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The physical oceanographic environment during the CCE-LTER Years: Changes in climate and concepts

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ABSTRACT

The California Current System (CCS) has been studied by the California Cooperative Oceanic Fisheries Investigations program for many decades. Since 2004, the Southern California Bight (SCB) and the oceanic region offshore has also been the site for the California Current Ecosystem (CCE) Long-Term Ecological Research (LTER) program, which has established long-term observational time series and executed several Process Cruises to better understand physical–biological variations, fluxes and interactions. Since the inception of the CCE-LTER, many new ideas have emerged about what physical processes are the key controls on CCS dynamics. These new perspectives include obtaining a better understanding of what climate patterns exert influences on CCS physical variations and what physical controls are most important in driving CCE ecological changes.

Physical oceanographic and climatological conditions in the CCS varied widely since the inception of the CCE-LTER observational time series, including unusual climate events and persistently anomalous states. Although the CCE-LTER project commenced in 2004 in the midst of normal ocean conditions near the climatological means, over the following decade, El Nino/Southern Oscillation conditions flickered weakly from warm to cold, with the Pacific Decadal Oscillation (PDO) generally tracking that behavior, while the North Pacific Gyre Oscillation (NPGO) evolved to persistent and strong positive conditions after 2007, indicative of enhanced upwelling from 2007 to 2012. Together the combined impact of the negative PDO state (La Nina conditions) and positive NPGO state (increased upwelling conditions) yielded remarkably persistent cool conditions in the CCS from late 2007 to early 2009 and from mid-2010 through 2012.

The broad-scale climate variations that occurred over the North Pacific and CCS during this time period are discussed here to provide physical context for the CCE-LTER time series observations and the CCE-LTER Process Cruises. Data assimilation fits, using the Regional Ocean Modeling System four-dimensional data assimilation framework, were successfully executed for the 1-month time period surrounding each of the Process Cruises. The fits provide additional information about how the physical flows evolve during the course of the multi-week Process Cruises. Relating these physical states to the numerous biological measurements gathered by the CCE-LTER time series observations and during the Process Cruises will yield vital long-term perspective of how changing climate conditions control the ocean ecosystem in this region and information on how this important ecosystem can be expected to evolve over the coming decades.

1. Introduction

The California Current System (CCS) is an ecologically, economically, and societally important coastal oceanic region along the U.S. West Coast (e.g., Hickey, 1998). It is part of the North Pacific subtropical gyre and is linked to several prominent patterns of basin-scale climate variability. As an upwelling system, it contains high biological production (e.g., Checkley and Barth, 2009), which supports numerous fisheries, and provides diverse recreational opportunities for millions of people.

The CCS has been measured by the California Cooperative Oceanic Fisheries Investigations (CalCOFI) program for over six decades. Since 2004, the Southern California Bight (SCB) and the oceanic region offshore has also been the site for the California Current Ecosystem (CCE) Long-Term Ecological Research (LTER) program (Ohman et al., 2013a), which has collected many long time series of biological observations on numerous platforms and executed several Process Cruises to better understand

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physical–biological variability, fluxes, and interactions. Over the time period since the inception of the CCE-LTER, many new ideas have emerged about what physical processes are involved in CCS dynamics, what climate patterns exert influences on its physical variations, and what physical controls are most important in driving ecological changes.

The goal here is to summarize those changes in physical oceanographic perspectives in the CCS and relate them to the physical fields that affected the biological fields observed in the SCB by the CCE-LTER program. Studying the CCE-LTER time period is vital because the biological variables, fluxes, and processes that were measured and studied under these physical oceanographic conditions form a new baseline for attempting to understand past biological observations seen in CalCOFI as well as future observations affected by global warming. More comprehensive reviews of the CCS include the works of Hickey (1998), Miller et al. (1999), Checkley and Barth (2009), Schwing et al. (2010) and Gangopadhyay et al. (2011).

In the next section, the developments of new ideas that help to explain CCS dynamical variations are summarized since the inception of the CCE-LTER in 2004. Section 3 describes the physical oceanographic conditions encountered during the CCE-LTER time period and relates them to broader-scale climate variations occurring over the North Pacific. Section 4 presents the data assimilation fits using the Process Cruises and relates them to the ambient broader-scale climate variations. Section 5 provides a summary and some connections to the biological responses observed during the Process Cruises.

2. Changes in perspectives of CCS physical processes

During the past decade, several important ideas and observations have arisen that changed the way the CCS is viewed. These dynamical issues range from small-scale to the basin-scale and from days to decades, with impacts on ecological variations that may be strong or subtle.

Perhaps the most notable change in perspective of the dynamics of CCS variability is the identification of a class of energetic small-scale variations in the upper ocean that are now referred to as submesoscale variations. Capet et al. (2008a, 2008b) noted that, in their numerical simulations of the CCS, when resolution was increased to a few km, vigorous current instabilities (~8 cm/s rms) occurred in model runs near the ocean surface that enhanced lateral and vertical mixing processes. These variations, with spatial scales of a few km and temporal scales of a few days, were also visible in satellite image sequences of the CCS (Capet et al., 2008b). Later work by others (e.g., Boccaletti et al., 2007; Fox-Kemper et al., 2009) revealed these features to have a strong ageostrophic component that is largely trapped to the mixed layer, in contrast to mesoscale instabilities that occur along the thermocline with quasigeostrophic dynamics. The submesoscale is now an active area of CCS research (e.g., Todd et al., 2012) and its importance in controlling CCS biological fluxes is still being identified (e.g., Johnston et al., 2011; Li et al., 2012).

Another fundamental advance in CCS dynamics is the identification of a new coherent climate mode, the North Pacific Gyre Oscillation (NPGO), which has attracted widespread interest because it links physical ocean changes with biological variables across the entire eastern North Pacific. While studying eddy-resolving model runs of the eastern North Pacific, Di Lorenzo et al. (2008) noticed that the second mode of sea-level height in the North Pacific had the same temporal variability as the salinity variations in the Southern California Bight. This alone is a startling result because the salinity variations in the CalCOFI data had been known for decades to be uncorrelated with temperature data and their driving mechanism was totally unclear up to that point. For example, Schneider et al. (2005) had suggested that random eddies and winds were the primary forcing for CCS salinity variations.

Identifying this forced component of CCS response led to the later discovery by Di Lorenzo et al. (2009) that salinity variations in the California Current are correlated to salinity variation along Line P, west of Vancouver Island. Although observationalists had been collecting these two datasets independently over many years, no one had noticed that they were correlated. It was only through the theoretical developments associated with the NPGO that it was realized how they should be correlated, and consequent model predictions were validated by the available observations.

Aspects of the multivariate structure of the NPGO (sea-level height, sea-surface temperature (SST), salinity, ocean currents, and wind-stress curl) had been previously discussed in the literature, although no one had linked them dynamically. The NPGO index turned out to be the same time series as the “Victoria mode” of SST (2nd EOF of Bond et al., 2003) and the “breathing mode” of sea-level height (1st mode of Cummins and Freeland, 2007). It turned out that while the Pacific Decadal Oscillation (PDO; Mantua et al., 1997) largely explained broad-scale temperature fluctuations in the CCS and acted most strongly in controlling upwelling in the northern CCS, the NPGO, in contrast, explained salinity variations in the CCS and controlled upwelling in the southern part of the CCS. Further research by Chhak et al. (2009) showed that NPGO is primarily driven by the North Pacific Oscillation (NPO) pattern of sea-level pressure variations, while PDO is predominantly controlled by changes in the Aleutian Low (Miller and Schneider, 2000; Schneider and Cornuelle, 2005; Ceballos et al., 2009). The results revealed why NPGO acts more strongly in the southern CCS and PDO acts more strongly in the northern CCS (also see Macias et al., 2012).

It is truly remarkable that so many aspects of the CalCOFI data now appear to be significantly controlled by the NPGO, including chlorophyll, nitrate, silicate, phosphate and oxygen. None of these are explicable by the PDO index, which many previous researchers had assumed to be the dominant climate mode. Scientists subsequently converged from all directions with time series that correlate with the NPGO. Hence, the NPGO is an important physical–chemical–biological climate mode in the North Pacific, which may eventually be used for diagnostics of climate regimes and possibly even forecasting of biological populations.

Another large-scale forcing effect that has had great impact on the way the CCE is now viewed was uncovered by Rykaczewski and Checkley (2008). They found that offshore Ekman pumping by wind-stress curl was equally important as coastal Ekman upwelling in supplying nutrients to the CCE. Thus changes in the large-scale offshore wind stress curl are correlated to long-term changes in sardine biomass, apparently due to changes in productivity of smaller-bodied mesozooplankton upon which the sardine depend for food.

Long-term decreases in dissolved oxygen have been observed below the thermocline in the SCB by Bograd et al. (2008). Although the reason for the decrease has not been clearly identified, it may be due to reduced vertical mixing because of increasing stratification in the CCS (Roemmich and McGowan, 1995; McGowan et al., 2003; Kim and Miller, 2007) or to changes in the oxygen content in the source of these deep waters that are advected in from the south (e.g., Deutsch et al., 2011). The impact of this depletion on benthic and demersal species at these depths is being actively investigated (e.g., McClatchie et al., 2010).

New observational tools generated significant advances in understanding of CCS physical processes, as well (e.g., Ohman et al., 2013b). Subsurface gliders, designed and deployed by Davis

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