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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 ($\sim$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 et al. (2008), revealed structures in the southern CCS not previously seen, most notably a persistent poleward flow at depths below 200 m and located 200 km offshore of the poleward flowing undercurrent. If only hydrography is used to compute geostrophic flow referenced to a level of no motion, then this new flow is not evident. Its impact on upper-ocean CCS processes and long-term changes in the CCE may become clearer as longer records from glider tracks become available.

New modeling capabilities now allow multi-decadal, finely resolved runs of the CCS, which can be diagnosed for intrinsic variations, forced responses and even coupled ocean–atmosphere interactions, to untangle the complicated processes involved in long-term variations in the system (e.g., Di Lorenzo et al., 2005; Capet et al., 2008a, 2008b; Seo et al., 2007; Centurioni et al., 2008; Veneziani et al., 2009; Jin et al., 2009; Kurian et al., 2011; Combes et al., 2013). These long simulations now involve physical, chemical and biological interactions as well (e.g., Gruber et al., 2006). A major highlight of this capability is the work of Goebel et al. (2010) who used the “Darwin Model” of Follows et al. (2007) to show how CCS regional physical characteristics allow representative phytoplankton communities to emerge with realistic patterns as a component of the model solution. Another important result is the capability of generating unprecedented connectivity matrices for various species of the SCB based on larval trajectories computed by frequently releasing large numbers of model particles in physical flows to compute Lagrangian particle statistics (Mitarai et al., 2009; Drake et al., 2011) over spawning regions.

New computational diagnostic tools also helped shed new light on previously difficult to study nonlinear processes. Generalized Stability Analysis codes (Moore et al., 2004) for the Regional Ocean Modeling System (ROMS), which were constructed using the tangent linear and adjoint models, can now provide metrics of sensitivity for chosen indices of the CCS. Applications of these techniques can quantify in unique and illuminating ways what variables cause the greatest changes in the chosen metrics of CCS variations. For example, Moore et al. (2009) showed that the sensitivity of the potential for baroclinic instability to occur is greatest when wind stress anomalies are concentrated along the core of the California Current when it is close to the coast, with consequently large horizontal temperature gradients from coastal upwelling.

Chhak and Di Lorenzo (2007) used the adjoint model of ROMS to show how upwelling changes in the CCS during PDO warm and cold phases. During cold years, the upwelling cell is very deep due to intensified vertical mixing driven by the stronger alongshore wind field, and vice versa during warm years. Surprisingly, the change in stability of the water column due to the SST change was not the dominant factor in setting the depth of the upwelling cell. Song et al. (2011) used a similar formalism to show how upwelling cells in the CCS are tremendously altered by the structure of coarsely resolved versus finely resolved wind stress forcing. These results have applications in understanding how long-term changes in wind conditions alter the source of upwelled waters and consequently primary production in the surface waters.

Ocean data assimilation tools (e.g., Moore et al., 2011a, 2011b, 2011c; Song et al., 2012b; Di Lorenzo et al., 2007) have been used recently in the CCS to provide multi-year analysis products (e.g., Broquet et al., 2009; Broquet et al., 2011; Dong et al., 2012), which allow long-term studies of variables that are only coarsely resolved by observational programs. Short-term ocean data assimilation fits, using dynamically consistent physics over month-long intervals, were generated by Song et al. (2012a) to show how offshore oceanic advection and the quality of upwelled source waters impacted observed sardine spawning habitat in the SCB.

Clearly, the dynamical understanding of the CCS in the SCB has changed tremendously since the launch of the CCE-LTER nine years ago. In the next section, a careful examination is made of how climate drivers and the hydrography of the CCS have changed since the inception of the CCE-LTER to help interpret the time series of biogeochemical measurements and intensive process experiments at sea.

3. CCS physical variations during the CCE-LTER observational period

The environmental conditions of the CCS fluctuated greatly over the CCE-LTER time series observational period as might be expected. Climate indices of PDO, NPGO and El Niño-Southern Oscillation (ENSO) provide a broad-brush indication of environmental conditions throughout the CCS, as shown in Fig. 1.

The PDO switched to a cold phase in 1999 and it was initially thought that this phase would persist for decades (Peterson and Schwing, 2003; Bond et al., 2003). However, by 2004, when the CCE-LTER began, the state of the CCS was instead characterized as being in the midst of “normal” ocean conditions near the climatological means, with no strong climate anomalies in place (Goericke et al., 2005). Over the following decade, ENSO conditions flickered weakly from warm to cold, with perhaps an increase in amplitude of the variations after the end of the decade. The PDO generally tracked that behavior, as would be expected through low-frequency integration of the atmospherically teleconnected signals in the midlatitudes (e.g., Newman et al., 2003; Schneider and Cornuelle, 2005). The NPGO went from nearly normal conditions at the outset of CCE-LTER, to weakly negative values in 2005, to persistent and strong positive conditions after 2007, indicative of enhanced upwelling from 2007 to 2012 (Chenillat et al., 2012), with a much stronger signature than PDO in the North Pacific climate during the latter time frame (Furtado et al., 2011; Yeh et al., 2011). Together the combined impact of the

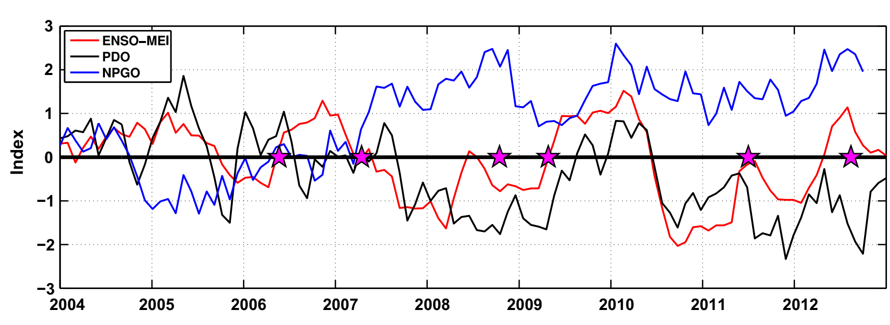

Fig. 1. Time series of Multivariate ENSO Index (red; Wolter and Timlin, 1993), Pacific Decadal Oscillation Index (black, Mantua et al., 1997) and North Pacific Gyre Oscillation Index (blue; Di Lorenzo et al., 2008) during the CCE-LTER years to date. CCE-LTER Process Cruise times are indicated with stars. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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 (Bjorkstedt et al., 2012). Weak El Ninos in 2006–2007 and 2009–2010 punctuated that predominantly cool long-term state.

In 2002, before the CCE-LTER was initiated, cold, fresh anomalies appeared in the upper 100–200 m of the CCS (Freeland et al., 2003). This feature instigated a great deal of research and speculation on their origin and impact (e.g., Huyer, 2003 outlines the contents of a special journal section dedicated to this event, and Venrick et al., 2003 describe its physical–biological impact and

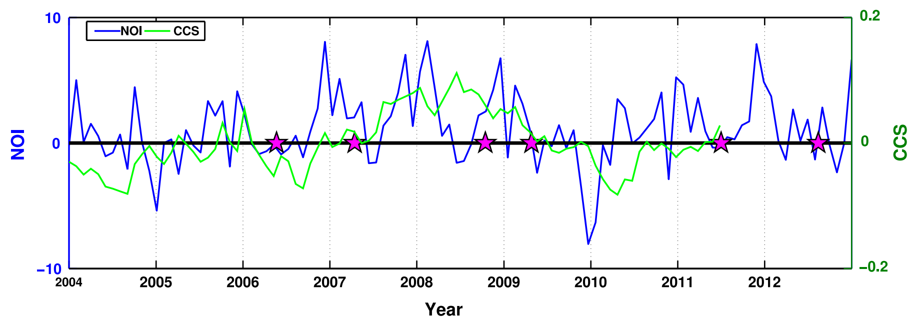

Fig. 2. Time series of CCS Strength Index (green; Cummins and Freeland, 2007) and Northern Oscillation Index (blue; Schwing et al., 2002) during the CCE-LTER years to date. CCE-LTER Process Cruise times are indicated with stars. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

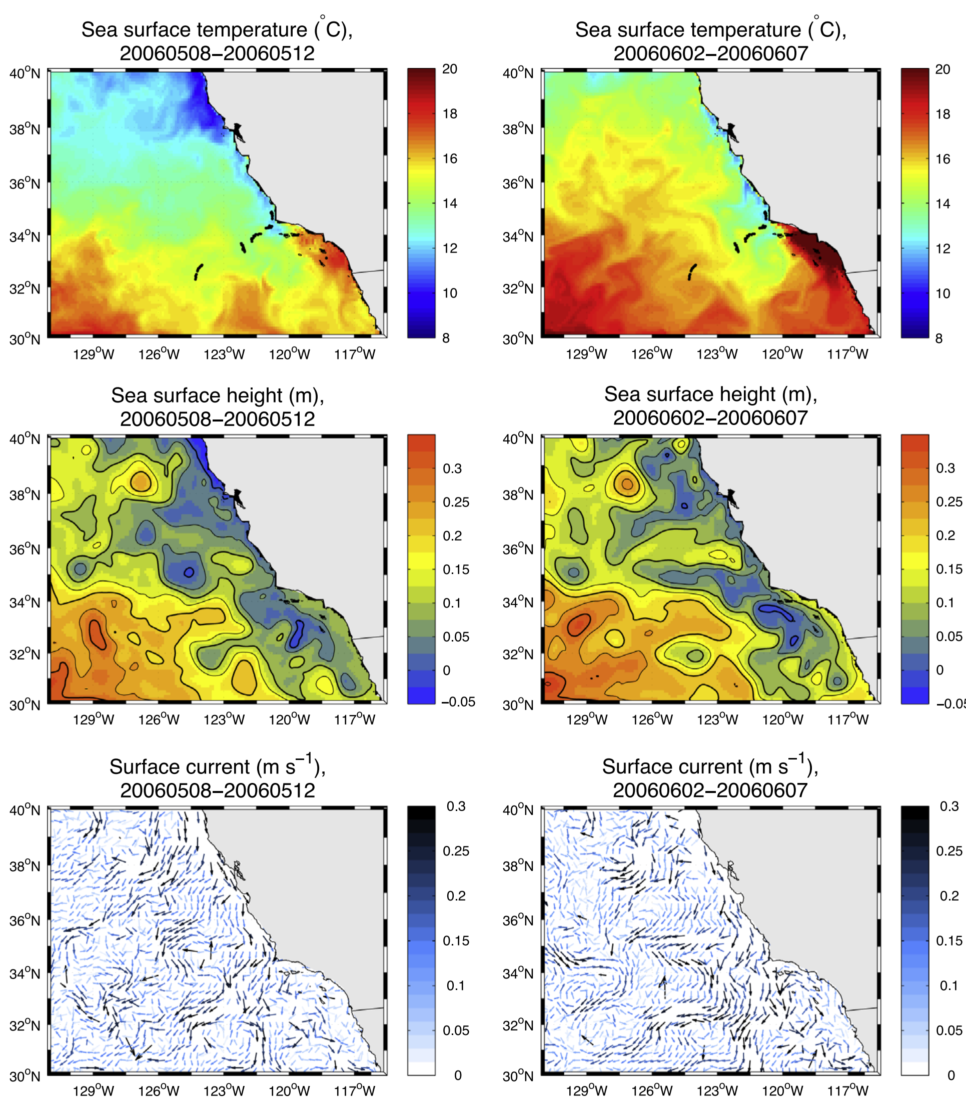

Fig. 3. Physical oceanographic evolution during 2006 CCE-LTER Process Cruise time interval as represented by a four-dimension variational (4Dvar) data assimilation fit. (left) May 8–12 average and (right) June 2–7 average of (top) SST, (middle) sea-level height and (bottom) surface currents. Station locations for this Process Cruise are indicated by dots in upper-left SST plot.

include a historical accounting of the e-mail messages that first discussed its appearance). The anomalies affected the entire U.S. West, especially along the Oregon coast where hypoxic conditions caused large die-offs of benthic fish and invertebrates (Grantham et al., 2004) and the origin of the anomalous waters appeared to be in the Gulf of Alaska. While some results indicated that the anomalies were due to an intensification of the CCS flowing south (Barth, 2003; Kosro, 2003; Strub and James, 2003; Cummins and Freeland, 2007), other results showed that an anomaly generated in the Gulf of Alaska could have been advected southward on the mean flow (Curchitser et al., 2005). These cool, fresh anomalies persisted throughout the CCS in 2003 (Goericke et al., 2004). Remnants of the fresh water anomalies could be found in the mixed layer of the southern CCS and SCB from the initiation of the CCE-LTER in 2004 and into early 2006 (Goericke et al., 2005; Goericke et al., 2007; Auad et al., 2011), but their broad-scale effects seem mostly to have been subsumed into local ocean climate variations by that time. No other similarly strong event has been observed since that time, as is evident in the time series of CCS salinity shown by Auad et al. (2011) and CalCOFI salinity shown by Bjorkstedt et al. (2011).

During the spring and summer of 2005, a delayed onset of the upwelling wind fields in the CCS (Schwing et al., 2006) fueled speculation that the phenology of the CCS might undergo potentially long-term changes that could seriously affect the ecosystem (e.g., Bograd et al., 2002; Peterson et al., 2006). A large number of studies examined the impact of this delay on the physical ocean and the local ecosystem (e.g, Barth et al., 2007; special collection of papers in *Geophysical Research Letters*, 2006). During later years, however, normal variability in timing and strength of CCS upwelling was observed (McClatchie et al., 2008, 2009; Bjorkstedt et al., 2010, 2011, 2012; Wells et al., 2013). The impact of this unique event was the generation of greater attention by the community to long-term monitoring of the quantified effects of CCS upwelling on the CCE (e.g., Bograd et al., 2009).

The establishment of the Argo Program (Roemmich et al., 2009) has allowed a quasi-direct estimation of the strength of the CCS by upper-ocean dynamic height computations from free-drifting profiling floats (Freeland and Cummins, 2005). Fig. 2 shows a CCS index (courtesy of H. Freeland, private communication, 2013; see Sydeman et al., 2014) computed as the dynamic height difference between two points, the highest spot in the subtropical gyre and the

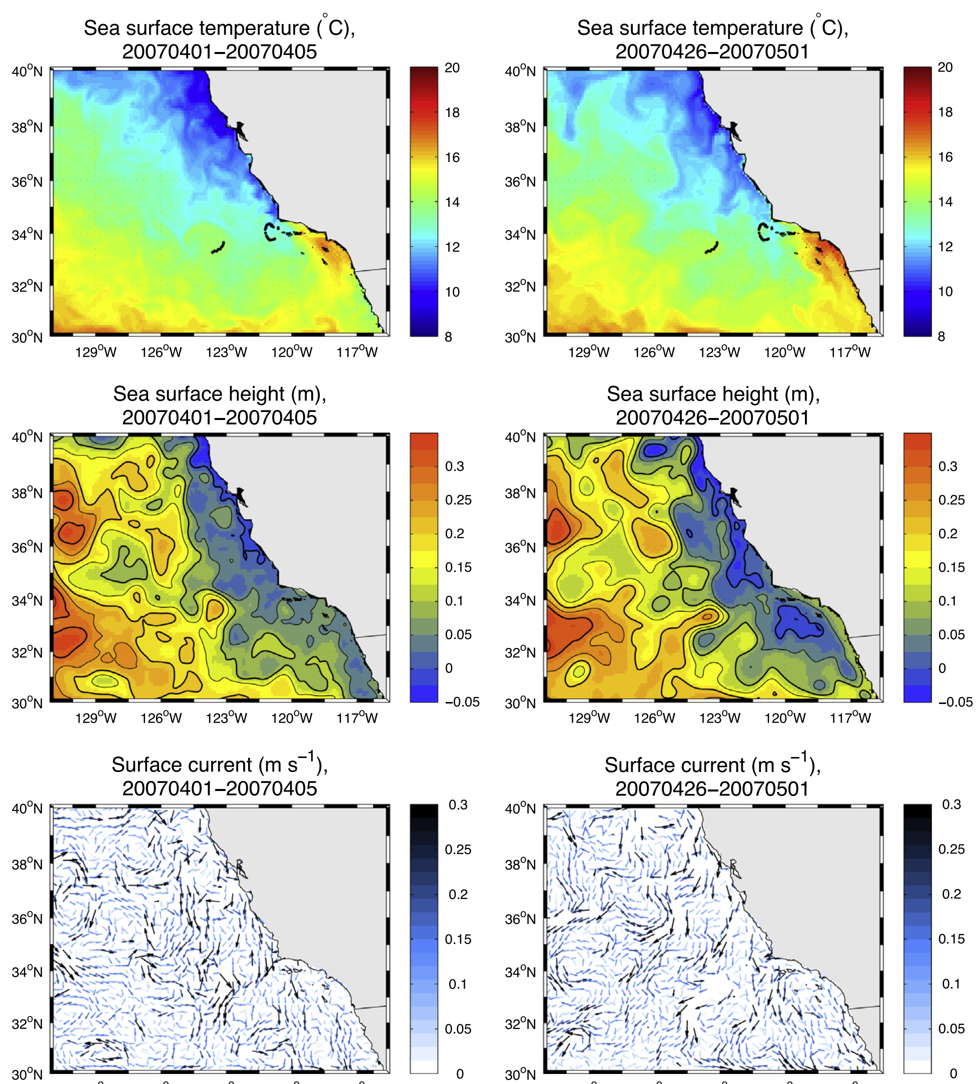

Fig. 4. Physical oceanographic evolution during 2007 CCE-LTER Process Cruise time interval as represented by a four-dimensional variational (4Dvar) data assimilation fit. (left) April 1–5 average and (right) April 26–May 1 average of (top) SST, (middle) sea-level height and (bottom) surface currents. Station locations for this Process Cruise are indicated by dots in upper-left SST plot.

near-coastal spot where the subtropical and subpolar gyres split (Freeland, 2006; Cummins and Freeland, 2007). Positive values correspond to stronger flows of the CCS. The CCS was in a lower flow state during the years 2004, 2006, and 2010, and flowed more strongly during 2008. These results are broadly consistent with the CCS kinetic energy index defined by Auad et al. (2011), also using Argo data. The persistently strong flows of the CCS between 2007 and 2009 correspond with a consistently positive NPGO index, which is evaluated independently from satellite sea-level height. The Northern Oscillation Index (NOI; Schwing et al., 2002), which is computed as the sea level pressure difference between the North Pacific High and Darwin, shows generally positive values during the 2007–2009 time frame as well (Fig. 2), supporting the idea the CCS was coherently strong in this period. For other periods, though, the three indices do not consistently corroborate each other.

With this perspective of large-scale climatic and oceanographic conditions in the CCS during the CCE-LTER time series observational period in mind, the next section examines the specific oceanographic conditions that were sampled during the Process Cruises, using data assimilation as a tool for extending the interpretation of the limited data.

4. CCE-LTER Process Cruises: data assimilation and climate context

The CCE-LTER has to date launched five Process Cruises (2006, 2007, 2008, 2011 and 2012) and one Student Cruise (2009) into the CCS, primarily along Line 80 of CalCOFI. The times of these are shown in Figs. 1 and 2 using stars. Station occupations during the six cruises are shown in Figs. 3–8, in the upper-left plots of SST. Data assimilation fits for these five Process Cruises and the Student Cruise (Figs. 3–8) have been generated, following the protocol of Song et al. (2012a) and using the Regional Ocean Modeling System (ROMS; Shchepetkin and McWilliams, 2005; Haidvogel et al., 2008). These 1-month simulations assimilate, in a dynamically consistent four-dimensional variational framework (Moore et al., 2011a), the available in situ hydrography, satellite altimetry, and SST to provide a time-dependent three-dimensional view of the physical state of the ocean during an individual Process Cruise time period. The model domain covers 30°N–40°N and 115°W–131°W with an approximately 9 km grid interval and 42 terrain-following vertical levels. Background initial and boundary conditions were extracted from the data-assimilated data set “CCS

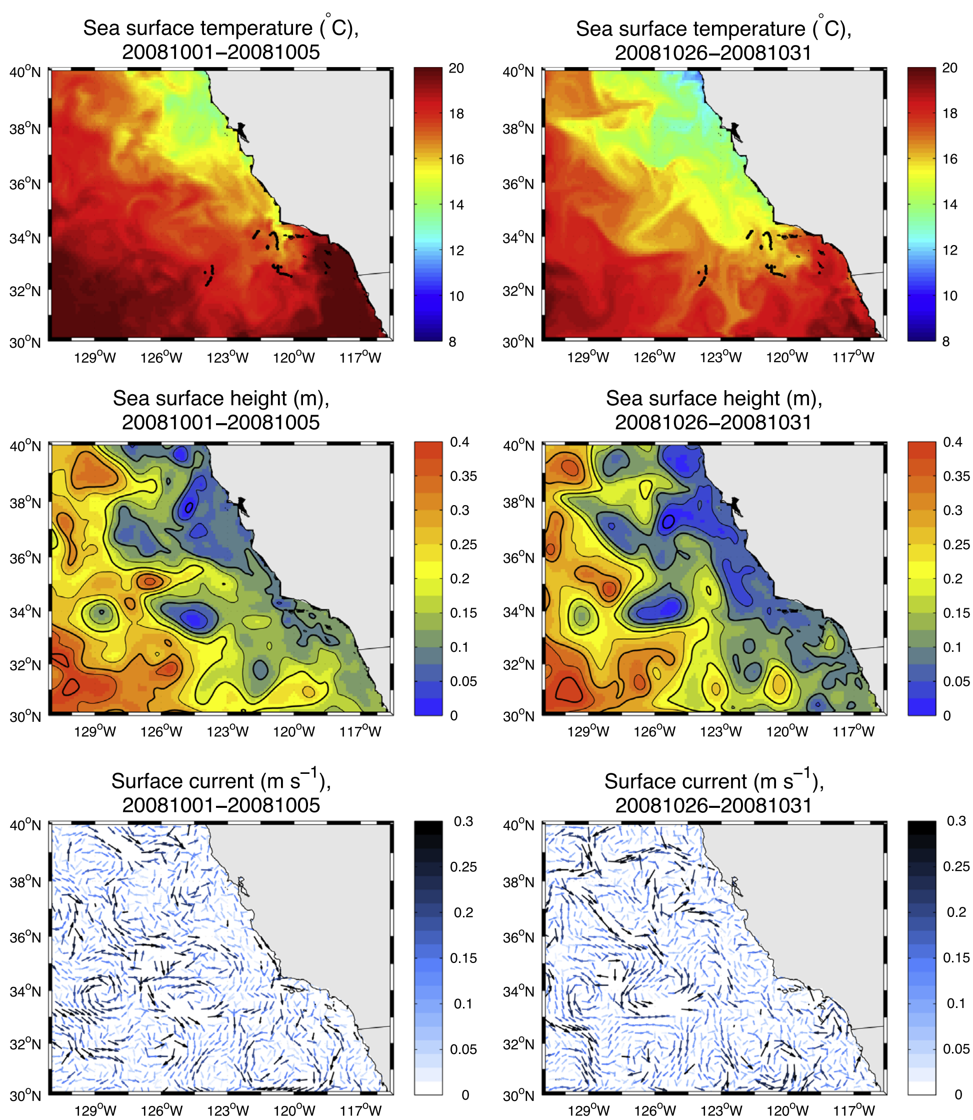

Fig. 5. Physical oceanographic evolution during 2008 CCE-LTER Process Cruise time interval as represented by a four-dimensional variational (4Dvar) data assimilation fit. (left) October 1–5 average and (right) October 26–31 average of (top) SST, (middle) Sea-level height and (bottom) surface currents. Station locations for this Process Cruise are indicated by dots in upper-left SST plot.

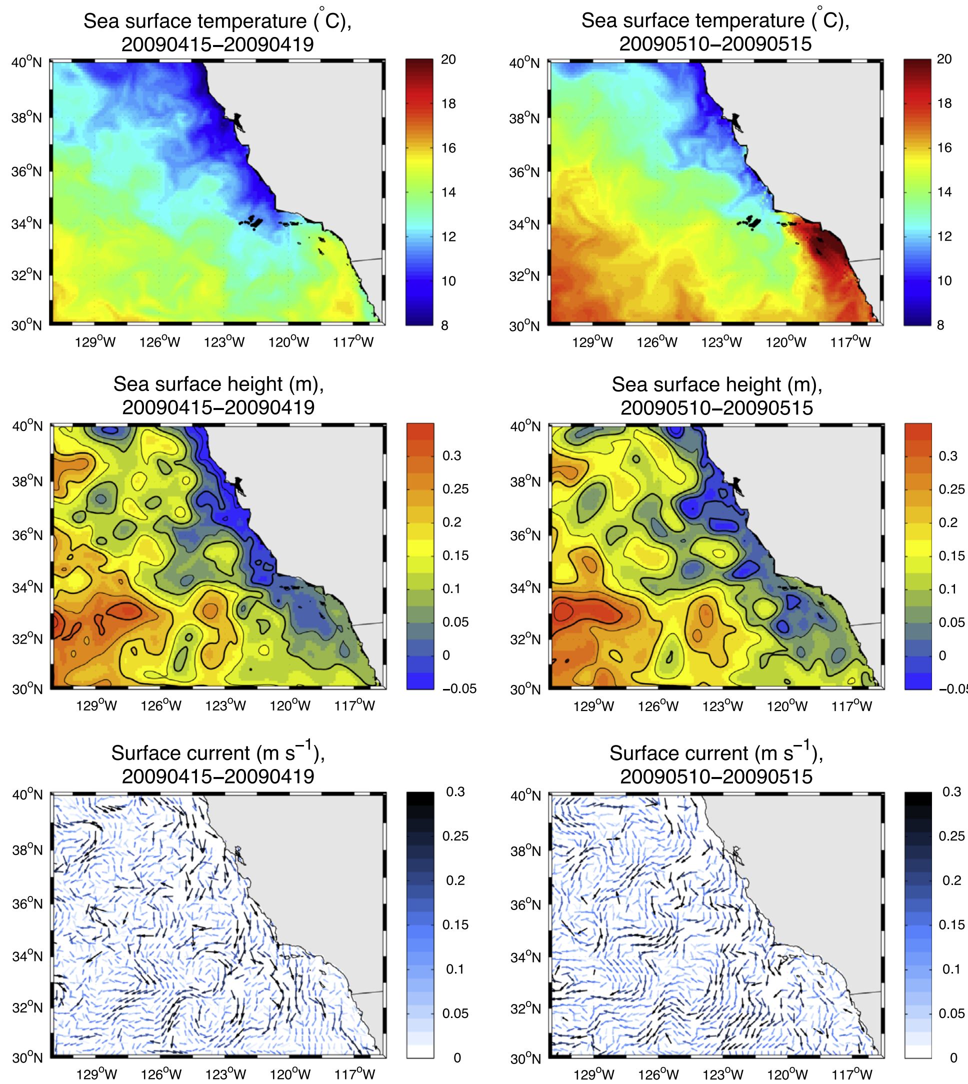

Fig. 6. Physical oceanographic evolution during 2009 CCE-LTER Process Cruise time interval as represented by a four-dimensional variational (4Dvar) data assimilation fit. (left) April 15–19 average and (right) May 10–15 average of (top) SST, (middle) Sea-level height and (bottom) surface currents. Station locations for this Process Cruise are indicated by dots in upper-left SST plot.

31-year Historical Reanalysis" (http://oceanmodeling.ucsc.edu/reanalccs31/)" and the surface boundary conditions were obtained from prior model solutions of the 9 km resolution COAMPS (Hodur et al., 2002) using bulk formulation. The fits were achieved by adjusting the initial conditions and surface forcing to allow the model simulation to fit all the observed data, including the Process Cruise hydrography, with given errors, in a least square sense. If only the initial condition is adjusted, information from the observations can be diminished with a month-long run. Adjusting the surface forcing allows the model to keep tracking the observed states more accurately over the 30-day assimilation window used here (compared with the 7-day window of Broquet et al., 2009).

These fits are now available on the LTER DataZoo website (http://oceaninformatics.ucsd.edu/datazoo/data/ccelter/other_data). In addition to these fits, which are tailored to the time intervals of these cruises, real-time 1-week fits by the University of California, Santa Cruz (UCSC) Ocean Modeling Group are also available (http://oceanmodeling.pmc.ucsc.edu/ccsnrt/), although they do not include the Process Cruise hydrographic data. Next, the physical oceanographic eddy conditions that were captured by and the background climate states that influenced each of those Process Cruise surveys are analyzed. CalCOFI Reports provide additional information by giving a state of the California Current summary every year, which are summarized here for establishing the antecedent and/or concurrent physical oceanographic conditions of the Process Cruises.

After the weak El Niño event in early 2005 with concomitant warm PDO conditions and a negative NPGO state, 2006 was essentially a neutral year for the first Process Cruise. Before the first Process Cruise in May 2006, CalCOFI measured a sinuous California Current flexing far offshore, with a weak signature of the Southern California Eddy (SCE) evident as a poleward flow near the coast (Goericke et al., 2007). During May 2006, the model fit (Fig. 3) reveals warm SST near the SCB coast that intensifies through surface heating rather than a coherent poleward flow. Southward flow associated with a cyclonic eddy west of the Channel Islands brings in cool water from the north near the upwelling field by Point Conception during this month. This intensified the cross-shelf SST gradient yielding a sharp representation of the transition from inshore productive waters to offshore oligotrophic waters.

The 2006 Process Cruise was focused along Line 80 off Point Conception and measured various locations with diverse physical–biological conditions (Landry, 2006). In the region near and around Point Conception, where strong diatom and dinoflagellate blooms were encountered, cool waters indicate upwelling and surface currents are directed offshore. Further offshore, where low

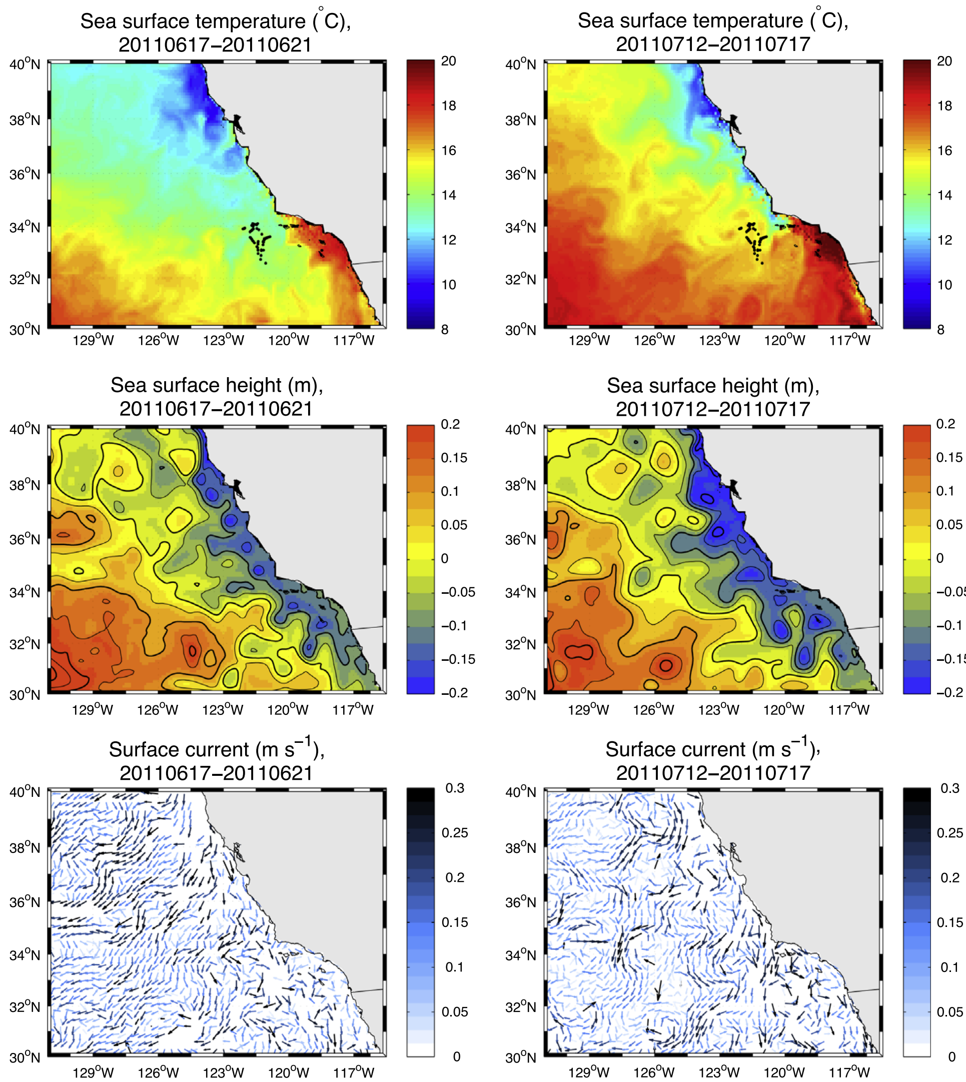

Fig. 7. Physical oceanographic evolution during 2011 CCE-LTER Process cruise time interval as represented by a four-dimensional variational (4Dvar) data assimilation fit. (left) June 17–21 average and (right) July 12–17 average of (top) SST, (middle) Sea-level height and (bottom) surface currents. Station locations for this Process Cruise are indicated by dots in upper-left SST plot.

nutrients and associated picoplankton populations were observed, a strong anticyclonic eddy indicates local downwelling conditions. By the end of the cruise, extensive surface warming occurred in the far offshore region along line 90, consistent with the deep chlorophyll maximum measured there.

After the weak El Niño of 2006, ENSO and PDO indices had returned to normal while the NPGO had jumped to positive values, suggesting enhanced upwelling in the SCB, by the start of the 2007 Process Cruise (Landry, 2007). Both nearshore cool and productive surface conditions southwest of Point Conception and a warm anticylonic eddy in offshore waters were observed during four experimental cycles. A southward cool jet between the nearshore and offshore sampling stations strengthened during the latter part of April, as did the anticyclonic eddy flow which trapped weakly productive waters, as evident from ocean color images (Landry, 2007).

The following spring, the second Process Cruise was launched concurrent with the April 2007 CalCOFI cruise (McClatchie et al., 2008). During these cruises the California Current was far offshore; the SCE was weak. Although upwelling was strong around Point Conception, warm surface waters prevailed in the southern coastal regions of the SCB. The SCE strengthens in the latter part of April, with concomitant increase in surface temperature near the coast east of the Channel Islands (Fig. 4). This intensifies the cross-shelf SST front that is associated with the southward advection of upwelled water from Point Conception.

The 2008 Process Cruise encountered completely different climatological conditions than the first two Process Cruises, since it occurred during October instead of spring upwelling conditions. However, relatively strong La Niña and negative PDO conditions were in play, along with a very strong positive NPGO state and strong CCS flow index, all suggesting enhanced upwelling and weak stratification relative to long-term averages. The fit (Fig. 5) reveals southward flow in early October from Point Conception, carrying cool and productive (Landry, 2008) waters into the regions sampled during the cruise. Later in the month the flows are less coherent, with no strong indication of transport from coastal regions into the waters west of the Channel Islands where the stations were located. Little indication of a large-scale SCE is apparent in the fits, consistent with fall conditions when it often collapses into a field of eddies (Di Lorenzo, 2003). Overall, the surface waters of the SCB had cooled considerably by the end of the month due to surface cooling. The end of this month-long Process Cruise focused on a deep-water frontal system dubbed the

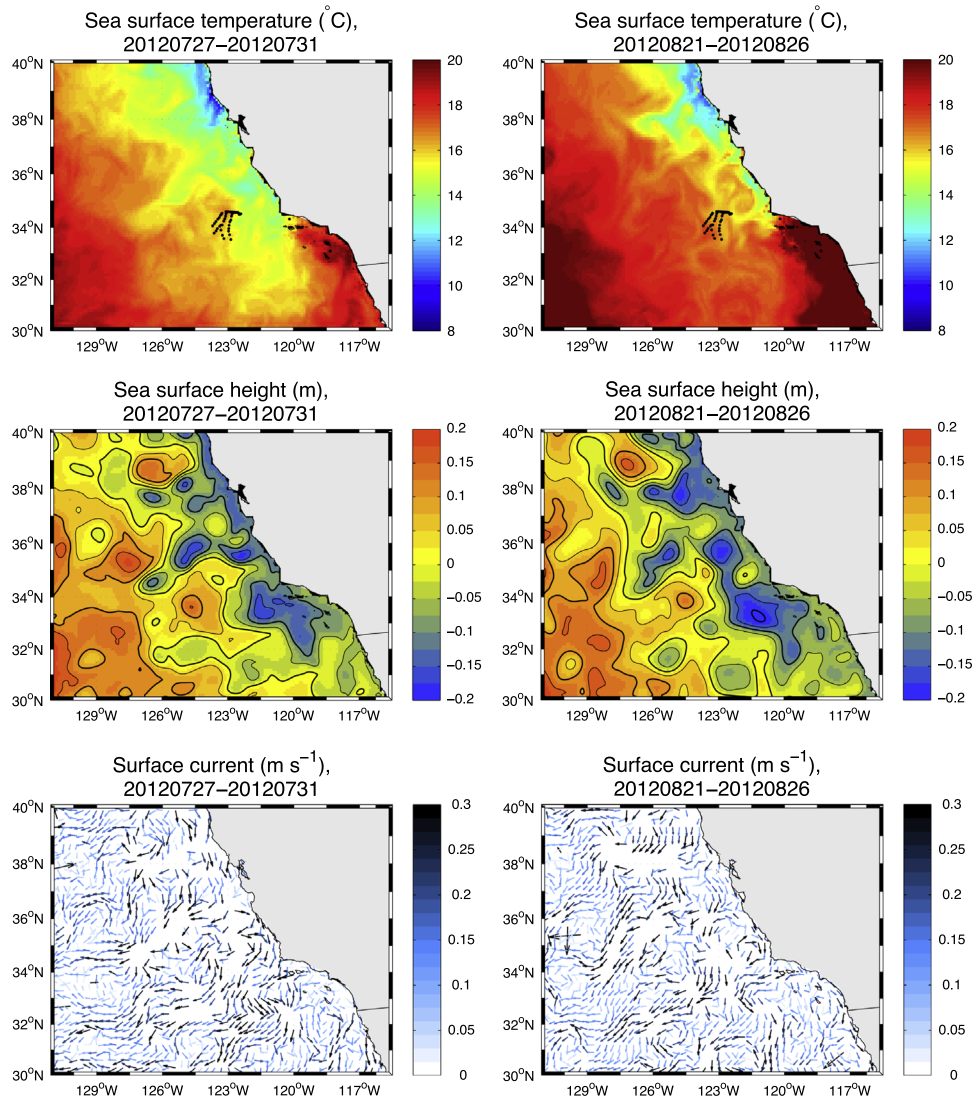

Fig. 8. Physical oceanographic evolution during 2012 CCE-LTER Process cruise time interval as represented by a four-dimensional variational (4Dvar) data assimilation fit. (left) July 27–31 average and (right) August 21–26 average of (top) SST, (middle) Sea-level height and (bottom) surface currents. Station locations for this Process Cruise are indicated by dots in upper-left SST plot.

A-Front and a special journal issue was devoted to analyses of biophysical consequences of this frontal feature (Landry et al., 2012).

The 2009 Student Cruise (Stukel, 2009) was launched under neutral tropical conditions, but with weakly negative PDO and weakly positive NPGO states, suggesting upwelling favorable flows in the CCS (Bjorkstedt et al., 2010). The fit (Fig. 6) reveals very cool waters in mid-April around Point Conception that are advected southward across Line 80 due to a meandering southward surface flow. Although this southward flow persisted into mid-May, the surface waters warmed considerably due to surface heating, especially in the coastal regions of the SCB. No strong evidence of a developed SCE is apparent in the fits. The sea level height maps reveal a strong anticyclonic eddy, with a signature of warmer SST, just west of the cool waters advected in from the upwelling zones. Stations chosen for the Student Cruise during this time interval sampled both sides of this strong frontal area.

The next Process Cruise was in June–July 2011 (Landry, 2011) and occurred with positive NPGO and slightly negative PDO states, and under neutral ENSO conditions, indicating a tendency for favorable upwelling flows in the CCS. Persistently strong anticyclonic wind anomalies over the eastern North Pacific contributed to the enhanced upwelling (Bjorkstedt et al., 2012). The fit (Fig. 7) reveals strong southward flow from upwelling conditions around Point Conception bringing cool waters into the regions west of the Channel Islands where the stations were located. The sea level height map reveals a chain of eddies all along the CCS. The fit reveals warming surface waters in the SCB, with no evidence of a developed SCE.

The most recent Process Cruise was in August 2012. Positive NPGO and negative PDO states prevailed, indicating a continuing propensity for favorable upwelling flows in the CCS (Wells et al., 2013). This summer cruise, however, was launched during warm tropical conditions, which may have increased the upper ocean stability through warming and pycnocline deepening. The fit (Fig. 8) exhibits eddying southward flow around the regions where the stations are located. Cruise participants launched drifters in the southward flowing region between the large offshore anticyclonic eddy and inshore cyclonic eddy situated along 34N. Very warm surface waters developed over this time period in the SCB, with some evidence of a developing SCE in the sea level height map.

5. Summary

Physical oceanographic and climatological conditions in the CCS varied widely (Figs. 1 and 2) since the inception of the CCE-LTER observational time series. The CCE-LTER project commenced in 2004 in the midst of normal ocean conditions near the climatological means, with no strong climate anomalies in place. Over the following decade, ENSO conditions flickered weakly from warm to cold, with perhaps an increase in amplitude of the variations in the later years. PDO generally tracked that behavior, while NPGO went from nearly normal conditions at the outset of CCE-LTER, to weakly negative values in 2005, 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.

During the past decade, many important new ideas and surprising observations have arisen that changed the way the CCS is viewed. The dynamical developments range from identifying ocean instability processes that lead to submesoscale structures in the CCS to recognizing large-scale coherencies in winds that drive basin-scale currents and upwelling associated with the North Pacific Gyre Oscillation. These physical mechanisms, along with the many others that were summarized in this study, have impacts on the ecological variations that may be strong or subtle (e.g., Capet et al., 2008a,2008b; Di Lorenzo et al., 2008).

Relating these observed environmental variations to the CCE-LTER biological dataset will provide a long-term perspective of how changing climate conditions control the ocean ecosystem in this region (e.g., Ohman et al., 2013a). Data assimilation fits (Figs. 3–8) of the physical variables observed during the CCE-LTER Process Cruises provide detailed information about how the ocean flows evolved during the course of the six multi-week cruises. Linking these structures to specific details of the biological fluxes measured in situ will give a quantified mechanistic link between mesoscale eddies and biological responses (e.g., Franks et al., 2013). Tying together all the intricate variations of the physical oceanography with the large-scale climate forcing and the numerous biological measurements gathered by the CCE-LTER will prove to be challenging. However, this work is essential if we are to develop the capacity to predict the response of the CCE to global climate change (e.g., Auad et al., 2006; Kim et al., 2009; Rykaczewski and Dunne, 2010; Ito et al., 2010; Doney et al., 2012). The observational program of the CCE-LTER will clearly be a focal point in this endeavor because it will likely provide indications of the mechanisms involved in other oceanic regions around the globe as they respond to global change, and will certainly influence the strategies employed for similarly monitoring and diagnosing physical–biological interactions under changing climatic conditions.

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