Status of the California Current Ecosystem: Major EBM Drivers and Pressures

Main Findings

- The CCLME is highly influenced by the southward flowing California Current. The CCLME is exhibiting natural interannual and multidecadal variability, but also undergoing changes in temperature, sea level, and upwelling consistent with anthropogenic global warming models. Time series correlations have confirmed that CCLME predator and prey populations are primarily driven by bottom-up physical oceanographic signals. Further understanding and incorporating the physical forcing in ecosystem models will improve our management of CCLME fisheries.
- Broad CCLME indices such as the North Pacific Gyre Oscillation (NPGO), PDO, MEI, Northern Oscillation Index (NOI), and the Cumulative Upwelling Index (CUI) have all shown an increasing trend over the past 50 years including increased interannual variability.
- Over the past 50 years, the CCLME shows general increasing trends in sea surface temperature in Monterey Bay, California, Newport, Oregon, and the Southern California Bight; sea level from Cape Flattery, San Francisco, and San Diego; and surface chl *a* throughout most of the CCLME.
- Long-term ocean time series have trended towards lower dissolved oxygen (DO) in the upper pycnocline, from Southern California to Oregon. Shoaling of the hypoxic boundary in parts of the CCLME may lead to habitat compression. Hypoxic events on continental shelf hypoxia have become more common off Oregon and can have lethal consequences for coastal benthic species.
- Over the past 5 years, intense upwelling was documented in 2006 to 2008. A cool phase since 1999 continued to be observed in both low PDO and high NPGO values. From late 2009 to early 2010, downwelling favorable conditions were dominant due to a short duration El Niño. The El Niño was quickly followed by increased offshore transport with La Niña conditions in summer of 2010. Resultant increased upwelling and productivity are likely to persist through mid-2011.

EBM Driver and Pressure: Climate

Physical Drivers and State Variables

Large scale climate forcing

PDO—This is a low frequency signal in North Pacific sea surface temperatures that affects biological productivity in the Northeast Pacific. Cold (negative values of the PDO) eras are associated with enhanced productivity in the CCLME and vice versa. The PDO index (Figure 32) has been largely in a positive (i.e., warm California Current and Northeast Pacific) state since late 1977, resulting in warmer waters along the coast of the CCLME with negative periods from 1998 to 2002 and 2006 to 2008. Over the past 5 years, the winter index declined from 2005 to 2009 with a sharp increase in 2010. The summer index was more stable with a sharp trough in 2007.

MEI—The index describes ocean-atmosphere coupling in the equatorial Pacific. Positive (negative) values of the MEI represent El Niño (La Niña) conditions. El Niño conditions in the CCLME are associated with warmer surface water temperatures and weaker upwelling winds. The MEI also had an increasing trend, with more positive values since 1977 (Figure 32). Most recently, the MEI had a relatively strong negative value in the winter of 2008 indicating more productive, greater upwelling, La Niña conditions. The MEI switched to positive suggesting El Niño conditions in the beginning of 2010, which switched to a negative value in the summer of 2010. Projections indicate continued La Niña conditions through mid-2011.

NPGO—This is a low frequency signal in sea surface heights over the Northeast Pacific. Positive (negative) values of the NPGO are linked with increased (decreased) surface salinities, nutrients, and chl *a* values in the CCLME. Since 1975 there have been more extreme and longer duration events with positive NPGO values than earlier in the time series (Figure 32). Winter and summer trends were very similar with a broad low from 1991 to 1997 and a peak from 1998 to 2004. Since 2006 values have been increasing with one near 0.0 year in 2009.

NOI—This index of sea level pressure difference between the North Pacific High and Darwin, Australia, describes the strength of atmospheric forcing between the equatorial Pacific and the North Pacific, particularly in terms with ENSO. Positive (negative) values are associated with cooler (warmer) SST in biologically important regions of the CCLME. NOI was largely positive from 1950 to 1977, but switched to more negative values until 1998 (Figure 32). In the winter, NOI values were positive from 2006 to 2009 with a drop and overall negative trend in 2010. In summer 2010, NOI values became strongly positive, which should result in increased coastal upwelling in the California Current.

CUI—This is an index of the cumulative upwelling. Upwelling has been variable, with an apparent general increase in NOAA's west coast upwelling index (Schwing and Mendelssohn 1997). The 2005 upwelling season was unusual in terms of its initiation, duration, and intensity. In 2005 upwelling was delayed or interrupted and SSTs were approximately 2–6°C warmer than normal (GRL 2006). The situation in the southern ecoregion was different in both 2005 and 2006, as average upwelling and SST prevailed (Peterson et al. 2006). Other than a brief period

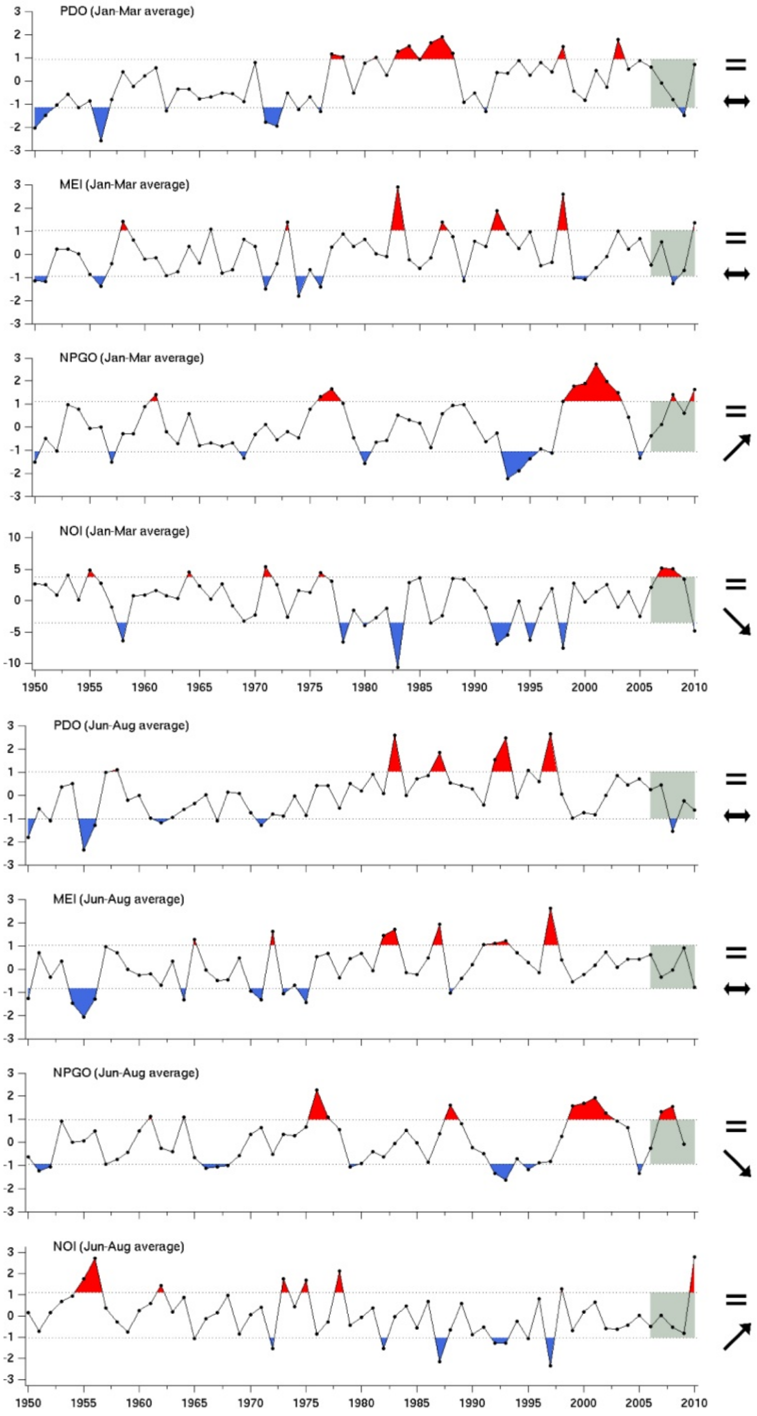

Figure 32. Winter (January-March) and summer (June-August) averages of PDO, MEI, NPGO, and NOI. Dashed lines reflect 1 SD above and below the long-term mean. Positive/negative PDO values indicate warm/cool eastern North Pacific SSTs. Positive/negative MEI values reflect El Niño/La Niña events. Positive/negative NPGO values indicate a strong/weak North Pacific Gyre and increased/decreased advective transport from the north into the CCLME. Positive/negative NOI values indicate a cooler/warmer SST in the biologically important regions of the CCLME. On the right side of each line chart, the equal sign indicates that the 2006–2010 mean is within the long-term SD; the up, down, and horizontal arrows indicate whether the 2006–2010 trend is above, below, or within 1 SD.

of weaker than normal upwelling in the summer of 2008, west coast upwelling has been increasing since the late summer of 2006 (Figure 33). Wind patterns in early 2009 reflect anomalously strong high pressure over the Northeast Pacific and very high upwelling while early to mid 2010 appears to be a below average upwelling year at lat 35–45°N.

Large scale physical and biological conditions

SST—Cold upwelled water often results in high productivity but nutrient content depends on remotely forced state of the ocean, which can be indicated by large-scale climate indices (NPGO, PDO, MEI, and NOI). Negative NPGO, positive PDO, and positive MEI would act in concert to create an extremely warm, low-productivity regime in the CCLME. According to many long-term data sets, SSTs have increased by 0.5°C to 1.0°C over the past 50 years (IPCC 2007). SST from three NOAA National Data Buoy Center (NDBC) buoys showed highs in 1983 and 1998 corresponding with increased MEI values (Figure 34). North of Cape Mendocino (excluding buoy C), winter SST values showed a cool, productive period from 1999 to 2002, changing to a warm, relatively unproductive period from 2003 to 2006. South of Cape Blanco, buoys B and C show a declining trend in SST from 2006 to 2010. From 1999 to 2008, spatial patterns in winter SST show a zonal gradient from warm in the south to cold in the north. In the summer, upwelled waters result in cooler SSTs hugging the coast north of Cape Mendocino, while the Southern California Bight shows no appreciable cooling from upwelling.

Winds—Northerly winds in the CCLME result in offshore transport and upwelling of cold, nutrient rich water into the photic zone. In the winter, meridional (north/south) winds were consistently northward in 1998 and 2010, indicative of downwelling favorable conditions (positive MEI and NOI; Figure 35). In winter 2006, winds were also indicative of downwelling although less extreme than 1998 and 2010. In summer 2006 and winter 2007, there were highly favorable upwelling winds at the northern buoys (A and B). In summer 2010, upwelling favorable winds dominated all three buoys. Spatial patterns in winter winds show a change in a direction from upwelling favorable above lat 42°N to downwelling favorable south. A local maximum in northerly winds was between long 120 and 125°W and below lat 35°N. In the summer, the CCLME consists of entirely northerly winds with a peak at lat 39°N and long 124°W near buoy B.

Sea level—Sea level heights are used as proxies for nearshore surface current strength and direction. In the winter, sea levels are high due to the poleward flowing counter current (Davidson Current). With the onset of upwelling winds in the spring, sea levels lower and the current is directed equatorward; the equatorward flow is dominant in the spring and summer. Since 1950, there has been an increasing trend particularly until 1977 with subsequent higher interannual variability and more numerous positive anomalies (Figure 36). Over the past five winters, station 1 showed an increasing trend since 2006 while all three stations had high values in 2010. For the past five summers, sea level height has declined with 2010 a particularly low year.

Hypoxia—The northern CCLME has had increased continental shelf hypoxia and shoaling of the hypoxic boundary resulting from enhanced upwelling, primary production, and respiration. Severe and persistent anoxic events have had downstream effects on both demersal fish and benthic invertebrate communities off Oregon. For example, during a severe anoxic

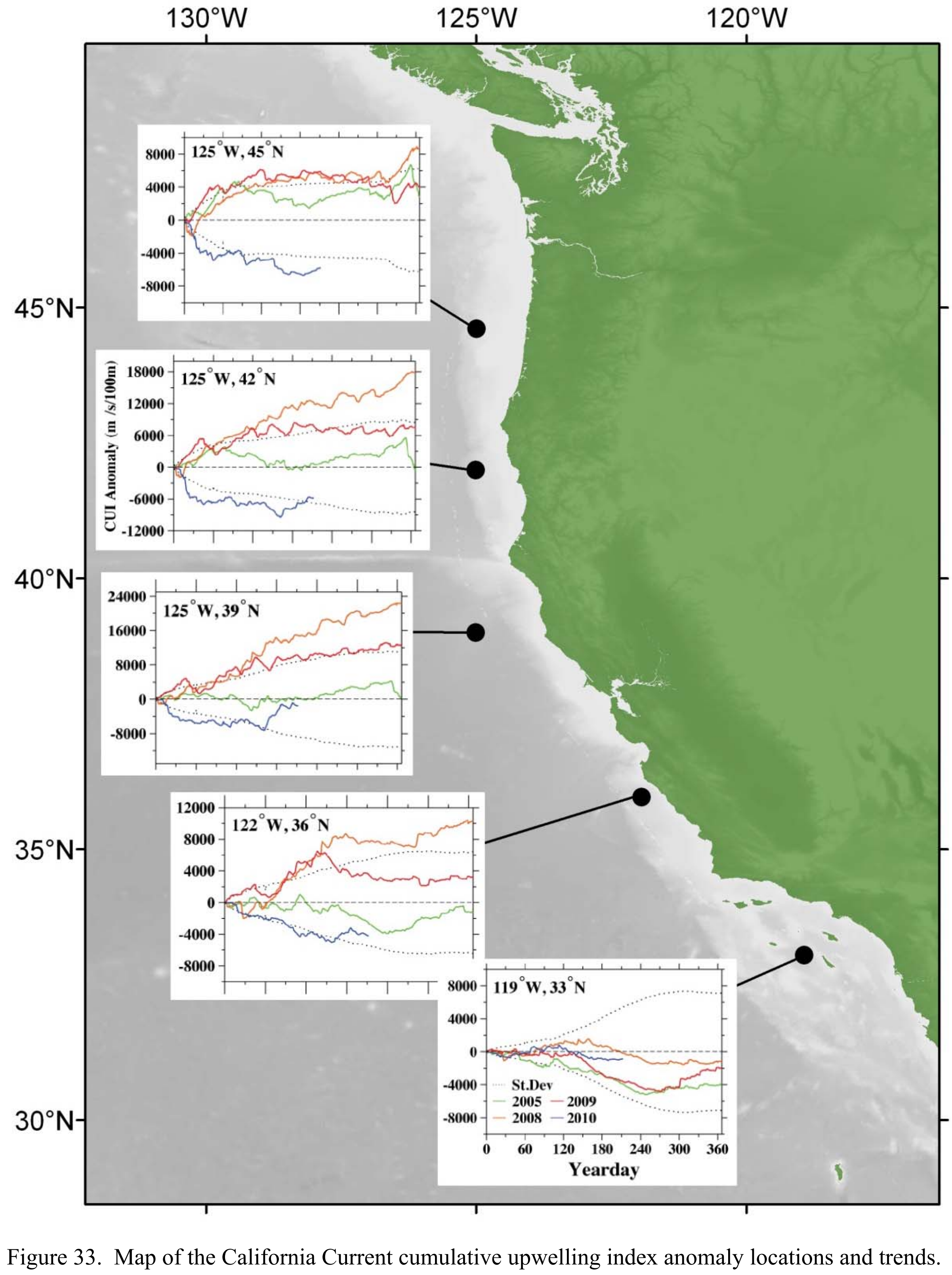

Figure 33. Map of the California Current cumulative upwelling index anomaly locations and trends. Filled circles represent the position of measurements, while each inset plot shows the difference from mean upwelling since 1967. Years 2005 (anomalous late), 2008 (normal), 2009, and 2010 are shown for reference.

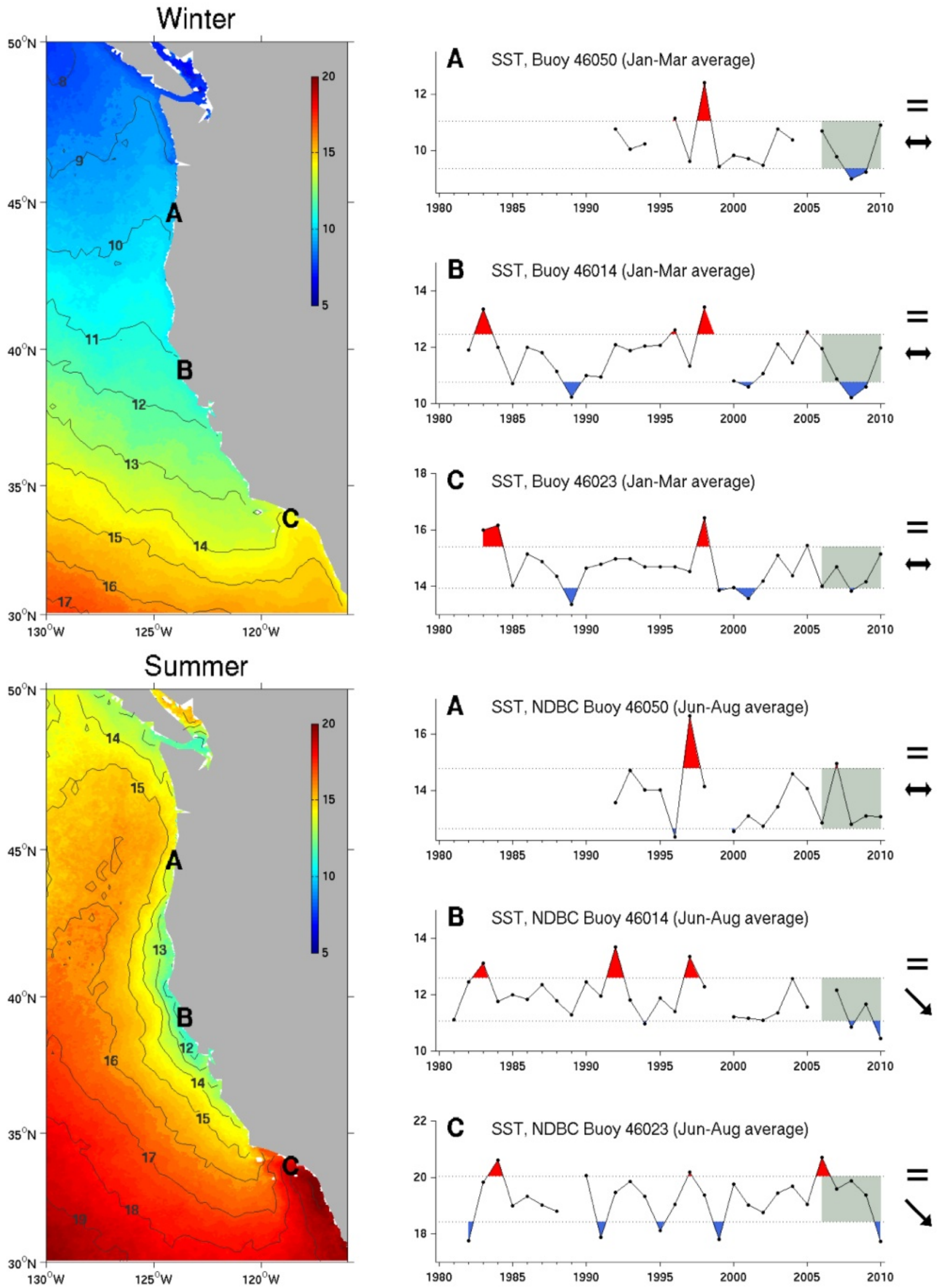

Figure 34. Winter and summer spatial means of Pathfinder SST (1999–2008) and SST time series from NDBC buoys. The locations of the NDBC buoys where the SST time series are taken from are labeled with the letters A, B, and C. All values on the figure have units of degrees Celsius. On the right side of each line chart, the equal sign indicates that the 2006–2010 mean is within the long-term SD; the down and horizontal arrows indicate whether the 2006–2010 trend is below or within 1 SD.

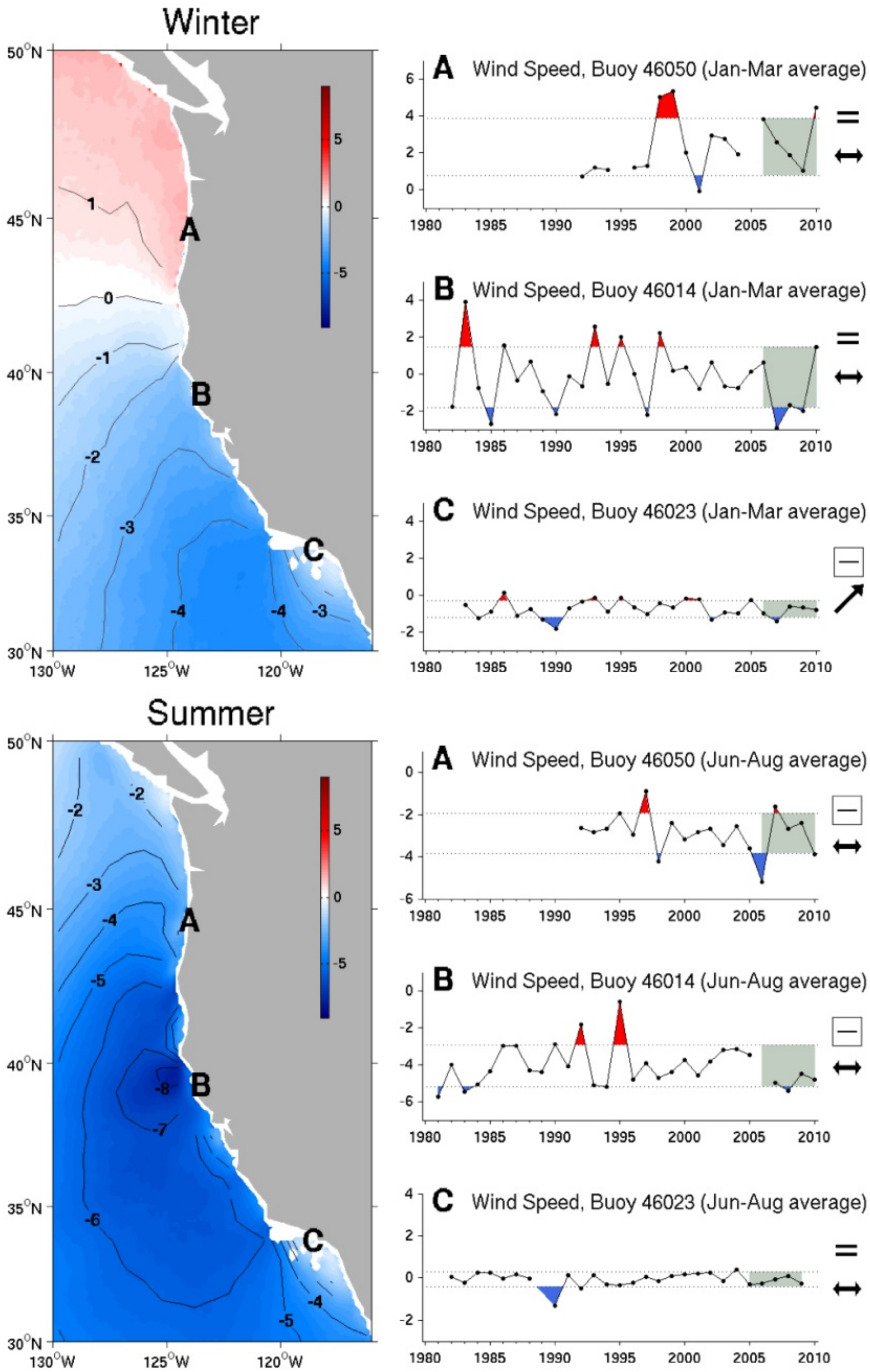

Figure 35. Winter and summer spatial means of QuikSCAT meridional winds (1999–2008) and meridional winds time series from NDBC buoys. Positive values indicate southerly winds and negative values indicate northerly, upwelling favorable winds. The locations of the NDBC buoys where the SST time series are taken from are labeled with the letters A, B, and C. All values on the figures have units of meters per second. On the right side of each line chart, the minus and equal signs indicate whether the 2006–2010 mean is below or within the long-term SD; the up and horizontal arrows indicate whether the 2006–2010 trend is above or within 1 SD.

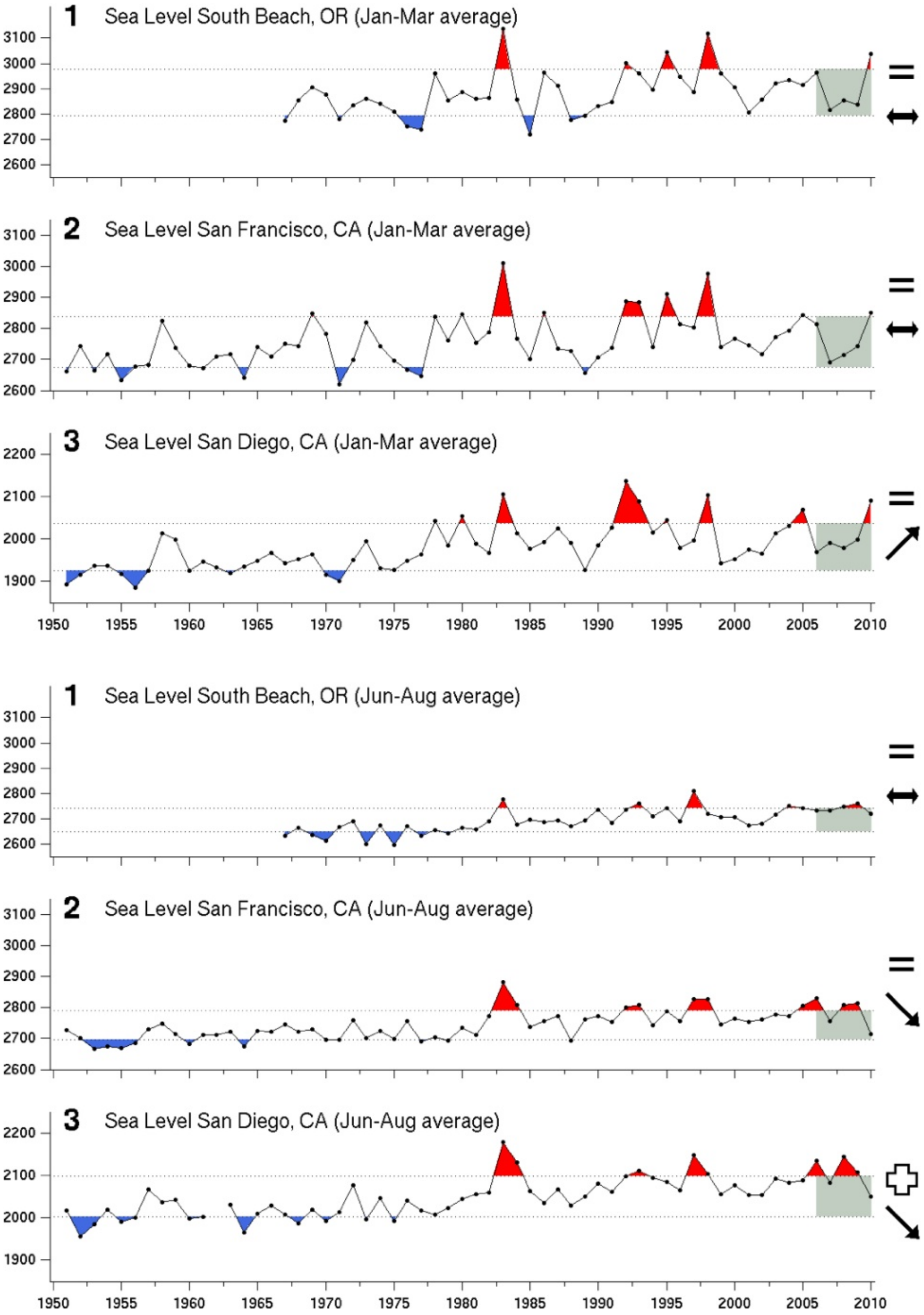

Figure 36. Winter (January-March) and summer (June-August) of sea level heights at three locations in the CCLME. All values on the y-axes have units of millimeters. On the right side of each line chart, the plus and equal signs indicate whether the 2006–2010 mean is above or within the long-term SD; the up, down, and horizontal arrows indicate whether the 2006–2010 trend is above, below, or within 1 SD.

event in August 2006, surveys found an absence of rockfish on rocky reefs and a large mortality event of macroscopic benthic invertebrates (Chan et al. 2008). Seasonality in oxygen concentrations shows summer hypoxia and well oxygenated winter waters along the Newport Hydrographic Line since September 2005. Strong summer upwelling in 2006 resulted in near anoxic water upwelled onto the shelf (Figure 37). In 2007 low oxygen concentrations were a result of relatively strong upwelling off Oregon. Despite higher than average upwelling in 2008, boundary waters remained well oxygenated save two occasions.

In the southern CCLME, deepening of the thermocline and decreased oxygen in deep source waters have resulted in increased subsurface oxygen depletion (Bograd et al. 2008, Figure 34). Large-scale wind forcing models predict hypoxia will continue to expand under Intergovernmental Panel on Climate Change warming scenarios (Rykaczewski and Checkley 2008).

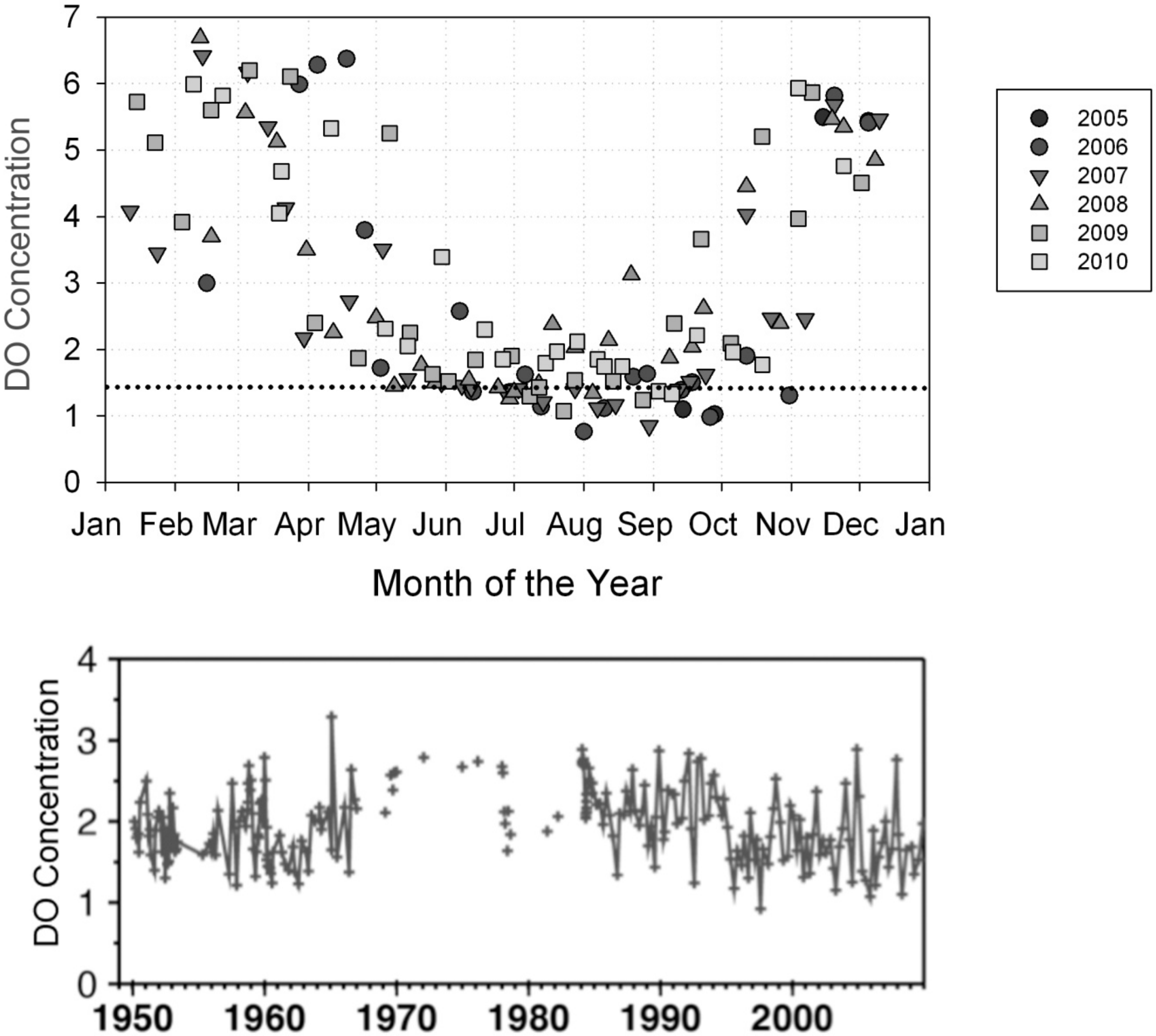

Figure 37. Dissolved oxygen concentrations (ml • L^{-1}) off the coast of Newport, Oregon, at 50 m depth at Newport Hydrographic Line Station NH 05 (upper chart). Dissolved oxygen at 200 m depth from the CalCOFI grid station 93.30 that is located off the coast of San Diego, California (lower chart).

Implications of Climate Drivers for Coastal and Marine Spatial Planning

There are regional differences within the CCLME in climate forcing and ecosystem response (Figure 32 through Figure 36). Therefore, an assessment of the southern California Current region may vary from that for the northern California Current (Figure 1). When considering an overall IEA for the CCLME, it may prove most useful to evaluate each ecoregion/subecosystem separately initially. But in no single region are all the physical and especially biological attributes available for comprehensive analyses. Therefore, to understand ecosystem form, function, and control, we must combine information between regions with the goal for a uniform CCLME IEA. The IEA is spatially and temporally targeted for specific management foci; thus IEA evaluations will be scenario driven as a function of the management strategies being evaluated.

The northern CCLME is dominated by strong seasonal variability in winds, temperature, upwelling, and plankton production. In addition to weak, delayed, or otherwise ineffectual upwelling, warm water conditions in this region could result from either onshore transport of offshore subtropical water or northward transport of subtropical coastal waters. Low copepod species richness and high abundance of northern boreal copepods (Figure 25) is apparently associated with cold, subarctic water masses transported to the northern CCLME from the Gulf of Alaska. Therefore, copepod community composition may be used as an indicator of this physical oceanographic process.

Preliminary evidence suggests covariation between ecoregions. As an example, when fatty, subarctic northern boreal copepods are present in the northern CCLME during cool water conditions, the productivity of the planktivorous Cassin's auklet in the central subregion increases. Conversely, when the less fatty subtropical copepods dominate the system in warm water years (i.e., a higher southern copepod index), Cassin's auklet breeding success is reduced (Bograd et al. 2010). Because patterns in northern copepods affect central bird species, it is important to perform analyses across boundaries and ecoregions.

As noted previously, there are regional differences in oceanography and biology. Moreover, within each region, there are differences in habitats that may be related to bathymetry and geology. Understanding the relationships between topography, oceanography, species distributions, and interactions will promote better management of CCLME resources spatially as well as temporally. The relationships between bottom topography and ecosystem productivity are not well known, but so-called benthic-pelagic coupling is likely to be an important driver for top predators. Identification and assessment of predictable locations of high species diversity and increased trophic interactions can serve as an important science basis for coastal and marine spatial planning and a common currency to assess trade-offs across sectoral uses of CCLME regions.

Effects of Anthropogenic Climate Change

Ocean temperatures have increased and are likely to continue to increase for the foreseeable future. Land is expected to heat faster than the ocean and these contrasts in temperatures may result in higher wind speeds (Bakun 1990, Snyder et al. 2003). Warmer waters are also increasing stratification (Roemmich and McGowan 1995, McGowan et al. 2003).

The effects of stronger winds and increased stratification on upwelling, temperature, and primary productivity in the CCLME are not well known (but see Schwing and Mendelssohn 1997, Mendelssohn and Schwing 2002), yet clearly will have ecosystem consequences beyond warming surface temperatures.

The timing of the seasonal cycle of productivity is changing (GRL 2006). Just as terrestrial biological systems are experiencing earlier phenology (IPCC 2007), we may observe an earlier (or later) start to the upwelling season in the CCLME, and these patterns may vary by ecoregion. If upwelling occurs earlier, this could result in an earlier seasonal cycle, from earlier phytoplankton blooms to earlier peaks in zooplankton abundance. In contrast, as noted previously, if the efficacy of upwelling is weakened or delayed by increased water stratification, the seasonal cycle of different organisms may be offset, leading to mismatches among trophic levels in both abundance and availability of prey.

With these contrasting scenarios in mind, the potential for increased interannual variability in the CCLME is probable. A more volatile climate with more extreme events will impact biological systems of the CCLME. Notably, by 2030 the minimum value of the PDO is expected to remain above the mean value for the twentieth century. In addition, evidence of variability and declines in biological systems in the CCLME since about 1990 has already been shown. Such changes and others (e.g., range shifts in species' distributions) are likely to continue.

Linkages between Climate Drivers and some EBM Components

We examined the hypothesis of covarying trends in physical and biological attributes of the CCLME. In summary, most of the time series exhibited significant trends or change in variability over time, and covariance with other measurements, thereby supporting our hypothesis. This indicates there has been substantial ecological change in the CCLME, spanning multiple trophic levels. Moreover, many of the biological changes are related to physical conditions of the ecosystem in a manner consistent to expectations under global warming. For the biological components investigated, with few exceptions, this generally meant a decline in abundance or productivity and in some cases an increase in variance. Increased variance results in higher standard error on management targets, potentially requiring more precautionary management of stocks and resources.

Of particular importance is the recent substantial decline of coho salmon survival off Oregon and the dramatic plunge of Chinook salmon escapement in California in 2007 and 2008 after a peak in 2002. Related to this observation is the reproductive failure of Farallon Island Cassin's auklets in 2005 and 2006 after gradually improving reproductive success throughout the 1990s and early 2000s to a peak in 2002. Previously, changes in seabirds and salmon in central California have been related to one another (Roth et al. 2007), although the salmonid declines lag changes in other fish and birds by at least one year. Sydeman et al. (2006) and Jahncke et al. (2008) suggested that the decline in auklet breeding success in 2005 was tied to a reduction of prey abundance (euphausiid crustaceans) due to atmospheric blocking and weak upwelling, but the results in these papers were not conclusive due to limited information on the prey. Chinook salmon are known to feed directly on euphausiids (Brodeur 1990), particularly during their initial time at sea, as well as forage fish such as Pacific herring (Brodeur and Pearcy 1992), which are known to prey on euphausiids (Foy and Norcross 1999). The abundance and availability of euphausiids to these predators is undoubtedly related to oceanographic processes, such as upwelling and possibly currents, but to date the environmental forcing of these important zooplankton remains largely unknown.

We found no association between the abundance of *Thysanoessa spinifera* larvae from British Columbia and auklets or salmon in California, but that is not surprising given the distance between regions. These top predator species appear sensitive to variation in the abundance of prey, which are highly dependent on climatic and oceanic conditions, but linkages have been difficult to establish and may have more to do with spatial availability of prey rather than prey abundance. However, declines in the relative abundance of forage fish (juvenile rockfish, herring, and juvenile hake) were recorded and related to changes in salmon and seabird populations and productivity. Thus it is clear that predator-prey relationships are key to understanding recent failures in these species and that marine climate variability is playing a role in driving predator-prey interactions.

EBM Driver and Pressure: Fisheries

Work documenting the status and trends of fisheries affects on EBM components will commence in FY2011.

EBM Driver and Pressure: Habitat degradation

Work documenting the status and trends of habitat degradation and its effects on EBM components will commence in FY2011.

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NOAA Technical Memorandum NMFS-NWFSC-109

Technical background for an Integrated Ecosystem Assessment of the California Current

Groundfish, Salmon, Green Sturgeon, and Ecosystem Health

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April 2011

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service

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This document should be referenced as follows:

Levin, P.S., and F.B. Schwing (eds.) 2011. Technical background for an integrated ecosystem assessment of the California Current: Groundfish, salmon, green sturgeon, and ecosystem health. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-109, 330 p.

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