

# California Multivariate Ocean Climate Indicator (MOCI) and marine ecosystem dynamics

Marisol García-Reyes\*, William J. Sydeman

*Farallon Institute, 101 St. Suite Q, Petaluma, CA 94952, United States*



## ARTICLE INFO

### Article history:

Received 14 June 2016

Received in revised form 24 August 2016

Accepted 24 August 2016

### Keywords:

Coastal upwelling

Climate variability

California marine ecosystem

Biophysical relationships

Temperature

## ABSTRACT

Marine ecosystems are complex adaptive systems with physical and biological processes operating on multiple spatial and temporal scales. Here, we present an operational regional indicator for California's continental shelf system and investigate its skill in predicting a variety of biological responses across trophic levels. This updated Multivariate Ocean Climate Indicator (MOCI) version 2 includes data that are readily available from the Internet so the indicator can be automatically updated and shared regularly. MOCIv.2 is a simplified version of MOCIv.1, but it captures ocean-climate variability similarly. MOCIv.2 illustrates all major ENSO events that occurred over the past 25 years as well as the phasing and magnitude of the most recent North Pacific marine heat wave, dubbed 'The Blob'. It also shows differences in the magnitude and timing of ocean-climate variability in different regions off California. MOCIv.2 has skill in nowcasting marine ecosystem dynamics, from zooplankton to top predators, and therefore may be useful in establishing bio-physical relationships important to ecosystem-based fisheries and wildlife management in California.

© 2016 Elsevier Ltd. All rights reserved.

## 1. Introduction

Marine ecosystems are complex adaptive systems with physical and biological processes operating on a vast array of spatial and temporal scales (Levin, 1998). In particular, interacting scales of environmental variation, from seasons to years and decades, complicate understanding and forecasting of marine ecosystem structure and functions. To deal with complex marine physical-biological coupling, many indicators of environmental variation have been developed and operationalized, the most well-known of which is the Southern Oscillation Index (SOI), which provides an indicator of the magnitude and phasing of El Niño events (Rasmusson and Wallace, 1983). More recently, other large-scale indicators of ocean climatic variability have been developed, including the Pacific Decadal Oscillation (PDO), with a periodicity of 50–60 years (Mantua et al., 1997), and the Madden Julian Oscillation (MJO), with a periodicity of 30–60 days (Zhang, 2013). Each of these climate indices has been related to local ocean conditions including attributes such as water temperature, salinity, and circulation patterns (e.g., upwelling).

The complexity of oceanic, atmospheric, and climatic interactions, and the large number of indices that can be used to track them, makes it difficult to identify and select the most relevant variables for understanding ecosystem structure and functions. Therefore, there is need to develop regional- to local-scale indicators that capture and track changes in the ocean and ecosystem states in a simple, easily understood, and cost effective yet comprehensive manner. This is particularly important in the highly variable yet extraordinarily productive eastern boundary upwelling systems of the world (Messié et al., 2009), which include the California and Peru/Humboldt systems in the Pacific Ocean and the Canary and Benguela systems in the Atlantic Ocean. Embedded in the Pacific's California Current System (CCS), with more than 1600 km of coastline, California's continental shelf is responsive to a range of processes that drive local weather, biological productivity, and commercial and recreational fisheries. Given its latitudinal range, there is regional variation in California's coastal zone. For example, measurements of water temperature off southern California, an indicator of climate change (McGowan et al., 1998) used in sardine management in the region (Jacobson and MacCall, 1995), often do not coincide with central or northern California ocean temperatures or variability. Regional and temporal variability in upwelling-favorable winds adds another layer of complexity – the relative influence of water temperature and upwelling-favorable winds on the ecosystem is different in each region and sometimes

\* Corresponding author.

E-mail addresses: [marisolgr@faralloninstitute.org](mailto:marisolgr@faralloninstitute.org), [marisolgr@gmail.com](mailto:marisolgr@gmail.com) (M. García-Reyes), [wsydeman@faralloninstitute.org](mailto:wsydeman@faralloninstitute.org) (W.J. Sydeman).

confounding (Checkley and Barth, 2009; García-Reyes and Largier, 2012; Seo et al., 2012). At the same time, all regions are largely influenced by global and regional climate events such as El Niño (McPhaden et al., 2006) and other remote large-scale factors (Di Lorenzo et al., 2008, 2013).

For central-northern California, Sydeman et al. (2014) developed the Multivariate Ocean Climate Indicator (MOClv.1). This indicator synthesized a number of local and regional ocean and atmospheric variables that represent, in a holistic manner, the state of the ocean. MOClv.1 has been useful in summarizing the seasonal cycle and tracks well-known variability of the central California marine ecosystem. This integrated indicator was designed to serve as an environmental baseline to understand ecological changes in the State of California's Marine Protected Areas (MPAs). While a useful tool for historical coastal conditions and ecosystem variability, MOClv.1 was already four years old when published. Also, though simple and easily understood, it was not operational, a desired property of any environmental indicator (Aubrey and Elliott, 2006; Rees et al., 2008). However, as previously demonstrated by MOClv.1, the physical system varies coherently in different seasons, and many of the large-scale to local parameters are highly inter-correlated. This allows one to select frequently updated parameters as proxies for others, and use these data to update MOCI on a more regular basis.

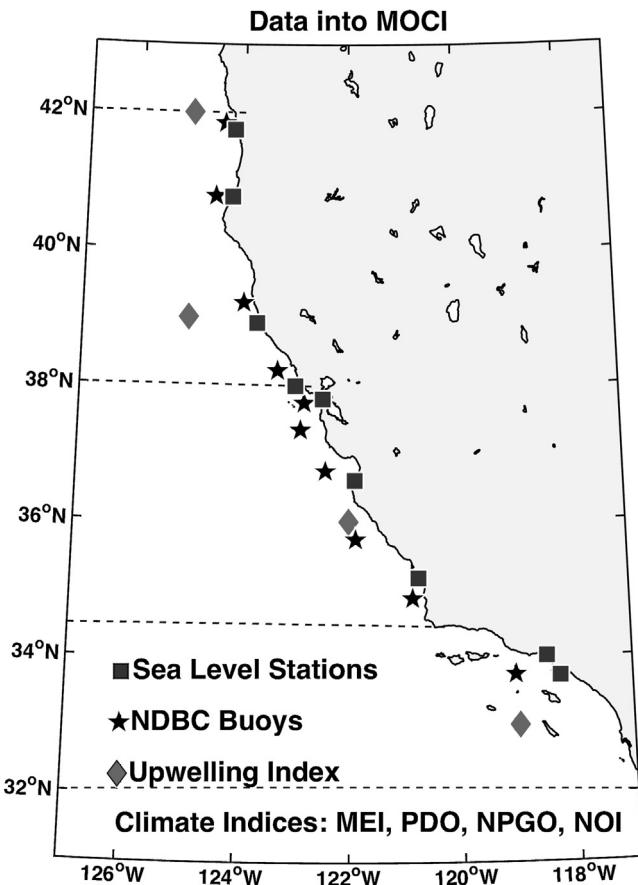
In this paper, while keeping with the general goal of presenting an indicator that represents environmental variability that is easy to interpret, we have two specific objectives: (i) to provide an easily updatable MOCI (v.2) for three different regions of California, and (ii) to show its utility as an indicator of variability of regional biology, as well as other local environmental variables not included in MOClv.2. To meet these objectives, we developed and provide three regional indices over the period 1991 through 2015 and compare them to 50 biological variables as well as eight other environmental variables at different locations (33 time series in total) to evaluate its capability to capture coastal processes relevant to coastal ecosystem processes and productivity.

## 2. Data & methods

Data for this updated version of MOCI were selected based upon the availability of continuously updated monthly values of the individual variables since 1991. This criterion resulted in the selection of ten parameters (Table 1): four climate indices (Multivariate ENSO Index, Pacific Decadal Oscillation, North Pacific Gyre Oscillation, and Northern Oscillation Index), the Bakun Upwelling Index, sea level from shore stations, and four variables measured at NOAA buoys over the continental shelf (alongshore wind stress, sea surface temperature, sea air temperature and sea level pressure). The spatial distribution of the data is shown in Fig. 1. Monthly data were averaged into seasonal values defined as: winter (January–March), spring (April–June), summer (July–September), and fall (October–December). All data processing and analysis were done in MATLAB R2015a.

### 2.1. Developing MOClv.2

For the calculation of MOClv.2, data were stratified by season and region. The regions were (Table 2): Northern California (38–42°N), Central California (34.5–38°N), and Southern California (32–34.5°N). We selected these regions based on well-established differences in physical coastal dynamics. Between Northern and Central California there is a clear change in seasonal sea surface temperature measured around Point Reyes (~38°N), which reflects a change in the wind/temperature relationship there (García-Reyes and Largier, 2012). Point Conception (34.5°N) is a biogeographic



**Fig. 1.** Map of study region and locations of data included in MOCI. Squares show the location of stations recording sea level; stars indicate the location of NDBC buoys that record alongshore wind stress, surface air and sea temperature and sea level pressure; and diamonds show the location of the Upwelling Index data. Divisions between regional MOCI are delimited by black dashed lines.

boundary due to the shift in the coastline orientation, shadowing the Southern California Bight from the upwelling-favorable, north-westerly winds (Checkley and Barth, 2009). For each region and season, we collated data into a single matrix, normalized each time series, and subjected each matrix to Principal Component Analysis (Jolliffe, 2002). The resulting leading mode of variability (PC1) is defined as the MOClv.2 for each region by season. Last, an integrated year round MOClv.2 was obtained by recombining all seasonal values for each region. The resultant MOClv.2 time series has winter-spring-summer-fall values from 1991 to date (in this manuscript, updated to 2015, with future updates provided online at: [www.faralloninstitute.org/MOCI](http://www.faralloninstitute.org/MOCI)). Aside from variable selection, this is the same process used by Sydeman et al. (2014) to develop MOClv.1.

### 2.2. Testing the skill of MOClv.2

In order to test the skill of MOClv.2 (hereafter MOCI) to represent environmental conditions in different regions of California, we compared each regional MOCI to (i) MOClv.1 developed by Sydeman et al. (2014), and (ii) other environmental data (Table 3) not included in the calculation of MOCI. These data included local ocean conditions (i.e., water temperature and salinity), atmospheric conditions (coastal fog), and a precipitation statistic (river runoff). We also compared the regional MOCI with biological measurements from the California and central Oregon shelf ecosystems. We included biological measurements from Oregon because there are no long-term biological measurements available from Northern

**Table 1**

Environmental parameters included in the calculation of the Multivariable Ocean Climate Indicator (MOCI) for California (by identifier, location, and source).

Variable	Location/Description	Source (as of January 2016)
Climate Indicators	Multivariate ENSO Index (MEI) Pacific Decadal Oscillation (PDO)  North Pacific Gyre Oscillation (NPGO)  Northern Oscillation Index (NOI)	NOAA, <a href="http://www.esrl.noaa.gov/psd/enso/mei">http://www.esrl.noaa.gov/psd/enso/mei</a> University of Washington, JISAO, <a href="http://jisao.washington.edu/pdo/PDO.latest">http://jisao.washington.edu/pdo/PDO.latest</a> Emanuele Di Lorenzo, <a href="http://www.o3d.org/nngo/nngo.php">http://www.o3d.org/nngo/nngo.php</a> NOAA <a href="http://www.pfsl.noaa.gov/products/PFELmodeled/indices/NOIx/data/noix.txt">http://www.pfsl.noaa.gov/products/PFELmodeled/indices/NOIx/data/noix.txt</a> NOAA, <a href="http://www.pfeg.noaa.gov/products/PFELData/upwell/monthly/upindex.mon">http://www.pfeg.noaa.gov/products/PFELData/upwell/monthly/upindex.mon</a>
Bakun Upwelling Index (UI)	33°N, 36°N, 39°N, 42°N	NOAA, <a href="http://www.ndbc.noaa.gov">http://www.ndbc.noaa.gov</a>
Sea Level (SL)	Los Angeles (LANG, 9410660), Santa Monica (SMON, 9410840), Port of San Luis (SLU, 9412110), Monterey Bay (MONT, 9413450), San Francisco (SANF, 9414290), Point Reyes (PREY, 9415020), Arena Cove (AREN, 9416841), Humboldt (HUMB, 9418767), Crescent City (CRES, 9419750)	NOAA, <a href="http://www.co-ops.nos.noaa.gov">http://www.co-ops.nos.noaa.gov</a>
Alongshore Wind Stress (AWS), Sea Surface Temperature (SST), Sea Air Temperature (SAT), Sea Level Pressure (SLP)	Buoys 46011 (Santa Maria), 46012 (Half Moon Bay), 46013 (Bodega Bay), 46014 (Point Arena), 46022 (Eel River), 46025 (Santa Monica), 46026 (San Francisco), 46027 (Crescent City), 46028 (Morro Bay), 46042 (Monterey Bay)	NOAA, <a href="http://www.ndbc.noaa.gov">http://www.ndbc.noaa.gov</a>

**Table 2**

Percent explained variance (%) and eigenvalue of seasonal-regional PCA-based MOCI.

Region	Winter	Spring	Summer	Fall
Northern California (38–42°N)	72%, 18.6	64%, 16.6	45%, 11.6	54%, 13.9
Central California (34.5–38°N)	70%, 20.3	61%, 17.7	46%, 13.2	54%, 15.6
Southern California (32–34.5°N)	58%, 6.4	49%, 5.4	49%, 5.4	54%, 5.9

California and biological measurements from Oregon are known to covary with biological measurements in Northern/Central California (García-Reyes et al., 2013). These biological datasets expand on those used by Sydeman et al. (2014), providing a better estimation of MOCI as predictor of ecosystem productivity (Table 3). Biological and environmental comparisons were done using Spearman correlations ( $\rho$ ) of MOCI with seasonal or annual biological measurements. This method was selected as MOCI has high/low values driven by climatic events (like El Niño) and rank correlation is robust to outliers and non-linear points. As some biological parameters may have delayed responses to environmental variation, correlations were calculated using current year MOCI values as well as values from the previous year. Correlations with a  $p < 0.05$  were considered significant.

### 3. Results

#### 3.1. Regional MOCI

Seasonal MOCI explain, on average, 56% of the variability in environmental conditions, ranging from 72% in winter for Northern California to 45% in summer for Northern California (Table 2, see SM for numerical values). The highest explained variance was in Northern California in winter and spring, and the lowest values were in summer for both Northern and Central California. The explained variance in Southern California varied the least between seasons (58% in winter and 49% in spring and summer).

All regional MOCI showed similar interannual variability (Figs. 2 and SM1), but with different ranges of variability. The Southern California MOCI showed a smaller standard deviation ( $\sigma = 2.36$ ) than the other two regional MOCI ( $\sigma = 3.84$  and  $\sigma = 4.09$  for Northern and Central California, respectively). A quantitative comparison among regional MOCI was done by calculating the correlations between regions (Table SM1). In all cases, regional MOCI were highly correlated and showed similarity in interannual variabil-

ity and extreme seasons. The comparison between the regional MOCIv.2 with MOCIv.1 (Table SM1 and Fig. SM1) showed strong correlations for all regions, but the Northern and Central California MOCI ( $\rho = 0.91$ ,  $p < 0.0001$ ) were a little stronger than Southern California, as their regions overlap with those of Sydeman et al. (2014) (Southern California  $\rho = 0.79$ ,  $p < 0.0001$ ).

#### 3.2. MOCI loadings

For the Central and Northern California regional MOCI, the same parameters had high loadings (Fig. 3). For all seasons and regions, sea level, sea surface temperature, and air temperature were most relevant (loadings  $> 0.15$ ). Local alongshore wind stress, upwelling index, and sea level pressure were more important in winter and spring than summer and fall. For Southern California MOCI, however, winds were less relevant in all seasons except summer (although the upwelling index showed high relevance in spring). Loadings for Southern California were higher than in other regions due to the smaller number of parameters included. Northern Oscillation Index (NOI), Multivariate ENSO Index (MEI), and PDO were relevant in all seasons, with little variation between regions. The North Pacific Gyre Oscillation (NPGO) was most relevant for spring and summer conditions, and had little relevance in winter and fall for Northern and Central MOCI.

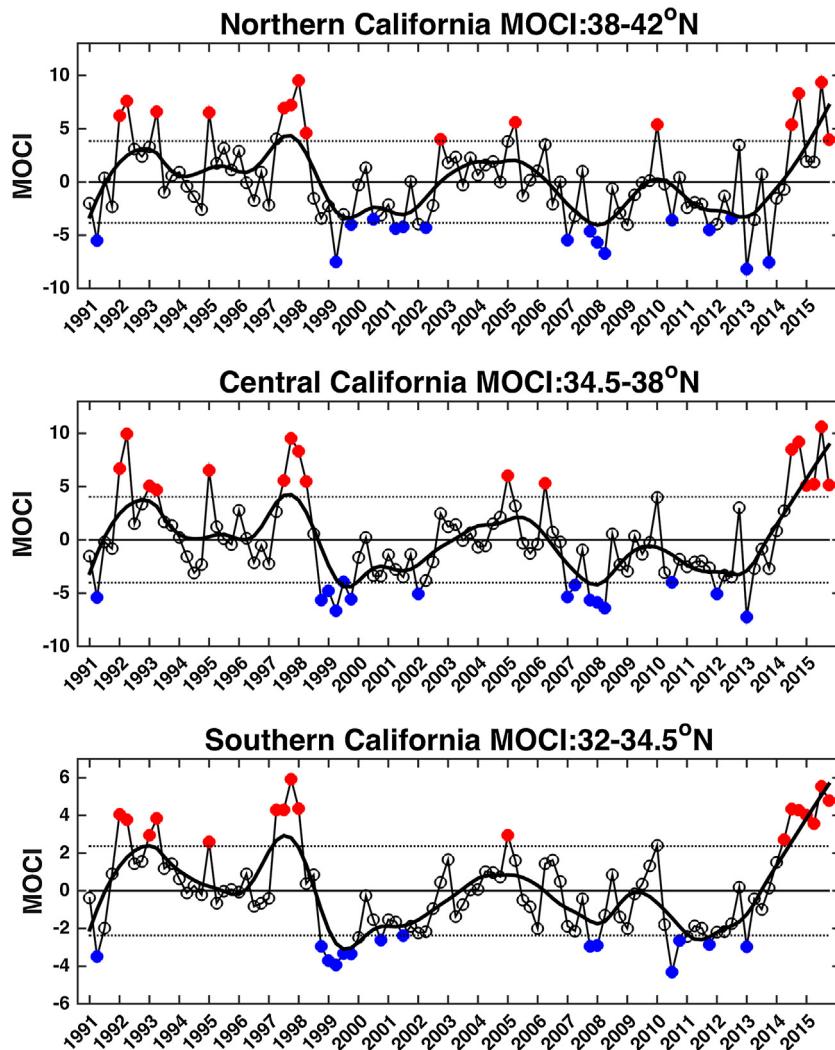
#### 3.3. Regional MOCI and other environmental indicators

Shore station salinities were negatively correlated with MOCI in all seasons except fall, while shore station temperatures were positively correlated, with some minor regional differences (Fig. 4). For example, in fall, Northern California MOCI showed no significant correlation with temperatures, although this correlation was strong in other seasons. Fall Northern California MOCI was correlated with fall river discharge for all regional rivers, but showed negative correlations in the summer. Notably, summer fog at the Arcata and Monterey airports (combined index, Johnstone and Dawson, 2010) was significantly negatively correlated with the Northern and Central California MOCI. In central California, CalCOFI data from line 67 off Monterey (temperature, salinity and nitrates within 30 m of the surface) showed good correlations with winter and spring MOCI, but not with summer (no data in the fall). Surface flow, obtained from HF Radar in central California (Halle and Largier, 2011; data from J. Largier/UC Davis), only showed significant correlation in the

**Table 3**

Environmental and biological measurements used to evaluate the relevance of regional MOCI.

Variable	Period	Location and Source (as of January 2016)
<i>Environmental Parameters</i>		
Surface temperature (T), Salinity (S), Nitrates	1997–2013	CalCOFI Line 67, Monterey Bay, <a href="http://www3.mbari.org/bog/roadmap/roadmap.htm">http://www3.mbari.org/bog/roadmap/roadmap.htm</a>
Shore temperatures	Different periods 1991–2015	Farallon Islands, Granite Canyon, Balboa, Pacific Grove, Santa Barbara, Scripps Pier, San Clemente, Point Dume, Trinidad Bay, Trinidad Beach, <a href="http://shorestations.ucsd.edu">http://shorestations.ucsd.edu</a>
Shore salinity	Different periods 1991–2015	Farallon Islands, Balboa, Scripps Pier, San Clemente, Trinidad Beach, <a href="http://shorestations.ucsd.edu">http://shorestations.ucsd.edu</a>
Surface flow	2001–2015	Four locations off Point Reyes, John Largier, UC Davis, Bodega Marine Lab
River discharge	1991–2015	Northern California: Smith, Russian, Redwood Creek, Navarro, Matole, Mad, Klamath, Eel Rivers, <a href="http://waterdata.usgs.gov">http://waterdata.usgs.gov</a>
Coastal summer fog	1991–2015	Arcata and Monterey Airport, <a href="#">Johnstone and Dawson (2010)</a>
<i>Biological Indicators</i>		
Northern Copepod Index (NCI)	1996–2014	Newport Hydrographic Line, Bill Peterson, pers. comm.
Trinidad Copepod Index (TCI)	2008–2015	Trinidad Hydrographic Line, Erick Bjorkstedt, pers. comm.
Krill abundance	1991–2012	Central California, <a href="#">Ralston et al. (2015)</a>
Herring biomass	1991–2012	San Francisco Bay, California Department of Fish and Wildlife
Sardine and anchovy adult abundance	1991–2012	Central California, <a href="#">Ralston et al. (2015)</a>
Sardine recruitment	1993–2014	California, <a href="#">Hill et al. (2015)</a>
Anchovy January/April egg/larvae abundance index, Anchovy combined egg and larvae index, Anchovy calibrated egg biomass	Different periods from 1991–2012	CalCOFI survey area, Southern California, <a href="#">MacCall et al. (2015)</a>
Age-0 hake abundance, Age-0 lingcod abundance, Age-0 rockfish abundance	1991–2012	Central California, <a href="#">Ralston et al. (2015)</a>
Hake number of age-0 recruits	1991–2014	U.S. and Canada west coast, Hake stock assessment 2014 by the International Joint Technical Committee for <a href="#">Pacific Hake (2014)</a>
Hake spawning biomass	1991–2014	U.S. and Canada west coast, Hake stock assessment 2014 by the International Joint Technical Committee for <a href="#">Pacific Hake (2014)</a>
Splitnose and Yelloweye rockfish growth	1991–2006	Central and Northern California, Bryan Black, pers. comm.
Aurora rockfish growth	1991–2003	Oregon, Bryan Black, pers. comm.
Chinook salmon Sacramento Index (SI)	1991–2014	Sacramento River, <a href="#">Pacific Fisheries Management Council (2015)</a> Pre-season Report
Chinook salmon returns	2000–2013	Russian River, Sonoma County Water Agency, unpublished
Coho salmon smolt-to-adult (SAR) Index	1991–2014	Newport, Oregon, Bill Peterson, pers. comm.
Salmon growth index (SGI)	1991–2001	Central and Northern California, Brian Wells, pers. comm.
Common murre, Cassin's auklet, Brandt's cormorant, and pigeon guillemot lay date (LD)	1991–2003/2006	Farallon Island, <a href="#">Schroeder et al. (2009)</a>
Common murre, Cassin's auklet, Brandt's cormorant, rhinoceros auklet, pigeon guillemot, pelagic cormorant, Western gull, and ashy storm-petrel reproductive success (RS)	1991–2014	Farallon Island, <a href="#">Warzybok et al. (2014)</a>
Common murre, Cassin's auklet, and rhinoceros auklet survival	Different periods 1991–2001	Farallon Island, <a href="#">Warzybok et al. (2014)</a>
Brandt's cormorant reproductive success	1995–2009	Alcatraz Island, Julie Thayer pers. comm.
Rhinoceros auklet reproductive success	1993–2012	Año Nuevo Island, Oikonos Group, <a href="#">Beck et al. (2015)</a>
Brown pelican nest attempts	SBI: 1991–2006, ANA: 1991–2002	Santa Barbara Island (SBI), and Anacapa Island (ANA), SBI: Frank Gress pers. comm., ANA: <a href="#">Sydeman et al. (2001)</a> and updated by Frank Gress
Brown pelican productivity	SBI: 1991–2003, ANA: 1991–2004, 2012, 2014	Santa Barbara Island (SBI), and Anacapa Island (ANA), SBI: Frank Gress pers. comm., ANA: <a href="#">Sydeman et al. (2001)</a>
California sea lion pup abundance	1991–2008	Southern California, Mark Lowry, pers. comm.
Blue whale and humpback whale abundance	1992–2006, 1991–2007	U.S. west coast, <a href="#">Calambokidis et al. (2007)</a> ; <a href="#">Calambokidis (2009)</a>



**Fig. 2.** Combined seasonal MOCI for each region, 1991–2015. Red dots represent values 1 standard deviation above the mean (warm conditions and weak upwelling), while blue dots represent values 1 standard deviation below the mean (cold conditions and strong upwelling).

fall for mid-shelf regions. All of the eight environmental parameters compared to regional MOCI showed significant correlations with the indicator for at least one season.

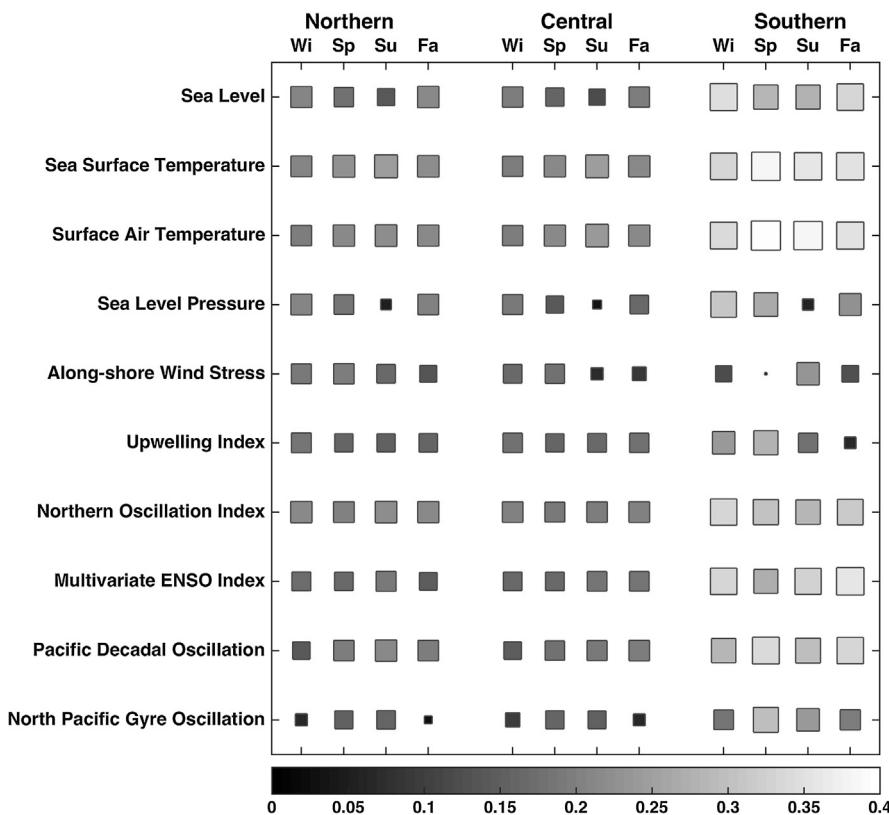
#### 3.4. Regional MOCI and biology

Thirty-nine of the 50 (78%) biological measurements had significant correlations with regional MOCI (Figure SM2). We selected relationships showing significant ( $p < 0.05$ ) correlations, of the same sign, for at least two seasons (Fig. 5) to illustrate the skill of MOCI relative to biotic variability (assuming that relationships with different signs may be spurious). Correlations were found at all trophic levels. The Northern Copepod Index (NCI) and the Trinidad Copepod Index (TCI), both indicators of the relative abundance of boreal copepod species, were inversely correlated with winter and spring Northern California MOCI. Similarly, krill abundance was negatively correlated with winter and spring Central California MOCI. Fish indices also showed significant correlations: anchovy egg abundance in January was negatively associated and sardine recruitment was positively correlated with Southern California MOCI. The annual growth of splitnose rockfish was negatively correlated with Central California MOCI. Seabird indices showed positive and negative correlations with MOCI. Egg laying dates for Cassin's auklets and common murres at SE Farallon Island were

strongly positively correlated with winter and spring Central California MOCI (later breeding with positive MOCI), and there were negative correlations between the number of brown pelican nests on Anacapa Island with winter and spring Southern California MOCI (fewer nests with more positive MOCI values). Additional significant correlations are shown in Figure SM2. In particular, salmon indices showed some correlations with central California MOCI. The Salmon Growth Index (SGI) showed a strong negative correlation with spring MOCI, while the Coho smolt-to-adult (SAR) Index and Chinook Sacramento Index (SI) showed negative lagged correlations with the previous year MOCI (winter and summer, respectively). Seabird indices showed strong correlations with Central California MOCI, particularly for winter and spring, but there were also some lagged correlations with the previous summer and winter MOCI for Cassin's auklets and pigeon guillemots. California sea lion pup and humpback whale abundance showed significant correlations (of opposite signs) with the previous year fall MOCI for Southern and Northern California, respectively.

#### 4. Discussion

Our goal in developing, publishing, and promoting regional MOCI for California is to improve the ability of coastal resource managers to incorporate variable ocean conditions into tactical



**Fig. 3.** PCA loadings of regional MOCI for all seasons (columns: Wi = winter, Sp = spring, Su = summer, Fa = Fall). For each variable, average loadings values were calculated for all stations/buoy in a region. Absolute value of loadings (positive) shown to facilitate interpretation.

and strategic management. To meet this objective, a regionally relevant, easily interpretable, and frequently updated MOCI is required. For this updated MOCI version, we synthesized a number of physical parameters into an indicator that describes variability in the coastal environment for three regions in California. Building from the MOCI developed by Sydeman et al. (2014), this new version includes parameters that track the most important environmental conditions and relevant processes for ecosystem function and productivity along the California coast: wind-driven coastal upwelling and ocean temperatures – the first bringing nutrients to the euphotic zone, the later modulating its efficacy (Bakun et al., 2015). However, for this version we only included data that are freely available and frequently updated so regional MOCI can be shared in near-real time ([www.faralloninstitute.org/MOCI](http://www.faralloninstitute.org/MOCI)).

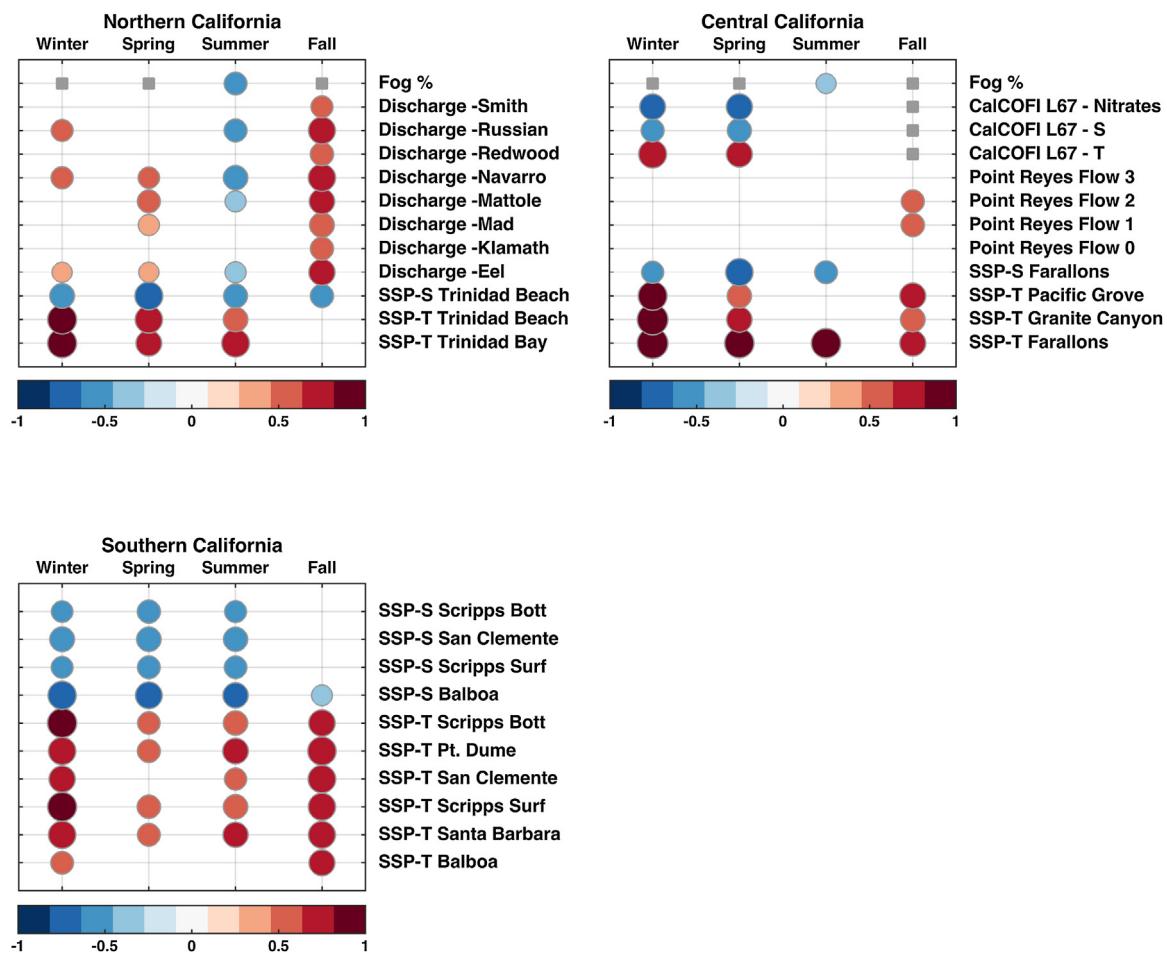
#### 4.1. Comparison of MOCIv.2 and MOCIv.1

MOCIv.2, similar to the MOCIv.1 developed by Sydeman et al. (2014), clearly represents known environmental events, with the advantage of providing insight into spatial (regional) heterogeneity. MOCI is easily interpreted: high MOCI represent warm temperatures and/or weak upwelling while negative values correspond to strong upwelling and cool temperatures. This interpretation is obvious during strong El Niño events (1992–1993, 1997–1998) and the marine heat wave of late 2014/early 2015 (Bond et al., 2015), followed by the 2015–2016 El Niño ([www.ncdc.noaa.gov/monitoring-references/dyk/elnino-2015-2016](http://www.ncdc.noaa.gov/monitoring-references/dyk/elnino-2015-2016)). Also evident is the 2005 weak upwelling event, which impacted all regions (Schwing et al., 2006) and induced biological effects such as an unprecedented reproductive failure of Cassin's auklets (Sydeman et al., 2006). However, there are differences among regions in the magnitude and persistence of the effects of these events. For example, the most recent MOCI positive anomalies related to 'The Blob'

combined with El Niño in 2014–2016 are visible in all regions. In Southern California, MOCI showed consistent high values (above 1 standard deviation) from early 2014 through 2015. However, the Northern California MOCI showed normal values (within 1 standard deviation) in early 2014 and early 2015, while the Central California MOCI showed normal values only in early 2014. It is worth noting that the anomalously high values started one season earlier (spring 2014) in Southern California than in other regions. This early signal in Southern California was also observed in the 1997–1998 El Niño, but this pattern was not evident for the 1992–1993 El Niño event when all regions showed synchronous anomalies (although with different magnitudes). The strong upwelling and cooler conditions of 2007–2008 and early 2013 were mostly evident and persistent in the Central and Northern California MOCI and not the Southern MOCI. In contrast, the La Niña event in 1999 was more persistent (low anomalous values) in Central and Southern California than in the Northern MOCI.

#### 4.2. Comparison of regional MOCI

The range of interannual variability within regions differs: Southern California MOCI variability was the smallest, the North was the most variable, and the Central California MOCI showed large extremes. These differences in variability may be related to differences in conditions, but the relative importance of each variable that goes into each regional MOCI (PC scores) is also important. For example, in the Southern California MOCI, alongshore wind stress had a smaller coefficient (was of lesser importance) compared to those of other parameters like temperature or sea level (Fig. 3). In contrast, for Central or Northern California MOCI, wind was as prominent as SST or sea level. This difference translates into milder responses to strong upwelling conditions (blue dots in Fig. 2) in Southern California than in the other regions where upwelling



**Fig. 4.** Spearman correlations between seasonal regional MOCI and environmental data not included in MOCI, listed in Tables 3 and SM2. Color and size show the magnitude and sign of the ranked correlation. Only significant ( $p < 0.05$ ) correlations are shown. Squares indicate seasons with no data available.

is a more important process, in agreement with previous regional descriptions (Checkley and Barth, 2009). In summary, an important characteristic of MOCI is that it captures, in a single indicator, the most relevant physical processes that take place in the California coastal environment, mainly coastal upwelling and water temperature variation with climate events, while simultaneously highlighting the regional differences in relative influence of those processes.

#### 4.3. MOCI as a predictor of local conditions

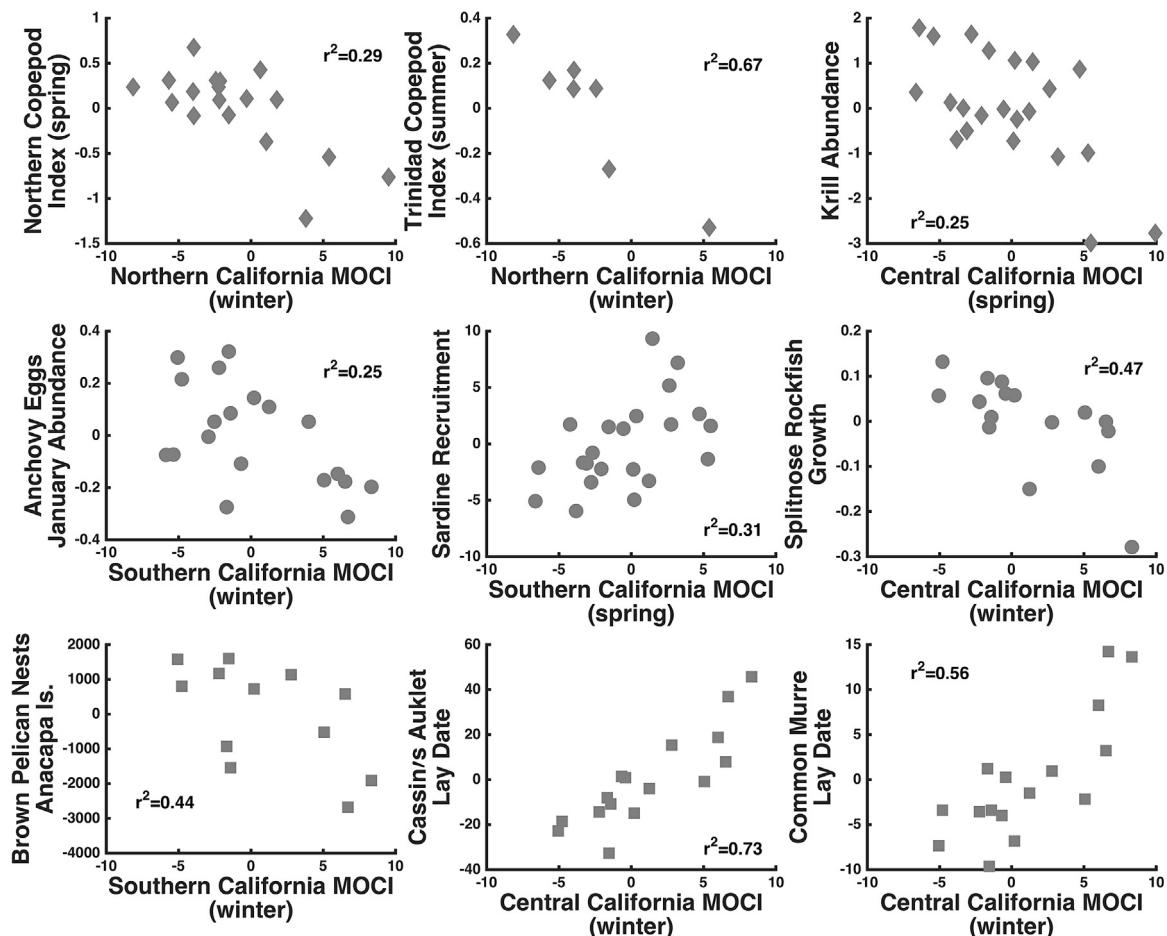
MOCI captures environmental variability of not only those variables involved in its calculation, but also for others that cannot be included due to lack of data continuity or short time series, such as coastal fog or water nutrient concentration. This confirms large-scale coherence in the variability of the California coastal environment and shows that MOCI is able to capture and quantify change in these diverse and often-dominant factors. Notably, surface current flow off Point Reyes shows poor correlations with MOCI during most seasons. While unexpected, as surface flow is driven by wind and MOCI captures wind in that region in most seasons, it is likely due to the effect of a mesoscale eddy in this region (Kim et al., 2011), which can show reversed or weak flow alongshore at times depending on the strength and position of the eddy.

Other multivariate indices in upwelling regions have also shown covariability in climate, atmospheric, oceanographic and biogeochemical variables. In the San Francisco Bay estuary, climate indices

and local temperatures covary with water run-off and nutrient content (Lehman, 2000), while in the Benguela Upwelling System, the St. Helena Climate Index shows that upwelling-related temperature, sea level pressure, and precipitation covary as well (Feistel et al., 2003). Above and beyond our MOCI, these other multivariate indicators show that developing holistic perspectives using this approach is feasible for many ecosystems.

#### 4.4. MOCI as a predictor of biology

MOCI shows skill as an ecosystem indicator by relating to biological measurements across trophic levels, suggesting that it captures biophysical processes relevant to ecosystem productivity. There are many examples of environmental indices, based on one or more parameters, that have been used to track ecosystem variability in the California Current (Wells et al., 2007; Black et al., 2014; Schroeder et al., 2013; García-Reyes et al., 2014), but sometimes such correlations break down over time (Miller and Sydeman, 2004). A possible advantage of MOCI is that it captures different, and sometimes confounding, physical processes that influence the ecosystem, and, in doing so, may not be affected by changing bivariate relationships (Schmidt et al., 2014). In particular, MOCI captures variability partially due to atmospheric drivers of upwelling-favorable winds, as well as the oceanic modulation of upwelled water characteristics (i.e., temperature, nutrient entrainment, oxygen concentrations) that directly impact the coastal ecosystem. In time, we will be able to assess if MOCI provides a



**Fig. 5.** Regional MOCI vs. selected biological indicators (those significantly correlated with MOCI for two seasons). Biological indicators details are shown in Tables 3 and SM3.

better indicator of complex biophysical relations than any single physical environmental attribute.

Furthermore, MOCI could be used as a predictive tool, in addition to giving current observations a historical context. Environmental correlations (Fig. 4) show that MOCI can help interpret variability seen in fog and river discharge, as well as estimate (predict) these parameters for (1) the current season or year when data are not yet available, or (2) in hindsight for years and seasons when data were not collected. Similarly, MOCI can help estimate biological indicators in real time in cases where biological data are not readily available until after the field season is over and raw data are analyzed. In some cases, it can serve as a predictive indicator, either due to the slow response of a biological indicator or to environmental autocorrelations. For example, predictive capabilities are shown by spring and winter northern California MOCI for the summer Trinidad Copepod Index (TCI) and spring Northern Copepod Index (NCI), as well as previous year fall and current year winter MOCI to predict splitnose rockfish growth and sardine recruitment (Fig. 5). These examples provide insight into the utility of MOCI as a management tool for near-real time decision-making.

Finally, MOCIv.1, as with other similar multivariate indicators (Lehman, 2000; Feistel et al., 2003; Hemery et al., 2008), have shown that is possible to develop integrated and simplified indicators capable of quantifying and communicating relevant environmental change. MOCIv.2 adds two more desirable properties (Rees et al., 2008): (1) operational capability, and (2) ability to serve as an early warning signal of change. The current availability of data and the simple and accessible methodology used to develop

this indicator could be followed to develop similar indicators in other marine areas.

## 5. Conclusion

MOCI is a simple yet relevant indicator of environmental conditions important to ecosystem dynamics. We plan to make an updated MOCI available quarterly, which would make it applicable for resource management in California and perhaps motivate its use or development of similar indicators elsewhere in the world. End-users of our MOCI for California could include local, state, and federal marine fisheries and wildlife agencies as well as management councils (e.g., the Pacific Fisheries Management Council). It is our hope that MOCI can be used in the development of harvest control rules (e.g., fisheries quotas) where the environment is known to affect population dynamics of harvested species, as well as species of conservation concern in California and elsewhere.

## Acknowledgments

The authors thank James Johnstone, Eric Bjorkstedt, William Peterson, John Largier, Marcel Losekoot and Brian Wells for providing data for this analysis, and to Sarah Ann Thompson for her support with the data, and the revising and editing of this manuscript. This project was funded by the California Sea Grant Project R/MPA-31C.

## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.ecolind.2016.08.045>.

## References

- Aubrey, A., Elliott, M., 2006. The use of environmental integrative indicators to assess seabed disturbance in estuaries and coasts: application to the Humber Estuary, UK. *Mar. Pollut. Bull.* 53 (1), 175–185.
- Bakun, A., Black, B.A., Bograd, S.J., García-Reyes, M., Miller, A.J., Rykaczewski, R.R., Sydeman, W.J., 2015. Anticipated effects of climate change on coastal upwelling ecosystems. *Curr. Clim. Change Rep.* 1 (2), 85–93.
- Beck, J., Carle, R., Calleri, D., Hester, M., 2015. Ano Nuevo State Park Seabird Conservation and Habitat Restoration: Report 2015. Oikonomos (45 pp).
- Black, B.A., Sydeman, W.J., Frank, D.C., Griffin, D., Stahle, D.W., García-Reyes, M., Rykaczewski, R.R., Bograd, S.J., 2014. Six centuries of variability and extremes in a coupled marine-terrestrial ecosystem. *Science* 345, 1498–1502.
- Bond, N.A., Cronin, M.F., Freeland, H., Mantua, N., 2015. Causes and impacts of the 2014 warm anomaly in the NE Pacific. *Geophys. Res. Lett.* 42, 3414–3420.
- Calambokidis, J., Douglas, A., Falcone, E., Schlender, L., 2007. Abundance Blue Whales off the U.S. West Coast Using Photo Identification, Final Report. Cascadia Research (13 pp).
- Calambokidis, J., 2009. Abundance Estimates of Humpback and Blue Whales off the US West Coast Based on Mark-recapture of Photo-identified Individuals Through 2008. Cascadia Research, Olympia, Washington.
- Checkley, D.M., Barth, J.A., 2009. Patterns and processes in the California Current System. *Prog. Oceanogr.* 83, 49–64.
- Di Lorenzo, E., Schneider, N., Cobb, K.M., Franks, P.J.S., Chhak, K., Miller, A.J., McWilliams, J.C., Bograd, S.J., Arango, H., Curchitser, E., Powell, T.M., Riviere, P., 2008. North Pacific Gyre Oscillation links ocean climate and ecosystem change. *Geophys. Res. Lett.* 35, L08607.
- Di Lorenzo, E., Combes, V., Keister, J.E., Strub, P.T., Thomas, A.C., Franks, P.J.S., Ohman, M.D., Furtado, J.C., Bracco, A., Bograd, S.J., Peterson, W.T., Schwing, F.B., Chiba, S., Taguchi, B., Hormazabal, S., Parada, C., 2013. Synthesis of Pacific Ocean climate and ecosystem dynamics. *Oceanography* 26, 68–81.
- Feistel, R., Hagen, E., Grant, K., 2003. Climatic changes in the subtropical southeast atlantic: the St. Helena island climate index (1893–1999). *Prog. Oceanogr.* 59 (2), 321–337.
- García-Reyes, M., Largier, J.L., 2012. Seasonality of coastal upwelling off central and northern California: new insights, including temporal and spatial variability. *J. Geophys. Res.* 117, C03028.
- García-Reyes, M., Sydeman, W.J., Thompson, S.A., Black, B.A., Rykaczewski, R.R., Thayer, J.A., Bograd, S.J., 2013. Integrated assessment of wind effects on Central California's pelagic ecosystem. *Ecosystems* 16, 722–735.
- García-Reyes, M., Largier, J.L., Sydeman, W.J., 2014. Synoptic-scale upwelling indices and predictions of phyto- and zooplankton populations. *Prog. Oceanogr.* 120, 177–188.
- Halle, C.M., Largier, J.L., 2011. Surface circulation downstream of the Point Arena upwelling center. *Cont. Shelf Res.* 31, 1260–1272.
- Heimery, G., D'Amico, F., Castege, I., Dupont, B., D'Elbee, J., Lalanne, Y., Mouches, C., 2008. Detecting the impact of oceano-climatic changes on marine ecosystems using a multivariate index: the case of the Bay of Biscay (North Atlantic-European Ocean). *Global Change Biol.* 14 (1), 27–38.
- Hill, K.T., Crone, P.R., Dorval, E., Macewicz, B.J., 2015. Assessment of the Pacific Sardine Resource in 2015 for U.S.A. Management in 2015–16. National Marine Fisheries Service, Southwest Fisheries Science Center, La Jolla, California (168 pp).
- International Joint Technical Committee for Pacific Hake, 2014. In: Taylor, N., Hicks, A.C., Taylor, I.G., Grandin, C., Cox, S. (Eds.), Status of the Pacific Hake (whiting) Stock in U.S. and Canadian Waters in 2014 with a Management Strategy Evaluation. International Joint Technical Committee for Pacific Hake (194 pp).
- Jacobson, L.D., MacCall, A.D., 1995. Stock-recruitment models for Pacific sardine (*Sardinops sagax*). *Can. J. Fish. Aquat. Sci.* 52, 566–577.
- Johnstone, J.A., Dawson, T.E., 2010. Climatic context and ecological implications of summer fog decline in the coast redwood region. *Proc. Natl. Acad. Sci. U. S. A.* 107, 4533–4538.
- Jolliffe, I.T., 2002. *Principal Component Analysis*. Springer-Verlag New York, Inc., New York.
- Kim, S.Y., Terrill, E.J., Cornuelle, B.D., Jones, B., Washburn, L., Moline, M.A., Paduan, J.D., Garfield, N., Largier, J.L., Crawford, G., Kosro, P.M., 2011. Mapping the U.S. West Coast surface circulation: a multiyear analysis of high-frequency radar observations. *J. Geophys. Res.* 116, C03011.
- Lehman, P.W., 2000. The influence of climate on phytoplankton community biomass in San Francisco Bay Estuary. *Limnol. Oceanogr.* 45 (3), 580–590.
- Levin, S.A., 1998. Ecosystems and the biosphere as complex adaptive systems. *Ecosystems* 1, 431–436.
- MacCall, A.D., Sydeman, W.J., Davison, P.C., Thayer, J.A., 2015. Recent collapse of northern anchovy biomass off California. *Fish. Oceanogr.* 175, 87–94.
- Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., Francis, R.C., 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. *Bull. Am. Meteorol. Soc.* 78, 1069–1079.
- McGowan, J.A., Cayan, D.R., Dorman, L.M., 1998. Climate-ocean variability and ecosystem response in the Northeast Pacific. *Science* 281, 210–217.
- McPhaden, M.J., Zebrak, S.E., Glantz, M.H., 2006. ENSO as an integrating concept in earth science. *Science* 314, 1740–1745.
- Messié, M., Ledesma, J., Kolber, D.D., Michisaki, R.P., Foley, D.G., Chavez, F.P., 2009. Potential new production estimates in four eastern boundary upwelling ecosystems. *Prog. Oceanogr.* 83, 151–158.
- Miller, A.K., Sydeman, W.J., 2004. Rockfish response to low-frequency ocean climate change as revealed by the diet of a marine bird over multiple time scales. *Mar. Ecol. Prog. Ser.* 281, 207–216.
- Pacific Fishery Management Council, 2015. Preseason Report I: Stock Abundance Analysis and Environmental Assessment Part 1 for 2015 Ocean Salmon Fishery Regulation. Portland, Oregon.
- Ralston, S., Field, J.C., Sakuma, K.M., 2015. Long-term variation in a central California pelagic forage assemblage. *J. Mar. Syst.* 146, 26–37.
- Rasmusson, E.M., Wallace, J.M., 1983. Meteorological aspects of the el nino southern oscillation. *Science* 222, 1195–1202.
- Rees, H.L., Hyland, J.L., Hylland, K., Clarke, C.S.M., Roff, J.C., Ware, S., 2008. Environmental indicators: utility in meeting regulatory needs: an overview. *ICES J. Mar. Sci.: Journal du Conseil* 65 (8), 1381–1386.
- Schmidt, A.E., Botsford, L.W., Eadie, J.M., Bradley, R.W., Di Lorenzo, E., Jahncke, J., 2014. Non-stationary seabird responses reveal shifting ENSO dynamics in the northeast Pacific. *Mar. Ecol. Prog. Ser.* 499, 249–258.
- Schroeder, I.D., Sydeman, W.J., Sarkar, N., Thompson, S.A., Bograd, S.J., Schwing, F.B., 2009. Winter pre-conditioning of seabird phenology in the California Current. *Mar. Ecol. Prog. Ser.* 393, 211–223.
- Schroeder, I.D., Black, B.A., Sydeman, W.J., Bograd, S.J., Hazen, E.L., Santora, J.A., Wells, B.K., 2013. The north pacific high and wintertime pre-conditioning of California current productivity. *Geophys. Res. Lett.* 40, 541–546.
- Schwing, F.B., Bond, N.A., Bograd, S.J., Mitchell, T., Alexander, M.A., Mantua, N., 2006. Delayed coastal upwelling along the US West Coast in 2005: a historical perspective. *Geophys. Res. Lett.* 33, L22S01.
- Seo, H., Brink, K.H., Dorman, C.E., Koracik, D., Edwards, C.A., 2012. What determines the spatial pattern in summer upwelling trends on the US West Coast? *J. Geophys. Res.: Oceans*, 117(C8).
- Sydeman, W.J., Hester, M., Thayer, J.A., Gress, F., Martin, P., Buffa, J., 2001. Climate change, reproductive performance and diet composition of marine birds in the southern California Current System, 1967–1997. *Prog. Oceanogr.* 49, 309–329.
- Sydeman, W.J., Bradley, R.W., Warzybok, P., Abraham, C.L., Jahncke, J., Hyrenbach, K.D., Kousky, V., Hipfner, J.M., Ohman, M.D., 2006. Planktivorous auklet *Ptychoramphus aleuticus* responses to ocean climate, 2005: unusual atmospheric blocking? *Geophys. Res. Lett.* 33, L22S09.
- Sydeman, W.J., Thompson, S.A., García-Reyes, M., Kahru, M., Peterson, W.T., Largier, J.L., 2014. Multivariate ocean-climate indicators (MOCI) for the central California current: environmental change, 1990–2010. *Prog. Oceanogr.* 120, 352–369.
- Warzybok, P., Johns, M., Bradley, R.W., 2014. Status of Seabirds on Southeast Farallon Island During the 2014 Breeding Season, Report to the U.S. Fish and Wildlife Service, Farallon National Wildlife Refuge. California Current Group, Point Blue Conservation Science (14 pp).
- Wells, B.K., Grimes, C.B., Waldvogel, J.B., 2007. Quantifying the effects of wind, upwelling, curl, sea surface temperature and sea level height on growth and maturation of a California Chinook salmon (*Oncorhynchus tshawytscha*) population. *Fish. Oceanogr.* 16, 363–382.
- Zhang, C.D., 2013. Madden-Julian Oscillation: bridging weather and climate. *Bull. Am. Meteorol. Soc.* 94, 1849–1870.