Progress in Oceanography 120 (2014) 352–369

Contents lists available at ScienceDirect

Progress in Oceanography

journal homepage: www.elsevier.com/locate/pocean

Multivariate ocean-climate indicators (MOCI) for the central California Current: Environmental change, 1990–2010

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ARTICLE INFO

Article history:
Received 13 March 2013
Received in revised form 29 October 2013
Accepted 30 October 2013
Available online 14 November 2013

ABSTRACT

Temporal environmental variability may confound interpretations of management actions, such as reduced fisheries mortality when Marine Protected Areas are implemented. To aid in the evaluation of recent ecosystem protection decisions in central-northern California, we designed and implemented multivariate ocean-climate indicators (MOCI) of environmental variability. To assess the validity of the MOCI, we evaluated interannual and longer-term variability in relation to previously recognized environmental variability in the region, and correlated MOCI to a suite of biological indicators including proxies for lower- (phytoplankton, copepods, krill), and upper-level (seabirds) taxa. To develop the MOCI, we selected, compiled, and synthesized 14 well-known atmospheric and oceanographic indicators of large-scale and regional processes (transport and upwelling), as well as local atmospheric and oceanic response variables such as wind stress, sea surface temperature, and salinity. We derived seasonally-stratified MOCI using principal component analysis. Over the 21-year study period (1990–2010), the ENSO cycle weakened while extra-tropical influences increased with a strengthening of the North Pacific Gyre Oscillation (NPGO) and cooling of the Pacific Decadal Oscillation (PDO). Correspondingly, the Northern Oscillation Index (NOI) strengthened, leading to enhanced upwelling-favorable wind stress and cooling of air and ocean surface temperatures. The seasonal MOCI related well to subarctic copepod biomass and seabird productivity, but poorly to chlorophyll-a concentration and krill abundance. Our results support a hypothesis of enhanced sub-arctic influence (transport from the north) and upwelling intensification in north-central California over the past two decades. Such environmental conditions may favor population growth for species with sub-arctic zoogeographic affinities within the central-northern California Current coastal ecosystem.

1. Introduction

Ocean-climate variability has been shown to strongly affect marine life, including plankton, fish, and top predators, with clear applications in fisheries, wildlife, and ecosystem management (Hjort, 1914; Beaugrand et al., 2003; Cury et al., 2008; Carr et al., 2011). Compared to many of the world's seas, the effects of ocean-climate variability on the California Current ecosystem (CCE) have been particularly well-studied (Peña and Bograd, 2007). This marine realm, situated off the west coast of Canada, the U.S., and Baja California, Mexico, is affected by basin-scale atmospheric–oceanic coupling due to the combined effects of El Niño Southern Oscillation events (ENSO; Lenarz et al., 1995; McPhaden et al., 2006), the decadal-scale North Pacific Gyre Oscillation (Di Lorenzo et al., 2008), and Pacific Decadal Oscillation (PDO; Mantua et al., 1997). Regional coastal and offshore upwelling also affects biotic variability of the CCE from daily to decadal time scales (Huyer, 1983; García-Reyes and Largier, 2010, 2012). Mechanistically, currents associated with tropical and extra-tropical transport bring waters of varying characteristics into the system (Chelton et al., 1982). Subsequently, regional upwelling and its vertical and offshore displacement operate on these water masses, dispersing nutrients and plankton, which in turn determines primary and secondary productivity (Checkley and Barth, 2009). Thus, to understand how climate variability relates to marine life in the CCE, consideration of the interactive effects of horizontal (currents) and vertical (upwelling) transport is required. Although a variety of indicators are available as proxies of these

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http://dx.doi.org/10.1016/j.pocean.2013.10.017

processes, rarely have they been combined in a holistic manner to examine bio-physical interactions in this or other ecosystems globally (but see Hemery et al., 2008 for a multivariate approach).

Ocean-climate variability also may confound interpretations of management actions, such as reduced fisheries mortality after Marine Protected Areas are implemented. Recently, the State of California established a network of 124 Marine Protected Areas (MPAs) and 15 special closures in which fisheries and other human activities were either curtailed or eliminated entirely. This management action was taken primarily to promote the recovery of depleted groundfish (*Sebastes* spp.) and their associated ecosystem. In conjunction with implementation, an evaluation program designed to provide information on biotic responses to reductions in fisheries mortality and other factors was initiated. Though local environmental fluctuations may be important for MPAs, we focus on regional and larger scale environmental fluctuations since they have an important impact on the local ecosystem. Indeed, many of the focal *Sebastes* spp. are known to respond to variation in large-scale and local ocean climate with effects on growth (e.g., Black et al., 2011) and proxies of reproductive success (Ralston et al., 2013). Thus, to place biological observations in an environmental context, we designed and implemented a framework for ocean-climate indicators for the central and north-central California Current by combining a suite of well-known indicators using multivariate statistical procedures (see also Mackas et al., 2007; Hemery et al., 2008). Our principal goal was to provide an assessment of environmental conditions leading up to MPA establishment in the mid-late 2000s. Because CCE biota respond to seasonal variation in environmental conditions (e.g., Hooff and Peterson, 2006; Black et al., 2010, 2011; Thompson et al., 2012), we produced indicators for variability stratified by season. The utility of complex multivariate indicators can be challenged if they are difficult to interpret or do not accurately represent known environmental variability (Rice and Rochet, 2005). Therefore, based on the literature, we developed a series of expectations to evaluate multivariate indicators. These include El Niño conditions that affected the region in 1992–1993, 1997–1998, 2003, and 2009–2010 (Bjorkstedt et al., 2010), the warm-water non-El Niño event of 2005 (GRL Special Section, 2006), and strong La Niña conditions in 1999 and 2008. These conditions have been well described in

Table 1
Data sets used. Shown for each variable is the year of the beginning of the full time series (all data sets extend through 2010) and the source for the data.

Variable type	Variable	Beginning year of time series	Data source
Sub-tropical Climate Indices	Southern Oscillation Index	1900	Climate Analysis Section, National Center for Atmospheric Research
	Multivariate El Niño-Southern Oscillation Index	1950	Earth System Research Laboratory, National Oceanic and Atmospheric Administration
	Oceanic Niño Index	1950	Center for Climate Prediction, National Weather Service, National Oceanic and Atmospheric Administration
Sub-arctic Climate Indices	North Pacific Index	1900	Climate Analysis Section, National Center for Atmospheric Research
	North Pacific Gyre Oscillation	1950	Emanuele Di Lorenzo, Georgia Institute of Technology
	Pacific Decadal Oscillation	1900	Joint Institute for the Study of the Atmosphere and Ocean, University of Washington
Upwelling	Northern Oscillation Index	1970	Pacific Fisheries Environmental Laboratory, National Oceanic and Atmospheric Administration
	Bakun Upwelling Index 36°N	1946	Environmental Research Division, National Oceanic and Atmospheric Administration
	Bakun Upwelling Index 39°N	1946	
Wind stress	Bodega Bay	1982	Marisol Garcia-Reyes, University of California Davis
	San Francisco	1982	
	Half Moon Bay	1982	
	Monterey Bay	1982	
Sea level	South Beach	1967	National Water Level Observation Network, Center for Operational Oceanographic Products and Services
	Crescent City	1933	
	San Francisco	1901	
Sea surface temperature	Point Arena	1982	National Oceanic and Atmospheric Administration
	Bodega Marine Lab	1988	Bodega Ocean Observing Node, Bodega Marine Lab, University of California Davis
	Bodega Bay	1981	National Oceanic and Atmospheric Administration
	San Francisco	1983	
	Farallon Islands	1955	Scripps Institution of Oceanography Shore Stations Program
	Half Moon Bay	1981	National Oceanic and Atmospheric Administration
	Monterey Bay	1987	
Salinity	Bodega Marine Lab	1988	Bodega Ocean Observing Node, Bodega Marine Lab, University of California Davis
	Farallon Islands	1955	Scripps Institution of Oceanography Shore Stations Program
Air temperature	Fort Ross	1950	National Climate Data Center, National Oceanic and Atmospheric Administration
	Bodega Marine Lab	1988	Bodega Ocean Observing Node, Bodega Marine Lab, University of California Davis
	San Francisco	1959	National Climate Data Center, National Oceanic and Atmospheric Administration
	Pacifica	1984	
	Half Moon Bay	1939	
Precipitation	Fort Ross	1931	National Climate Data Center, National Oceanic and Atmospheric Administration
	San Francisco	1959	
	Pacifica	1984	
	Half Moon Bay	1939	
Biological	Chlorophyll-a Concentration	1997	Mati Kahru, Scripps Photobiology Group, Scripps Institution of Oceanography
	Northern Copepod Index	1996	William Peterson, Northwest Fisheries Science Center, National Oceanic and Atmospheric Administration
	Krill Abundance	1990	John Field, Southwest Fisheries Science Center, National Oceanic and Atmospheric Administration
	Seabird Reproductive Success	1971, 1972	Point Blue Conservation Science