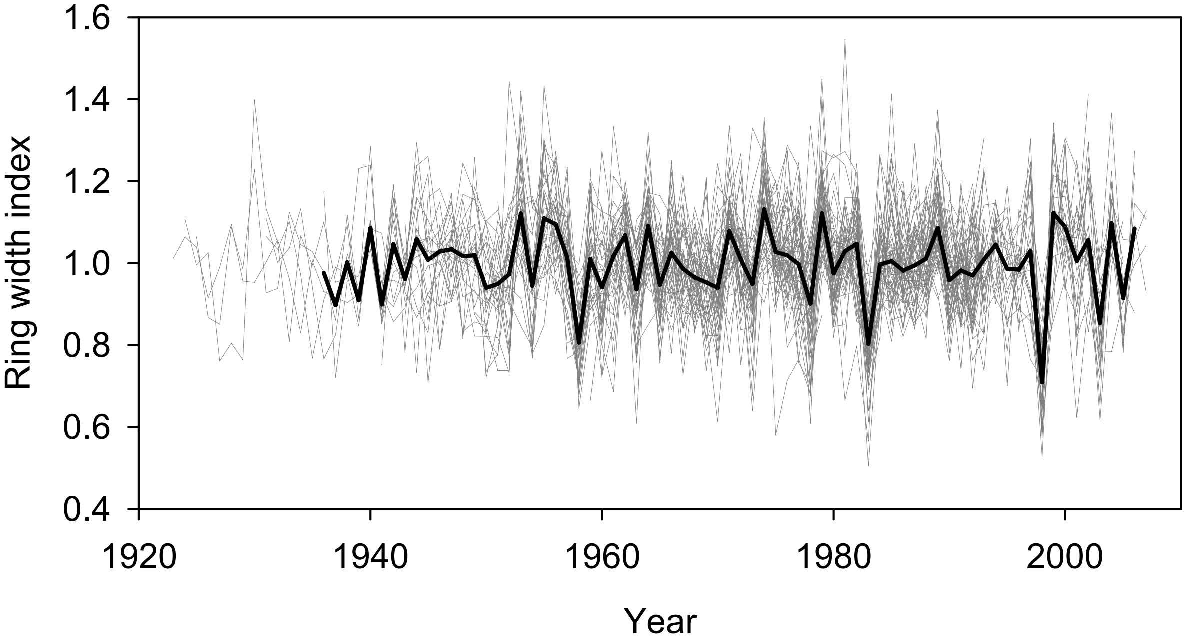

Figure 1. Detrended measurement time series for 72 splitnose rockfish otoliths (gray lines). The mean (master) growth chronology for splitnose rockfish; 1936-2006 (black line).

Although not originally included as part of our proposal, we had the unique and unexpected opportunity to develop a chronology from the scale growth increments of Chinook salmon measured and provided by Wells et al. (2008). Briefly, scales were collected from all returning female salmon at Mill Creek, a tributary of Smith River, California, between 1981 and 2002 (N = 613). All sampled fish were "ocean-type," having migrated to sea before their first winter. An acetate impression was made of each scale and growth-increment widths were measured from the origin along a line oriented 20º relative to the maximum scale length (Wells et al. 2008). The final chronology was developed by normalizing age-specific (one through four) increment-width to a mean of zero and standard deviation of one, then averaging these normalized values with respect to calendar year. A total of 1,729 normalized increment widths were used to develop the master chronology, which spanned 1978-2001 (Figure 2). Only those calendar years with at least twenty normalized increment widths were retained in order to guarantee that the population-wide growth pattern (signal of interest) was not masked by individual-fish variability (noise).

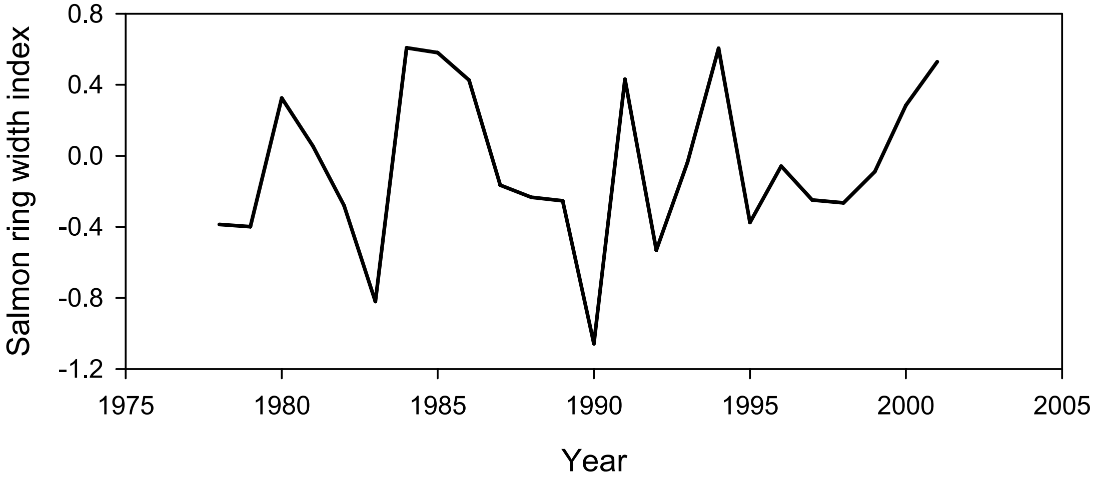

Figure 2. Salmon scale growth-increment chronology for the Smith River, central California.

Integration of physical and biological time series.
We have employed multivariate time series techniques (EOF analysis) to quantify the co-variance among different parameters (time series). To date, seven biological time series specific to the central California Current Ecosystem have been integrated: average annual egg-laying date for the planktivorous seabird, Cassin's auklet, and the omnivorous seabird, common murre, annual breeding success (offspring pair^{-1}) for the auklet and the murre, annual otolith-based growth chronologies for the planktivorous splitnose and piscivorous yelloweye rockfish, and Chinook salmon chronology. These seven time series overlap spatially (central CCE), and temporally (common interval of 1978-2001. The leading components captured 58% of the total variance (eigenvalue = 4.1) while the second component captured an additional 16% of the total variance (eigenvalue = 1.1) (Figure 4). Both principal components could serve as important ecological indicators for the region considering the diverse biological time series from which they were derived.

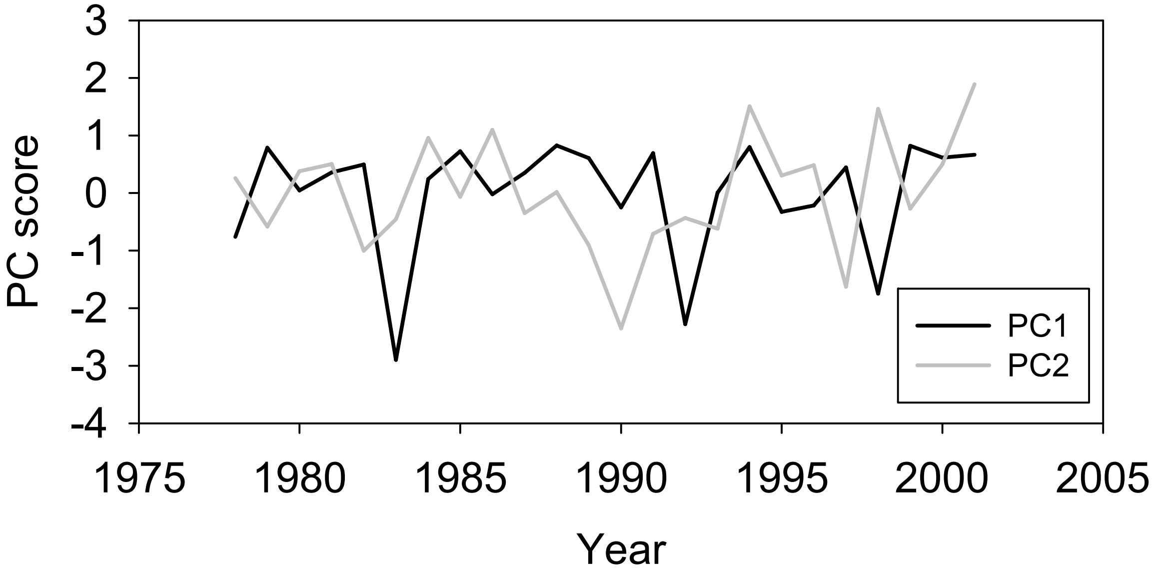

Figure 4. Leading two principal components from seven biological time series in the central California Current Ecosystem.

Relationships to climate

Several climate indices were considered, though upwelling provided the strongest results. Mean monthly sea level at San Francisco was also used as a more local ocean indicator, obtained through the University of Hawaii Sea Level Center. The leading two principal components from the seven biological time series were correlated with upwelling and sea level records. These correlations indicate that PC1 from the biological time series is strongly related to wintertime upwelling while PC2 from the biological time series is strongly related to late summertime upwelling (Figure 5).

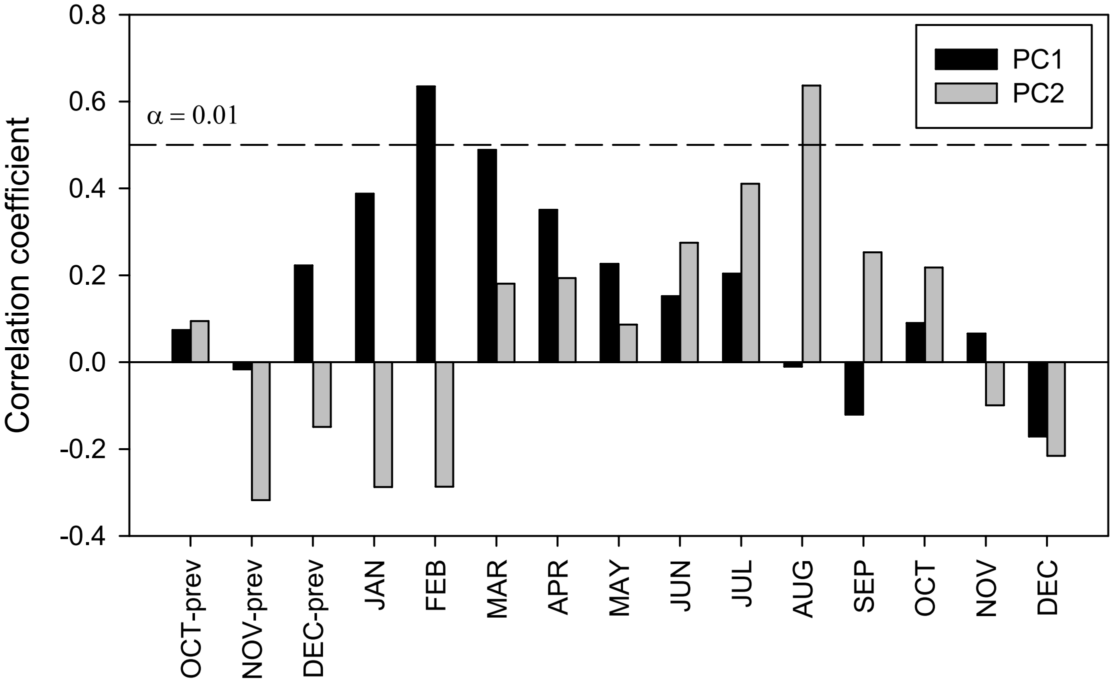

Figure 5. Correlation between monthly-averaged upwelling and the leading two principal components from seven biological time series in the California Current Ecosystem. Dotted line indicates significance at the $p < 0.01$ level.

The correspondence between PC1 from the biological time series and wintertime ocean conditions is particularly strong with sea level data. Indeed, the mean of Jan, Feb, and Mar sea level at San Francisco relates to PC1 with an R^2 of 0.84. This relationship is non-linear and suggests a threshold response heavily influenced by years with poor ocean conditions (Figure 6). Years with the lowest sea level and PC1 values are El Niño years, including 1983, 1992, and 1998.

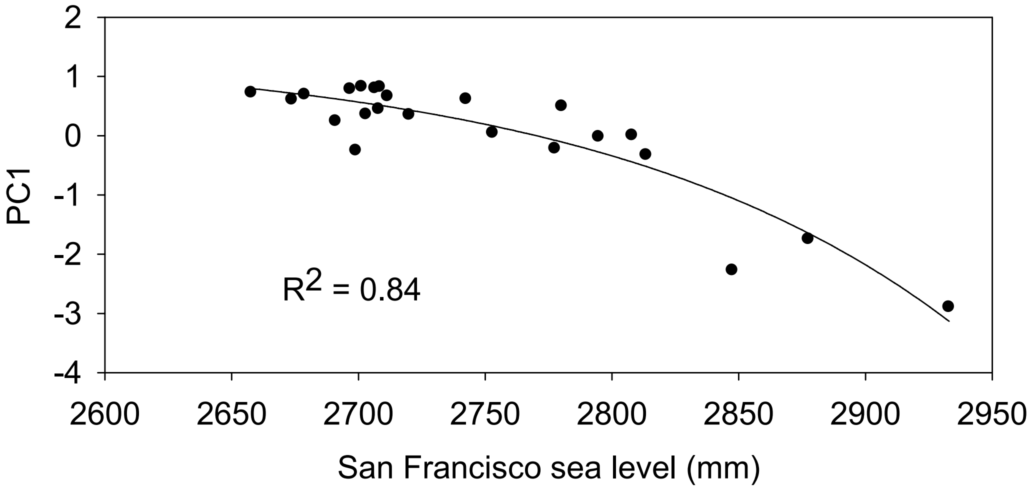

Figure 6. Relationship between wintertime sea level at San Francisco and the leading principal component from seven biological time series in the central California Current Ecosystem.

Climate seasonality

To explore the issue of seasonality, monthly-averaged upwelling indices were entered into a principal components analysis. The leading PC explained 24% of the variance in the data set while the second component explained an additional 14% of the variance. The two components display very unique signals, in which PC1 contains long-term trends, including a significant ($p < 0.01$) increase, while PC2 is dominated by high-frequency variability associated with ENSO events (Figure 7A,B). Indeed, PC2 strongly correlates with the Northern Oscillation Index, a measure of El Niño Southern Oscillation influences on the northeast Pacific (Schwing et al. 2002) (Figure 7B). An interesting property of these components is that they correlate in a very seasonal pattern with the original upwelling data. PC1 correlates very strongly with upwelling during the summer months while PC2 correlates very strongly with upwelling during the winter months (Figure 7C). Thus, upwelling in the CCE is dominated by separate climate "modes;" a winter mode dominated by high-frequency variability and a summer mode dominated by low-frequency variability. These winter and summer modes appear when the analysis is repeated at other latitudes in the CCE (data not shown).

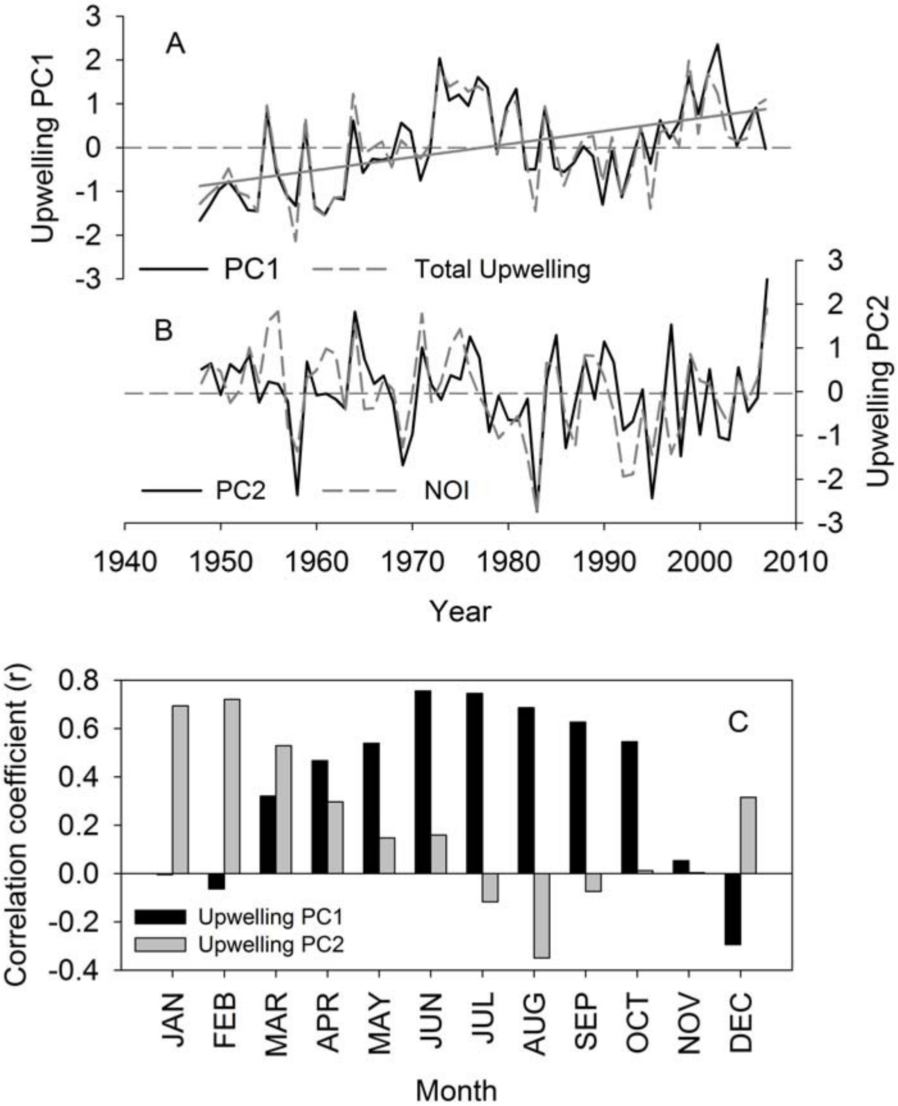

Figure 7. The leading principal component (PC1) of extracted from monthly-resolved upwelling intensity data at 39ºN. Total annual upwelling at 39ºN latitude is superimposed, as is a linear regression fit to PC1 ($R^2 = 0.27$). B) The second principal component (PC2) of upwelling at 39ºN latitude. The Northern Oscillation Index (NOI) is also shown. C) Spearman correlations (loadings) between the leading two principal components at 39ºN and monthly upwelling intensity data used to generate the principal component.

Seasonal climate modes and seasonal biological responses

Some biological time series, including auklet fledgling success and the salmon chronology, were principally aligned with summer mode upwelling, while other biological time series were aligned with winter mode upwelling (Black et al. in prep.). The leading principal components for the biological time series represented a winter "guild" and a summer "guild" while the two leading principal components from the upwelling data represented a summer climate "mode" and a winter climate "mode".

Thus, certain biological processes appear to be sensitive to specific climate modes, tied to seasons. Not only does this underscore the importance of wintertime conditions in the CCE, but also the significance of seasonality, and the biological time series may follow very different patterns depending on the season to which they are most sensitive.

Table 1. Spearman's rank coefficients (Sρ) and level of significance (p) for correlations between upwelling modes in the California Current Ecosystem and biological and physical time series used in this study. Biological time series are mean annual lay date and fledgling success for common murre and Cassin's auklet, as well as otolith growth-increment chronologies for yelloweye and splitnose rockfish, and a scale growth-increment chronology for Chinook salmon. Also included are the two leading principal components from the seven biological time series (PC1 bio and PC2 bio). The leading principal component (UW PC1) of upwelling data is "summer mode" while the secondary (UW PC2) is "winter mode." Correlations significant at the p < 0.05 level are shaded.

		39° N latitude			
Time series	Span	UW PC 1		UW PC 2	
Biological	(years)	Sρ	P	Sρ	p
Murre lay date	1972:2007	0.04	0.81	**-0.39**	**0.02**
Auklet lay date	1972:2007	-0.25	0.14	**-0.55**	**0.00**
Murre success	1972:2007	0.03	0.84	**0.36**	**0.03**
Auklet success	1972:2007	**0.48**	**0.00**	-0.14	0.41
Splitnose crn	1936:2006	0.17	0.19	**0.44**	**0.00**
Yelloweye crn	1946:2001	-0.08	0.58	**0.34**	**0.01**
Salmon crn	1978:2001	**0.42**	**0.04**	0.27	0.20
PC1 bio	1978:2001	0.32	0.13	**0.68**	**0.00**
PC2 bio	1978:2001	**0.54**	**0.01**	-0.32	0.13

MEM/wavelet analyses of spectra to evaluate periodicity and amplitude of coupled physical and biological changes.

A wavelet coherency analysis was performed to demonstrate the phase relationships between the winter / summer upwelling on the winter / summer biological response. First, the winter upwelling "mode" was related to the winter biological "guild" (the leading principal component from the seven biological time series). Then the summer upwelling "mode" was related to the summer biological "guild" (the second principal component from the seven biological time series). The analysis shows that the winter biological guild is in-phase with the winter upwelling mode, especially for wavelengths between 2 – 4 years (Figure 8A). By contrast, the summer biological "guild" is in-phase with the summer upwelling mode for longer wavelengths, centered at approximately 8 years (Figure 8B). The in-phase relationship for both the winter and summer time series demonstrates that when the upwelling is high, then the biological response is favorable and characterized by early bird egg laying dates, high numbers of chicks fledged, and robust fish growth. Moreover, the year-to-year variability in winter upwelling "mode" is transferred to the winter biological "guild," as reflected by strong coherence between these two time series in the higher-frequency domains (Figure 8A). By contrast, the decadal patters observed in the summer upwelling “mode” are transferred to the summer biological “guild,” as indicated by coherence at lower frequencies (Figure 8B). Thus, different seasons experience variability at different timescales, and biological responses will reflect the patterns in the season to which they are most sensitive. Thus, seasonality is critical and must be considered in assessing biological responses of the CCE.

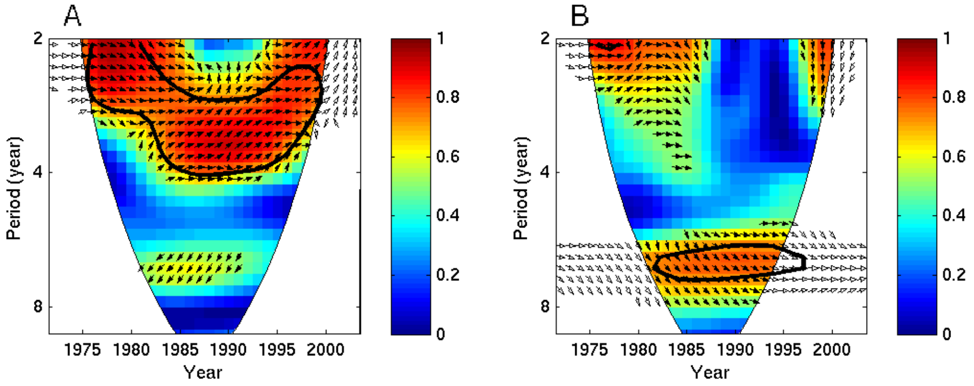

Figure 8. The squared wavelet coherence between: (A) UW pc2 and PC1 bio and (B) UW pc1 and PC2 bio time series. The bold contour is the 5% significance level. The arrows show the relative phase relationship; the arrows pointing right show an in-phase relationship.

GOAL 2

The physical mechanisms behind winter upwelling and its impacts on the biology of the CCE are also being investigated. To this end, we acquired and analyzed high-resolution satellite observations of surface winds (Quikscat, North American Regional Reanalysis, and NDBC buoys) and SST (AVHRR and NDBC buoys) to provide spatial context for the forcing and oceanic response of winter upwelling. We are in the process of analyzing high-resolution data on water column structure (including degree of stratification, thermocline depth, and nutricline depth) and primary productivity from the M1 and M2 moorings of Monterey Bay. To date, the majority of work has been completed at the M2 mooring, located approximately 50 km offshore of Monterey Bay with daily temperature/salinity measurements available since 1998. The measurements are at standard depths to 350 m.

Our leading hypothesis for the importance of wintertime upwelling is that stratification during the winter is weak, and modest meridional (northerly) winds are sufficient to initiate upwelling, bringing nutrients into the photic zone. To explore this hypothesis, correlations were calculated between the 12°C isotherm depth anomalies at M2 and meridional wind anomalies throughout the study region. The 12°C isotherm depth is used as a proxy for the nutricline, indicating the proximity of nutrients to the surface, and correlations were calculated for the winter months (January – February) and the summer months (June – August) as a way to contrast the mechanisms between upwelling and biology during these two seasons. A high correlation between meridional (upwelling) winds and the 12°C isotherm depth indicate that the winds are indeed effective at bringing nutrients to the surface.

The winter correlations map shows the highest significant correlations of 0.8 centered at 29°N - 125°W (Figure 9A) while the summer correlations are much weaker (Figure 9B). This suggests that during the winter, meridional (upwelling-favorable) winds are quite effective at bringing nutrients to the surface of the CCE, which could help explain the close coupling between biological indicators and the upwelling index, which is derived from wind data. This also suggests that the relationships between isotherm depth (nutrients) and winds are much more complex in the summer months, underscoring the unique properties of winter and summer – physically and biologically – in the CCE.

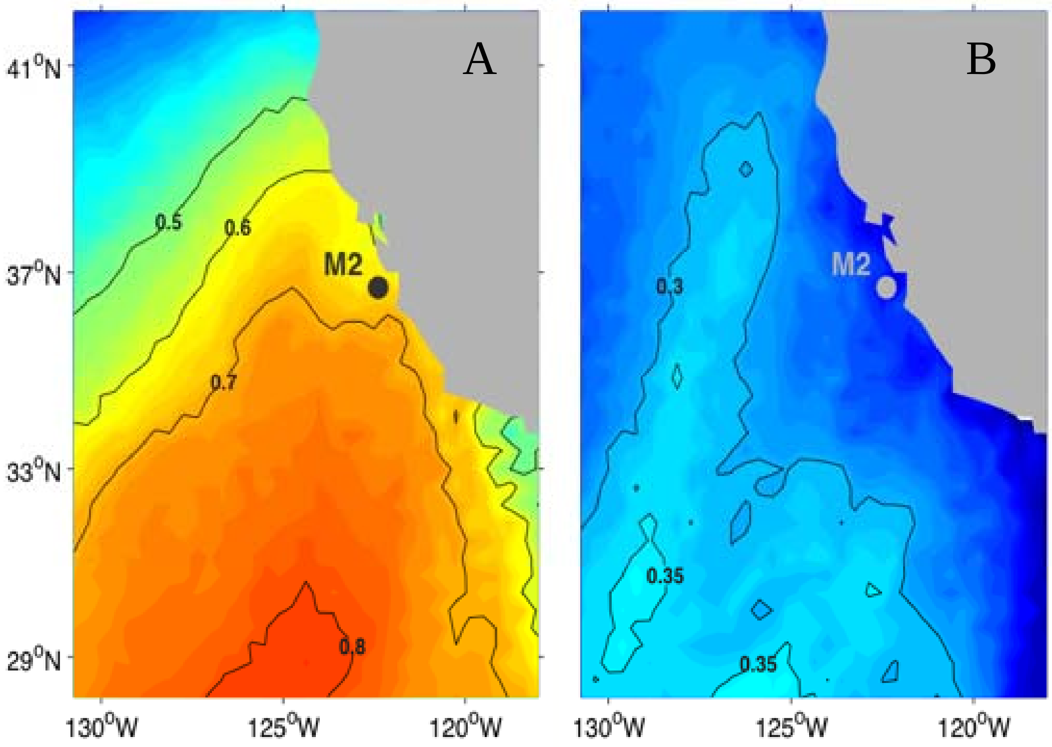

Figure 9. Correlation maps between the 11.5℃ isotherm depth and monthly meridional wind anomalies in winter (A) and summer (B). Black contours show regions of significant (p<0.01) correlation. The isotherm data is from the M2 mooring and the wind data is from the North American Regional Reanalysis.

GOALS 3-6: These three goals are for year two of the project. The environmental links between the biological time series and the physical forcing will be incorporated into a splitnose rockfish stock assessment and will be included into a predictive model for salmon returns. Goal (5) is currently being pursued; the information of the importance of winter upwelling is being incorporated into the current 2010 Integrated Ecosystem Assessment status report on the California Current.

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Publications related to this project:

BA Black, I Schroeder, W Sydeman, S Bograd, and P Lawson. 2010. Wintertime ocean conditions synchronize rockfish growth and seabird reproduction in the central California Current Ecosystem. *Canadian Journal of Fisheries and Aquatic Sciences.* 67:1149-1158

In preparation

BA Black et al. Winter and summer upwelling modes and their biological relevance in the California Current Ecosystem (in prep; Target: Climate Research).

ID Schroeder et al. Physical oceanographic changes associated with weak and strong winter and summer upwelling in the California Current (in prep; J. Geophysical Research)

Presentations related to this project:

BA Black. Sclerochronology and multi-species perspectives on past climate and ecological variability. Invited Keynote Address. Second International Conference on Sclerochronology. Johannes Gutenberg University, July 2010. Mainz, Germany.

BA Black. Growth increments, climate, and the interrelationships among diverse ecosystems of the Pacific Northwest, USA. University of New South Wales, March 2010. Sydney, New South Wales, Australia.

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