The California Current Integrated Ecosystem Assessment (IEA), Module II: Trends and Variability in Climate-Ecosystem State

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Final Report to NOAA/NMFS/Environmental Research Division

15 January 2010

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ABSTRACT

This report represents the second module in the development of an Integrated Ecosystem Assessment (IEA) for the California Current Large Marine Ecosystem (CCLME). IEAs are scientific tools for ecosystem-based management of the oceans (Levin et al. 2009), though relatively few have been developed (e.g., Kenny et al. 2009). Primary IEA goals are to assess human pressures and environmental forcing on the 'health' of large marine ecosystems. This IEA module focuses, in particular, on marine climate-ecosystem relationships in the CCLME over the past 50 years from the perspective of recent salmonid fisheries closures (Lindley et al. 2009) and seabird breeding failures (Sydeman et al. 2006) in the northern-central portion of the ecosystem. First, we present simple trend analyses of central tendency (mean) and variance of a balanced selection of pressure-state indicator variables (physical-biological). Second, to provide a holistic perspective on environmental and biological change we integrate these indicators, representing information from varying trophic levels from different regions of the CCLME.

We found increasing trends in the values of the North Pacific Gyre Oscillation, Multivariate ENSO Index, and Upwelling Index @ 39^{o}N, sea surface temperature (Monterey Bay) and sea level (San Francisco). Corresponding declines in plankton abundance (Southern California, Vancouver Island), and seabird, rockfish, and salmon productivity and/or survival (northern California, Oregon) from different regions show the LME-scale nature of change. We also found increasing interdecadal variance in SST, sea level, and some biological parameters. De-trended values of physical and biological indicators were well-related; de-trended local sea level correlated with all large-scale marine climate indices. The NPGO correlated with 9/13 biological indices, while intermediate physical oceanographic response variables (e.g., SST and sea level) did not show as many associations. Many biological indicators, regardless of where they were collected, were associated in a manner expected by a "bottom-up" trophic ecology conceptual model. We conclude that the CCLME is undergoing change in temperature, sea level, and upwelling in accordance with expectations under anthropogenic global warming, and that change in predator and prey populations is attributable to physical oceanographic marine climate signals. Climate change may have affected salmon and their fisheries leading to severe societal costs in recent years.

INTRODUCTION

The impacts of climate change on marine ecosystems are not well known (Richardson and Poloczanska 2008). Generally speaking, over the past 50-100 years, the maximal time period of most ocean studies programs, ocean temperatures have increased (Levitus et al. 2000, 2001). This trend is likely to continue for the foreseeable future (IPCC 2007), though there are understood to be significant regional variations in trends. Land is expected to heat more and faster than the adjacent ocean. The resulting contrasts in thermal gradients are expected to alter atmospheric pressure systems and coastal winds, with localized effects on upwelling and ocean circulation; this may be especially true for eastern boundary current systems such as the California Current (Bakun 1990). Warming ocean waters increase ocean stratification (Roemmich and McGowan 1995, McGowan et al. 2003, Palacios et al. 2004). Paradoxically, the effects of stronger coastal winds and increasing stratification may offset one another; potentially there could be little change in the actual flux of upwelling-derived nutrients to the photic zone and primary productivity, but this interaction has yet to be investigated. Regardless of the exact mechanisms of physical-biological interactions, there will be ecosystem consequences to ocean warming, changing winds, and altered circulation. The complexities and probable non-linearities of bio-physical relationships make it difficult to predict impacts, but investigations of empirical observational data may be revealing.

Indeed, ecosystem observations in the California Current Large Marine Ecosystem (CCLME) have shown remarkable changes in recent years. In 2005, the timing of the seasonal cycle of upwelling and productivity changed appreciably, with considerable ecosystem consequences from plankton to top predators (GRL Special Volume 2006). As in terrestrial ecosystems, species are experiencing changing phenologies in abundance and cyclical activities, and these changes may be related to both earlier as well as later starts to the upwelling season (Bograd et al. 2009). However, a synthesis of long-term change in both physical and biological attributes of the California Current has not been undertaken. Therefore, in this report, we examine the hypothesis that there are co-varying trends in physical and biological attributes of the California Current. This hypothesis has been examined to some extent by others (e.g., Field et al. 2006), but not in a comprehensive "ecosystem-wide" manner, nor from a "physics to predators" perspective. To examine this hypothesis we report on 20 time series of physical and biological conditions from various latitudes in the California Current, and evaluate each series for trends in a measure of central tendency (mean monthly or annual values) and variability (variance) of the monthly/annual parameter values. We also examine physical and biological datasets for cross-correlations in parameters that are expected to change with global warming. In particular, we investigate whether changes in biological variables are related to change in temperature, sea level, and circulation which are expected to change under IPCC climate change scenarios.

METHODS

STUDY ECOSYSTEM

The CCLME is a large, dynamic and spatially heterogeneous marine environment in the eastern North Pacific Ocean off the west coast of North America (Duda and Sherman 2002). It spans nearly 3,000 km of latitude, from approximately the northern tip of Vancouver Island, British Columbia, Canada to Punta Eugenia, Baja California, Mexico (Figure 1). Several major physical oceanographic processes, linked to variability in the atmospheric pressure cells that force winds and circulation, determine ecosystem structure, function, and services. These include *local effects* of coastal upwelling and *basin-scale* sub-arctic and sub-tropical water mass intrusions. From an oceanographic perspective, the CCLME is under influence from the northern and western Pacific, as well as the tropical eastern North Pacific.

ECO-REGIONS

The California Current is formed as the eastern leg of the North Pacific Gyre. The intensity of transport in the California Current is not well known, but probably varies by season, year, and decade. It fluctuates, in part, relative to the position and strength of the North Pacific Current/West Wind Drift, which traverses the sub-arctic North Pacific Ocean and bifurcates from British Columbia to northern Oregon into the Alaska and California currents. While Washington and southern British Columbia may be considered a "transition zone," we define the northern boundary of the CCLME as the northern tip of Vancouver Island, B.C., due to frequent upwelling along this section of the coastline in spring and summer (Allen et al. 2001, Yen et al. 2005). Based on physical and biological attributes, U.S. GLOBEC (1992) subdivided the CCLME into three distinct "sub-ecosystems": (1) southern British Columbia, Washington and Oregon to Cape Blanco; (2) Cape Blanco, southern Oregon, to Point Conception, California; and (3) southern California and Baja.

DATA SETS

Complete and detailed methods for all datasets can be found in Appendix 2; an abbreviated description of each dataset evaluated in this IEA is included below.

A. Physical Pressure Variables

The North Pacific Gyre Oscillation (NPGO) index, downloaded from http://eros.eas.gatech.edu/npgo/data/NPGO.txt, emerges from analyses of anomalies of Northeast Pacific sea-surface temperature and sea-surface height (Di Lorenzo et al. 2008). Positive values indicate a strong North Pacific gyre and advective transport from the north into the CCLME; negative values indicate a weak gyre and decreased southward transport.

The Multivariate ENSO Index (MEI) is based on six observed variables over the tropical Pacific. Negative values of the MEI represent the cold ENSO phase, (La Niña), while positive MEI values represent the warm ENSO phase (El Niño). Data were obtained at http://www.cdc.noaa.gov/people/klaus.wolter/MEI/table.html, from NOAA's Earth System Research Laboratory. In the CCLME, warm ENSO phases (positive MEI values) are associated with strong advection from the south and cold ENSO phases (negative MEI values) with weak northward transport.

Flow in the North Pacific, Alaska, and California Currents were calculated by Howard Freeland of Fisheries and Oceans Canada, from data collected by Argo profiling floats (http://www.argo.net/). Positive values indicate stronger flows, whereas negative values indicate weaker flows.

The Upwelling Index (UI) is calculated by NOAA's Environmental Research Division from estimates of the magnitude of the offshore component of the Ekman transport driven by wind stress. Positive values indicate upwelling while negative values indicate downwelling. Methods and details of computation are available from: http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/NA/how_computed.html.

B. Physical State Variables

Computation of the Pacific Decadal Oscillation (PDO) index was developed by Zhang et al. (1997). Data were downloaded from the Joint Institute for the Study of the Atmosphere and Ocean at the University of Washington. Methods and details of computation are available at http://jisao.washington.edu/pdo/PDO.latest. The PDO reflects SST for the entire North Pacific, including the CCLME, from > 20^{o}N.

Sea surface temperature (SST) data were collected from shore stations operated by the Shore Stations Program of Scripps Institution of Oceanography. Methods and data are available at http://shorestation.ucsd.edu/methods/index_methods.html. We selected SST data from Pacific Grove/Hopkins Marine Station in southern Monterey Bay (36.6^{o}N 121.9^{o}W) due to longevity and completeness of the series.

Sea level measurements (mm), compiled by the National Water Level Observation Network (NWLON), were obtained from the Center for Operational Oceanographic Products and Services (CO-OPS) (NOS 2008). We used monthly data, an average of daily values, from the San Francisco gauge (37.8^{o}N 122.5^{o} W). Methods and data were downloaded from the University of Hawaii Sea Level Center (http://uhslc.soest.hawaii.edu/).

C. Biological State Variables – Lower Trophic Levels

Satellite remotely-sensed chlorophyll concentration (mg m^{-3}) data were obtained from the Sea-viewing Wide Field-of-View Sensor (SeaWiFS; http://oceancolor.gsfc.nasa.gov/SeaWiFS/).

Monthly Level 3 mapped 9 km resolution data were provided by the NASA Goddard Space Flight Center (http://oceancolor.gsfc.nasa.gov/). We used monthly composites of 9x9 km pixels to assess changes in chlorophyll a; data were processed by Rob Suryan of Oregon State University. Here, we report on chlorophyll concentrations in a 9x9-km pixel centered on the Farallon Islands (37^{o} 42'N, 123^{o} 00'W) over the period 1998-2006.

Small plankton volume was measured from spatially averaged displacement volume of zooplankton sampled on the California Cooperative Oceanic Fisheries Investigation (CalCOFI) surveys off southern California (bounding box=27.1-35.1^{o}N, 117.3-124.9^{o}W). Filtering procedures are provided by Kramer et al. (1972); detailed methods are available from http://www.calcofi.org/newhome/cruises/sample_analysis.htm.

Zooplankton samples were collected along the Newport Hydrographic Line by NOAA's Northwest Fisheries Science Center. Copepod biomass was estimated by multiplying the number of individuals per m^3 by the known dry weight of the taxa. Biomass values were log-transformed, then the monthly average biomass and anomaly were calculated. The "northern/boreal" copepod index was calculated for three species with cold-water affinities. Methods from http://www.nwfsc.noaa.gov/research/divisions/fed/oeip/ka-hydrography-zoo-ichthyoplankton.cfm.

Biomass of larvae of the euphausiid *Thysanoessa spinifera* was estimated from samples collected from four stations in Barkley Sound (Vancouver Island, British Columbia). Median annual biomass was estimated from March to the following February to reflect the "biological year" on the basis of the beginning of spawning events.

D. Biological State Variables - Mid to Upper Trophic Levels

Abundance data of age-0 pelagic juvenile rockfish (*Sebastes* spp.) were collected in annual mid-water trawl surveys conducted by the National Marine Fisheries Service in May and early June from 1983-2007. Since 2004, the survey area has been from approximately the U.S./Mexico border to just south of Cape Mendocino, California. The 'Juvenile Rockfish Index' (JRI) was calculated after the raw catch was adjusted to a common age of 100 days to account for interannual differences in age structure.

The juvenile hake index was obtained from the stock assessment of Helser and Martell (2007, table 11a). Juvenile hake (longer than 30 mm) were collected as part of the NMFS juvenile rockfish survey described above (Sakuma and Ralston 1997). Catches of juvenile hake were transformed by $\log_e$(number/trawl+ 1). The index was based CPUE from the Monterey outside stratum only.

Forage fish prey brought to nests by Common murres (*Uria aalge*) on Southeast Farallon Island (SEFI) were identified by biologists from PRBO Conservation Science. The proportion of the diet composed of juvenile rockfish (all *Sebastes* spp.) was estimated by dividing the number of rockfish observed by the total number of forage fish identified each year. The long-term mean take of juvenile rockfish was calculated, and the annual data were expressed as an anomaly statistic (annual data – long-term mean).

Herring spawning biomass was estimated by the California Fish and Game Commission, and is reported each year in an annual "Final Supplemental Environmental Document for Pacific Herring Commercial Fishing Regulations" (http://www.dfg.ca.gov/marine/herring/ceqa.asp). From 1979-1989 and 2003-present, the spawning biomass estimate was derived from spawning deposition surveys in spawning grounds in San Francisco Bay. From 1990-2002, the estimate was derived from a combination of the results of the spawning deposition surveys and hydroacoustic surveys.

Data for herring fisheries landings are compiled by the California Department of Fish and Game (CDFG) from the weight of the catch (landings) recorded by fish buyers, markets, and canneries (Mason 2004), and published in the CalCOFI annual fisheries report.

The Oregon Production Index (OPI) is an index to the ocean survival (based on smolt-to-adult returns) for Coho salmon in Oregon. Data were obtained from tables in the Pacific Fishery Management Council's Preseason Report (http://www.pcouncil.org/salmon/salpre.html). The percent smolt-adult returns were calculated by the formula SAR=a/(b*1000)*100, where SAR is the percent smolt-adult return, a is the adult OPIH (thousands), and b is the total hatchery smolts released (millions).

The Central Valley Index (CVI) for Chinook salmon was obtained from the Pacific Fishery Management Council (http://www.pcouncil.org/salmon/salpre.html). Escapement values for the CVI extend through 2007, but were replaced with a similar 'Sacramento Index' in 2008. Because the two indices are highly correlated, we use a dataset compiled of fall escapement values from the CVI from 1970-2007, and the fall escapement value from the Sacramento Index for 2008.

Under contract with USFWS, a focal sample of breeding Cassin's auklet (*Ptychoramphus aleuticus*) was studied by PRBO Conservation Science at the breeding colony at Southeast Farallon Island to determine annual reproductive success, chicks fledged pair^{-1} (Sydeman et al. 2001). Individual nest sites were monitored (n=44 year^{-1}) at 1–7 day intervals for breeding activity. Fledging was assumed with departure of young from the nest site.

Data on Common murre (*Uria aalge*) mortality were collected from 32 beach segments, surveys conducted by the Gulf of the Farallones National Marine Sanctuary between Bodega Head and Año Nuevo (Roletto et al. 2003). Surveys for each beach were conducted at either two- or four-week intervals. Dead birds were quantified as the number of birds per kilometer of beach surveyed. More than 21,000 kilometers of beach were surveyed 1993-2008, with an average of 118 km/month.

California sea lion pup productivity was measured at southern California rookeries on several of the Channel Islands by aerial photography and ground counts since 1975. Since 1998, 126-mm format aerial photography has been used to count sea lion pups. Methods for data collection can be found in Lowry (1999). Non-decomposed dead pups were not distinguishable from live pups in the photographs and were included in the counts.

DATA PROCESSING AND ANALYSIS

For each dataset, we tested for trends by calculating the Spearman rank correlation coefficient over time using program STATA v. 8.2. For time series with only a single annual index, a linear regression coefficient was calculated to quantify change through time. We calculated and report summary statistics -- mean, sample size, standard deviation, and coefficient of variation (CV) -- on all variables that were collected over multiple decades. Change in variance over time was assessed by rank correlation analysis conducted on decadal CV for datasets that spanned at least four decades.

For each variable, we calculated residuals using a linear regression model to remove trends. In this manner, we decomposed the variance for each time series into the long-term trend and interannual signal. Then, using the residuals, we conducted cross-correlation analyses between physical and biological variable to test for the effects of marine climate on variables of interest. After detrending the physical datasets, we developed a "leading" index of physical conditions by averaging residuals from January through May of each year. For chlorophyll-a concentrations, we averaged residuals from April through August. For the Northern Copepod Index and Common Murre mortality, we averaged residuals for May through September. We selected these months as they represented appropriate 'seasons' for these variables. For all other biological variables, we used annual residuals. We used the residuals to test for relationships between each pairing of biological parameters to investigate the degree of co-variation between variables taken in different locations on multiple trophic levels. In this manner, we provide information on how ecosystem measurements taken in varying regions of the CCLME can be applied to other regions in this ecosystem.

RESULTS

Physical Indices

Many of the physical pressure-state indicators showed increasing trends and increasing variability. One is the NPGO (Fig. 2). Many of the NPGO 'events' since 1975 seem to have been more extreme or had a longer duration than those earlier in the time series. Correspondingly, variance in the NPGO in the 1990s and 2000s was greater than earlier in the time series (Table 3). The Multivariate ENSO Index (MEI) also had an increasing trend, with more positive values since 1977 (Fig. 3). Greater variance was seen in the middle of the time series (Table 3). The Upwelling Index at latitude 39^{o}N showed a significant, though shallow increase through time (Fig. 5). Sea surface temperature from the Pacific Grove (southern Monterey Bay) shore station showed a well-defined increase (Fig. 6), though there is little difference in the variation in SST between decades at this site (Table 3). There was an increasing trend for sea level at San Francisco (Fig. 7), but the interdecadal variance was consistent (Table 3).

Other indices showed no secular change, though none of the datasets had a negative trend. The Pacific Decadal Oscillation (PDO) showed no overall change in amplitude, but regime shifts were clear, with major shift changes around 1945 and 1975 (Fig. 4). Despite a hypothesized regime shift in the late 1990s, there is no conclusive evidence of this in the PDO index up through 2008. There were also no discernable trends in current strength for the Alaska Current, the North Pacific Current, or the California Current (Fig. 8), though interannual variability was clearly evident.

Predictably, there were many significant interrelationships amongst the physical variables, and all correlations were relatively strong (Table 7). All variables correlated with each other, with the exception of NPGO, which was associated only with sea level. Despite its weak correlations with physical parameters, the NPGO was the physical variable that correlated with the most biological variables. The NPGO correlated with five biological variables at $p<0.05$ (small plankton volume, Northern Copepod Index, euphausiid (*T. spinifera*) biomass, the Juvenile Rockfish Index, and the Coho salmon Oregon Production Index) and eight biological variables at $p<0.10$ (Table 8). Sea level in San Francisco correlated with all other physical parameters (Table 7). Though SST in Pacific Grove was correlated with MEI, PDO and sea level, it did not correlate with any biological variables (Table 8). Likewise, though sea level was a very good indicator of other oceanographic and atmospheric events, it correlated with only the Northern

Copepod Index and rockfish abundance in Common murre diet in the biological parameters (Table 8).

Lower Trophic Level Indices
Trends for lower trophic level indicators followed no particular pattern. Chlorophyll-a levels showed an increasing trend at the Farallon Islands, particularly since 2003 (Fig. 9). On the contrary, small plankton volume in the Southern California Bight showed a strong decreasing trend for all seasons, and variation in the measurements decreased across the time series (Fig. 10, Table 4). Overall, no change in the trend for northern copepods was evident, though two periods of significantly low abundance can be seen (Fig. 11). *T. spinifera* euphausiids had a declining trend for larvae biomass since 1991 (Fig. 12). Variance decreased across the time series for *T. spinifera* larvae, with less variance since 2000 (Fig. 12 and Table 4).

Chlorophyll-a concentrations did not correlate with any physical variables, and only correlated with California sea lion pup production in the biological set (Tables 8 and 9). The positive correlation suggests that when chlorophyll is more abundant, sea lion pups are also more abundant, and it is interesting that there were no correlations between chlorophyll-a and any other variables through fewer trophic levels than sea lions. Small plankton volume was strongly positively correlated with rockfish abundance (both measurements) and the Coho salmon Oregon Production Index (Table 9), suggesting that when small plankton volume is high, juvenile rockfish and Coho salmon are more abundant. The Northern Copepod Index was strongly correlated with three physical variables and three biological variables (Tables 8 and 9). Similar to results for chlorophyll-a, *T. spinifera* larval biomass correlated only with one variable, NPGO, out of the entire set of physical and biological parameters (Tables 8 and 9).

Higher Trophic Level Indices
Juvenile rockfish and other mid-trophic level fish tended to show a decreasing trend in abundance, whereas salmon and upper trophic predators such as seabirds and sea lions displayed a variety of patterns over time. Juvenile rockfish decreased over time (Fig. 14), but showed episodic productivity, with peaks around 1985 and 2002 and low abundance in the 1990s. Variation in the measurements followed these same patterns, decreasing over time and reflecting the peaks in success (Fig. 14, Table 5). Rockfish abundance in Common murre diets also showed an overall decrease over time, despite an increase from 2001-2004 (Fig. 15). Variance in this dataset was large at the beginning and end, the latter due to the peak in 2001-2004 (Table 5). The abundance of pre-recruit (age 0) hake had a decreasing trend since 1985 (Fig. 13). Herring spawning biomass exhibited a general decreasing trend over its time series, though there were occasional outliers of high biomass (Fig. 16). Variance increased (Table 5), attributable to the very high value in 2006. There was also a strong decrease in herring landings from 1977-2006, as well as a decrease in variation (Fig. 17).

Chinook salmon fall escapement had an increasing trend, though the values have plummeted since 2002 (Fig. 18); variance increased through time (Table 5). For Coho salmon, however, the percent smolt-to-adult returns showed a decline in trend and a decrease in variance since the 1970s (Fig. 19, Table 5). Cassin's auklets showed no overall change in reproductive success since the early 1970s, but increasing variation in success (Fig. 20, Table 5). Though there was no general trend, it is nonetheless crucial to note that reproductive success dropped severely from a peak in 2002, as did Chinook salmon fall escapement, and there was an unprecedented 0% reproductive success in 2005 and 2006 (Fig. 20). For Common murre mortality, an increase in the trend, particularly since 2002, was evident, and variance increased as mortality rose (Fig. 21, Table 5). An increase of abundance was readily apparent for California sea lion pups in Southern California (Fig. 22).

A number of higher trophic level parameters did not correlate with any physical variables, including hake pre-recruit abundance, herring spawning biomass, herring landings, Chinook salmon fall escapement, and Cassin's auklet reproductive success (Table 8). California sea lion pup production correlated with three physical parameters (Table 8), making it one of the best indicators of physical conditions that we examined. Herring landings and spawning biomass correlated only with each other (Table 9). The Juvenile Rockfish Index and Coho salmon Oregon Production Index each positively correlated with four biological parameters (Table 9).

DISCUSSION

Trends in Pressure-State Indicators

We examined the hypothesis of co-varying trends in physical and biological attributes of the California Current LME. In summary, most of the time series exhibited significant trends or change in variability in time, and co-variance with other measurements, thereby supporting our hypothesis. This indicates that 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 and/or productivity and in some cases an increase in variance.

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), though 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 upon euphausiids (Brodeur 1990), particularly during their initial time at sea, as well as forage fish such as herring (*Clupea pallasii*) (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 *T. spinifera* larvae from B.C., and auklet 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 in 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.

Integrating the Indicators

One of the promising results from our cross-correlation analysis is that January-May sea level correlated strongly with all other physical variables for the same period. Based on these results, sea level, as an easily obtained and interpretable measurement, appears to be an important pressure-state indicator as it integrates a variety of changes occurring in other physical environmental variable. It is also obtained at multiple locations in the CCLME, allowing for large- and local-scale assessments. However, sea level did not correlate with many of the biological variables. Instead, the January-May NPGO did well, correlating with most biological attributes (11/13 cases). We are uncertain why the NPGO is so well-related to the biological indices we selected for analysis. It could be that the NPGO integrates both upwelling and transport mechanisms, multiple processes which are known to influence biological productivity in the CCLME (McGowan et al. 2003).

The positive relationships we found between the Juvenile Rockfish Index and upper trophic level indicators is undoubtedly related to direct trophic links. Juvenile rockfish eat plankton such as copepods (Reilly et al. 1992) and Coho and Chinook salmon prey upon juvenile rockfish (Peterson et al. 1982, Emmett et al. 1986). Juvenile rockfish are also preyed upon by hake, and adult rockfish are also caught as bycatch in the hake fishery (Harvey et al. 2008). Given this information, a possible additional explanation for the positive correlation between juvenile hake abundance and the JRI could be that during hake fishery closures the abundance of adult rockfish increases due to decreased bycatch, but this is a complex mechanism. The increase in productive rockfish could lead to an increase in the abundance of juveniles, though the change in bycatch may be insufficient to cause a major change in the spawning biomass-recruitment relationship.

Other trophic relationships can also be seen in the cross-correlation analysis results. Associations between small plankton volume and juvenile rockfish (both measurements) and Coho salmon are expected since many prey species for those predators are encompassed in the small plankton volume dataset. Correlations between the Northern Copepod Index and hake abundance and Cassin's auklet reproductive success are also not surprising since copepods are important prey for both juvenile hake and auklets. The strong positive correlation between Chinook salmon fall escapement and the Coho salmon Oregon Production Index, both measurements of abundance, is interesting because it suggests that conditions that affect salmon abundance off the coast of Oregon and California do so for salmonids in general, rather than for one particular species or another.

It was somewhat surprising that relationships between physical variables and chlorophyll-a concentrations, and *T. spinifera* biomass, herring, and higher trophic level predators were not significant. Significant correlations are expected because of the well-known relationships - chlorophyll-a levels are highly dependent on ocean conditions and *T. spinifera* and herring serve as important food items for many predators. However, though some of the physical datasets are indices that cover vast geographical areas, many of the biological variables are specific to one small region or location. While all of the datasets together provide relatively thorough ecosystem-wide coverage, the difference in location (spatial mismatch) between many variables probably explains why certain correlations did not emerge from our analyses.

CONCLUSIONS

Many biological indicators, regardless of where they were collected, were associated in a manner expected by a "bottom-up" trophic ecology conceptual model, which previously has been suggested to be important for fisheries of the northern CCLME (Ware and Thomson 2005). Trends in measurements of central tendency and variance, coupled with cross-correlation analysis of inter-relationships indicate clear associations between environmental and biological change. We conclude that the CCLME is undergoing change in temperature, sea level, and upwelling in accordance with many expectations under anthropogenic global warming, and that change in predator and prey populations is attributable to physical oceanographic ‘marine climate’ signals. Climate change may therefore have affected salmon and their fisheries leading to severe societal costs in recent years.

ACKNOWLEDGEMENTS
We thank NOAA/Environmental Research Division and NOAA/Integrated Ocean Observing System for sponsoring this research. To all data contributors, agencies, and organizations listed Appendix 1, we offer our sincere gratitude for participating in this IEA effort. Finally, we thank Bill Peterson, Nate Mantua, Phil Levin, and Frank Schwing for reviewing and providing criticism on drafts of this document.

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Table 1. Trends in 21 physical and biological time series datasets for the California Current large marine ecosystem, noting name of time series, time resolution, sample size, trend through time, significance level, and rate of change. Bold indicates a significance of p<0.05. The table is organized by dataset type and general trophic level.

Dataset Name	Timespan	N	Spearman_rho	p>|t|	Regression Coefficient
Physical Indices					
North Pacific Gyre Oscillation Index	**1/1950-1/2008**	**697**	**0.1697**	**0**	
Currents, North Pacific					
Flow, Alaska Current	2/2002-4/2007	63	0.211	0.097	
Flow, West Wind Drift	2/2002-4/2007	63	0.0558	0.6641	
Flow, California Current	2/2002-4/2007	63	-0.1011	0.4305	
Upwelling Index, 39N	**1/1946-5/2009**	**761**	**0.1084**	**0.0027**	
Multivariate ENSO Index	**1/1950-5/2009**	**713**	**0.2176**	**0**	
Pacific Decadal Oscillation Index	1/1900-5/2009	1313	NA	NA	
SST, Pacific Grove	**1/1919-9/2008**	**1035**	**0.219**	**0**	
Sea Level, San Francisco	**1/1901-12/2004**	**1289**	**0.6983**	**0**	
Indices of Productivity					
Chlorophyll, Farallon Islands	**1/1998-12/2006**	**103**	**0.2809**	**0.004**	
Small Plankton Volume, July-September	**1951-2007**	**46**	**-0.5007**	**0.0004**	**-4.7813**
Northern Copepod Index	5/1996-9/2007	136	0.1426	0.0978	
Euphausiid Biomass (*T. spinifera* larvae)	**1991-2007**	**17**	**-0.6569**	**0.0042**	**-1.5006**
Juvenile Rockfish Index (mid-water trawls)	**1983-2007**	**25**	**-0.4546**	**0.0224**	**-1.2992**
Rockfish Index (Common Murre Diet)	**1975-2007**	**32**	**-0.581**	**0.0005**	**-0.0173**
Hake Log(Pre-recruit Abundance)	**1986-2006**	**21**	**-0.4792**	**0.0279**	**-0.1528**
Herring Spawning Biomass	**1979-2009**	**31**	**-0.4859**	**0.0056**	**-865.279**
Herring Landings	**1977-2007**	**31**	**-0.6544**	**0.0001**	**-206.1661**
Herring Landings Detrended	1977-2007	31	-0.0444	0.8127	
Predators					
Coho Percent Smolt-Adult Returns	**1970-2007**	**38**	**-0.6462**	**0**	**-0.1646**
Chinook Fall Escapement	**1970-2008**	**39**	**0.3526**	**0.0277**	**6088.627**
Cassin's Auklet Reproductive Success	1971-2007	37	-0.0937	0.581	
Common Murre Mortality	**10/1993-8/2008**	**179**	**0.2618**	**0.0004**	
California Sea Lion Pup Production	**1975-2007**	**33**	**0.9134**	**0**	**1365.667**

Table 2. Trends in 21 physical and biological time series datasets for the California Current large marine ecosystem organized by length of the time series by years. Bold indicates a significance of p<0.05.

Dataset Name	Timespan	Number of years	N	Spearman_rho	p>|t|	Regression Coefficient
Pacific Decadal Oscillation Index	1/1900-5/2009	109.42	1313	NA	NA	
Sea Level, San Francisco	**1/1901-12/2004**	**108.00**	**1289**	**0.6983**	**0**	
SST, Pacific Grove	**1/1919-9/2008**	**89.66**	**1035**	**0.219**	**0**	
Upwelling Index, 39N	**1/1946-5/2009**	**63.42**	**761**	**0.1084**	**0.0027**	
Multivariate ENSO Index	**1/1950-5/2009**	**59.42**	**713**	**0.2176**	**0**	
North Pacific Gyre Oscillation Index	**1/1950-1/2008**	**58.00**	**697**	**0.1697**	**0**	
Small Plankton Volume, July-September	**1951-2007**	**46.00**	**46**	**-0.5007**	**0.0004**	**-4.7813**
Chinook Fall Escapement	**1970-2008**	**39.00**	**39**	**0.3526**	**0.0277**	**6088.627**
Coho Percent Smolt-Adult Returns	**1970-2007**	**38.00**	**38**	**-0.6462**	**0**	**-0.1646**
Cassin's Auklet Reproductive Success	1971-2007	37.00	37	-0.0937	0.581	
California Sea Lion Pup Production	**1975-2007**	**33.00**	**33**	**0.9134**	**0**	**1365.667**
Rockfish Abundance (Common Murre Diet)	**1975-2007**	**32.00**	**32**	**-0.581**	**0.0005**	**-0.0173**
Herring Spawning Biomass	**1979-2009**	**31.00**	**31**	**-0.4859**	**0.0056**	**-865.279**
Herring Landings	**1977-2007**	**31.00**	**31**	**-0.6544**	**0.0001**	**-206.1661**
Herring Landings Detrended	1977-2007	31.00	31	-0.0444	0.8127	
Juvenile Rockfish Index	**1983-2007**	**25.00**	**25**	**-0.4546**	**0.0224**	**-1.2992**
Hake Log(Pre-recruit Abundance)	**1986-2006**	**21.00**	**21**	**-0.4792**	**0.0279**	**-0.1528**
Euphausiid Biomass (*T. spinifera* larvae)	**1991-2007**	**17.00**	**17**	**-0.6569**	**0.0042**	**-1.5006**
Common Murre Mortality	**10/1993-8/2008**	**14.92**	**179**	**0.2618**	**0.0004**	
Northern Copepod Index	5/1996-9/2007	11.33	136	0.1426	0.0978	
Chlorophyll, Farallon Islands	**1/1998-12/2006**	**8.58**	**103**	**0.2809**	**0.004**	
Currents, North Pacific						
Flow, Alaska Current	2/2002-4/2007	5.25	63	0.211	0.097	
Flow, West Wind Drift	2/2002-4/2007	5.25	63	0.0558	0.6641	
Flow, California Current	2/2002-4/2007	5.25	63	-0.1011	0.4305	

Table 3. Summary statistics for physical oceanographic indicators by decade.

Dataset	Time Period	Mean	N	Coefficient of Variation	Standard Deviation
North Pacific Gyre Oscillation Index	1950s	-0.3664	120		0.9241198
	1960s	-0.2209	120		1.007811
	1970s	0.4398667	120		1.045599
	1980s	0.013425	120		1.00361
	1990s	-0.6782417	120		1.299959
	2000s	1.035619	97		1.165986
Multivariate ENSO Index	1950s	-0.3047833	120		0.936799
	1960s	-0.1532833	120		0.705533
	1970s	-0.2800917	120		1.046969
	1980s	0.3831917	120		1.038509
	1990s	0.5615583	120		0.9969046
	2000s	0.0295487	113		0.6394618
Pacific Decadal Oscillation Index	1900s	0.2510833	120		0.7102122
	1910s	-0.0339167	120		0.6885136
	1920s	0.1466667	120		0.8615799
	1930s	0.4189167	120		0.9441227
	1940s	0.1840833	120		1.18809
	1950s	-0.6800833	120		1.139597
	1960s	-0.5383333	120		0.7326576
	1970s	-0.40425	120		0.9653986
	1980s	0.79825	120		0.8439659
	1990s	0.3345	120		1.147312
	2000s	-0.1199115	113		0.9492699
SST, Pacific Grove	1920s	12.30377	132	0.0782473	0.9627365
	1930s	13.1195	120	0.0911791	1.196224
	1940s	13.18851	108	0.0885514	1.167861
	1950s	13.12822	120	0.0942905	1.237866
	1960s	13.10582	120	0.0750101	0.9830695
	1970s	13.09378	94	0.0964299	1.262503
	1980s	13.51844	120	0.0894724	1.209527
	1990s	13.33044	119	0.1049757	1.399372
	2000s	13.60442	102	0.1022229	1.390683
Flow, North Pacific Current	2002-2007	0.6566381	63	0.0705111	0.0463003
Flow, Alaska Current	2002-2007	0.3992175	63	0.0834336	0.0333081
Flow, California Current	2002-2007	0.2574206	63	0.1270736	0.0327114
Sea Level, San Francisco	1900s	2612.185	108	0.0228321	59.64163
	1910s	2618.717	120	0.0226388	59.28456
	1920s	2610.367	120	0.0190816	49.80988
	1930s	2642.4	120	0.0196039	51.80124
	1940s	2673.277	119	0.023494	62.80599
	1950s	2695.308	120	0.0228994	61.72081
	1960s	2712.274	117	0.0232816	63.14606
	1970s	2712.735	117	0.0252421	68.47519
	1980s	2768.075	120	0.0301465	83.44768
	1990s	2780.9	120	0.028489	79.22518
	2000s	2765.269	108	0.0226884	62.73943

Upwelling Index, 39N	1946-1950s	60.91071	168	1.246589	75.93062
	1960s	70.84167	120	1.308345	92.68534
	1970s	104.1333	120	1.142723	118.9955
	1980s	83.3	120	1.279622	106.5925
	1990s	81.29167	120	1.316267	107.0016
	2000s	102.4513	113	1.068687	109.4884

Table 4. Summary statistics for lower trophic level indicators by decade.

Dataset	Time Period	Mean	N	Coefficient of Variation	Standard Deviation
Chlorophyll, Farallon Islands	1998-2006	2.939388	103	0.6826325	2.006522
Small Plankton Volume, July-September	1950s	310.8925	9	0.8663486	269.3413
	1960s	299.9629	9	0.475628	142.6708
	1970-1980s	182.9648	10	0.4286662	78.43081
	1990s	85.91662	10	0.3441613	29.56917
	2000s	134.8072	8	0.2724244	36.72478
Northern Copepod Index	1996-2007	-0.0468631	136	-24.51235	1.148725
Euphausiid Biomass (*T. spinifera* larvae)	1990s	19.19078	9	0.7134287	13.69125
	2000s	9.933375	8	0.8900768	8.841467

Table 5. Summary statistics for upper trophic level indicators by decade.

Dataset	Time Period	Mean	N	Coefficient of Variation	Standard Deviation
Juvenile Rockfish Index (CPUE in trawls)	1980s	32.71486	7	1.070453	35.01972
	1990s	2.5262	10	1.367985	3.455805
	2000s	4.74575	8	1.332391	6.323194
Rockfish Index (proportion in seabird diet)	1970s	0.7251446	4	0.4210403	0.3053151
	1980s	0.6049257	10	0.3593324	0.2173694
	1990s	0.1620068	10	0.7219701	0.1169641
	2000s	0.357624	8	0.9521104	0.3404975
Hake Log(pre-recruit abundance)	1986-1995	4.1026	10	0.4357636	1.787764
	1996-2006	2.694182	11	0.6344598	1.70935
Herring Spawning Biomass (tons)	1979-1989	58400	11	0.293913	17164.5
	1990s	51112	10	0.514944	26321.5
	2000s	38045	10	1.077042	40976.05
Herring Landings (MT)	1980s	6977.308	13	0.2936661	2048.999
	1990s	5436.4	10	0.543642	2955.455
	2000s	1752.375	8	0.8079673	1415.862
Coho Percent Smolt-Adult Returns (%)	1970s	6.888	10	0.4491344	3.093638
	1980s	3.566	10	0.4826848	1.721254
	1990s	1.314	10	1.059879	1.392681
	2000s	2.74875	8	0.372184	1.023041
Chinook Fall Escapement (number)	1970s	172159.5	10	0.2061531	35491.21
	1980s	204148.5	10	0.2754238	56227.36
	1990s	225657.4	10	0.5204946	117453.5
	2000s	391869.9	9	0.6057422	237372.1
Auklet Reproductive Success (number/pair)	1970s	0.7611111	9	0.08946	0.068089
	1980s	0.67	10	0.2638224	0.176761
	1990s	0.644	10	0.3652792	0.2352398
	2000s	0.61375	8	0.7507011	0.4607428
Common Murre Mortality (number/km)	1990s	0.2445333	75	1.352909	0.3308314
	2000s	0.3141346	104	1.318643	0.4142313
California Sea Lion Pup Production (number)	1975-1989	15581	15	0.2399777	3739.093
	1990s	30758.5	10	0.3152353	9696.165
	2000s	47768.25	8	0.1293285	6177.798

Table 6. Results of Spearman rank correlation analysis of coefficients of variation across decades for time series spanning at least four decades.

Dataset Name	N	rho	p>|t|
SST, Pacific Grove	9	0.65	0.0581
Sea Level, San Francisco	11	0.6	0.051
Upwelling Index, 39N	6	-0.1429	0.7872
Small Plankton Volume, July-September	5	-1	0
Rockfish Abundance (Common Murre Diet)	4	0.8	0.2
Coho Percent Smolt-Adult Returns	4	-0.2	0.8
Chinook Fall Escapement	4	1	0
Cassin's Auklet Reproductive Success	4	1	0

Table 7. Results of Spearman rank cross-correlation analysis for detrended January-May physical oceanographic variables. See text for analytical details. Listed are N (top), Spearman rho (center) and p>|t| (bottom). Bold indicates a significance of $p<0.05$.

	NPGO	MEI	PDO	Upwelling Index, 39N	SST, Pacific Grove
MEI	59 -0.1618 0.2209				
PDO	59 0.0139 0.9165	**60** **0.6458** **0.0000**			
Upwelling Index, 39N	59 0.2031 0.1229	**60** **-0.3458** **0.0068**	**64** **-0.3432** **0.0055**		
SST, Pacific Grove	57 -0.1650 0.2201	**57** **0.5393** **0.0000**	**87** **0.5128** **0.0000**	**61** **-0.5022** **0.0000**	
Sea Level, San Francisco	**59** **-0.5354** **0.0000**	**59** **0.4821** **0.0001**	**108** **0.3219** **0.0007**	**63** **-0.4828** **0.0001**	**87** **0.6472** **0.0000**

Table 8. Results of Spearman rank cross-correlation analysis on detrended biological and physical variables. Listed are N (top), Spearman rho (center) and p>|t| (bottom). Bold indicates a significance of $p<0.05$ and gray shading indicates $p<0.1$.

	NPGO	MEI	PDO	Upwelling Index, 39N	SST, Pacific Grove	Sea Level, San Francisco
Chlorophyll, Farallon Islands	9 0.0667 0.8647	9 -0.2833 0.4600	9 -0.2167 0.5755	9 -0.3167 0.4064	9 0.3000 0.4328	9 0.1500 0.7001
Small Plankton Volume, July-September	**46** **0.4091** **0.0048**	46 -0.1530 0.3100	46 -0.0349 0.8178	46 0.0976 0.5189	46 -0.1951 0.1939	46 -0.2506 0.0930
Northern Copepod Index	**12** **0.6643** **0.0185**	12 -0.5035 0.0952	**12** **-0.7902** **0.0022**	12 0.4895 0.1063	12 -0.2168 0.4986	**12** **-0.8042** **0.0016**
Euphausiid Biomass *(T. spinifera* larvae)	**17** **0.5490** **0.0225**	17 -0.0490 0.8518	17 -0.3971 0.1145	17 0.1397 0.5928	17 0.1667 0.5226	17 -0.0907 0.7292
Sebastes (all species) Relative Abundance	**25** **0.5085** **0.0095**	25 -0.0969 0.6449	25 0.0088 0.9665	**25** **0.4869** **0.0136**	25 -0.1446 0.4904	25 -0.3315 0.1054
Rockfish Abundance (Common Murre Diet)	32 0.2951 0.1011	32 -0.0180 0.9223	32 0.0390 0.9320	**32** **0.3768** **0.0335**	30 -0.2053 0.2764	**32** **-0.3772** **0.0333**
Hake Log(Pre-recruit Abundance)	21 0.0857 0.7118	21 -0.0338 0.8845	21 -0.0714 0.7583	21 0.3844 0.0853	21 0.0091 0.9688	21 -0.1610 0.4856
Herring Spawning Biomass	30 -0.1355 0.4753	31 -0.0706 0.7060	31 0.1125 0.5468	31 -0.1165 0.5324	30 -0.1471 0.4381	30 0.1600 0.3866
Herring Landings	31 -0.1395 0.4541	31 -0.0363 0.8463	31 -0.1506 0.4186	31 -0.0649 0.7286	30 -0.3197 0.0850	31 -0.0415 0.8244
Coho Percent Smolt-Adult Returns	**38** **0.4395** **0.0058**	38 -0.1141 0.4951	38 -0.2091 0.2077	38 0.1553 0.3519	36 -0.2450 0.1497	38 -0.2743 0.0956
Chinook Fall Escapement	39 0.2692 0.0974	39 -0.3030 0.0608	39 -0.0263 0.8736	39 0.1549 0.3465	37 0.0088 0.9589	39 -0.0921 0.5771
Cassin's Auklet Reproductive Success	37 0.3004 0.0709	37 -0.1275 0.4519	37 0.1138 0.5024	37 0.0922 0.5872	35 0.0896 0.6086	37 -0.1916 0.2560
Common Murre Mortality	15 -0.4464 0.0953	**15** **0.5357** **0.0396**	15 0.3000 0.2773	15 -0.1929 0.4910	15 -0.0214 0.9396	15 0.1929 0.4910
California Sea Lion Pup Production	33 0.0662 0.7144	**33** **-0.5628** **0.0007**	**33** **-0.4957** **0.0034**	**33** **0.4469** **0.0091**	31 -0.3383 0.0627	33 -0.2620 0.1407

Table 9. Results of Spearman rank cross-correlation analysis on detrended biological variables. Listed are N (top), Spearman rho (center) and p>|t| (bottom). Bold indicates a significance of $p<0.05$ and gray shading indicates $p<0.1$.

	Chlorophyll, Farallon Islands	Small Plankton Volume, July-September	Northern Copepod Index	Euphausiid Biomass *(T. spinifera* larvae)	*Sebastes* (all species) Relative Abundance	Rockfish Abundance (Common Murre Diet)	Hake Log(Pre-recruit Abundance)
Small Plankton Volume, S. California, July-September	9 0.3000 0.4328						
Northern Copepod Index	9 0.2333 0.5457	12 0.3986 0.1993					
Euphausiid Biomass *(T. spinifera* larvae)	9 0.6167 0.0769	17 0.2794 0.2774	12 0.3077 0.3306				
Sebastes (all species) Relative Abundance	9 0.0333 0.9322	**24** **0.6122** **0.0015**	12 0.5035 0.0952	17 0.0221 0.9330			
Rockfish Abundance (Common Murre Diet)	9 -0.1667 0.6682	**26** **0.4646** **0.0168**	12 0.3287 0.3969	17 -0.1446 0.5798	**25** **0.7777** **0.0000**		
Hake Log(Pre-recruit Abundance)	9 -0.1333 0.7324	21 0.1481 0.5219	**11** **0.6091** **0.0467**	16 0.0353 0.8968	**21** **0.4870** **0.0252**	21 0.1273 0.5825	
Herring Spawning Biomass	9 0.2667 0.4879	25 -0.0462 0.8266	12 -0.2727 0.3911	17 0.0368 0.8886	25 -0.2054 0.3247	29 -0.1163 0.5481	21 -0.0740 0.7498
Herring Landings	9 0.1667 0.6682	26 -0.3415 0.0877	12 0.3846 0.2170	17 -0.0760 0.7719	25 -0.2108 0.3119	30 -0.0567 0.7659	21 0.0429 0.8537
Coho Percent Smolt-Adult Returns	9 0.5167 0.1544	**28** **0.5025** **0.0064**	11 0.4182 0.2006	16 0.1441 0.5944	**24** **0.4548** **0.0256**	**31** **0.4819** **0.0061**	21 -0.0532 0.8187
Chinook Fall Escapement	9 -0.0333 0.9322	28 0.2485 0.2023	12 0.4196 0.1745	17 -0.1789 0.4920	25 0.3062 0.1366	32 0.2955 0.1006	21 -0.0052 0.9822
Cassin's Auklet Reproductive Success	9 -0.0667 0.8647	28 0.1346 0.4945	**12** **0.6224** **0.0307**	17 -0.0931 0.7222	25 0.2892 0.1608	32 0.3251 0.0694	21 0.2701 0.2363
Common Murre Mortality	9 0.1333 0.7324	14 -0.2615 0.3664	**12** **-0.5804** **0.0479**	14 -0.3275 0.2531	14 -0.3055 0.2882	14 -0.1824 0.5325	**13** **-0.7747** **0.0019**
California Sea Lion Pup Production	**9** **0.6833** **0.0424**	27 0.2454 0.2172	12 0.4476 0.1446	17 0.0319 0.9034	25 -0.0077 0.9709	32 -0.0770 0.6754	21 0.1260 0.5864

Table 9 continued.

	Herring Spawning Biomass	Herring Landings	Coho Percent Smolt-Adult Returns	Chinook Fall Escapement	Cassin's Auklet Reproductive Success	Common Murre Mortality
Herring Landings	**29** **0.4522** **0.0138**					
Coho Percent Smolt-Adult Returns	28 0.0350 0.8595	30 -0.0300 0.8748				
Chinook Fall Escapement	31 0.0830 0.6629	31 -0.0306 0.8700	**37** **0.5128** **0.0012**			
Cassin's Auklet Reproductive Success	29 -0.3113 0.1002	31 -0.1210 0.5168	36 0.2381 0.1620	**37** **0.5578** **0.0003**		
Common Murre Mortality	15 -0.4071 0.1320	14 -0.1824 0.5325	13 -0.3901 0.1876	15 -0.4893 0.0642	14 -0.4462 0.1098	
California Sea Lion Pup Production	29 0.2980 0.1164	31 -0.0774 0.6789	32 0.1232 0.5018	33 0.2473 0.1652	33 0.0752 0.6775	14 -0.2440 0.4006

Figure 1. The California Current Large Marine Ecosystem (CCLME).

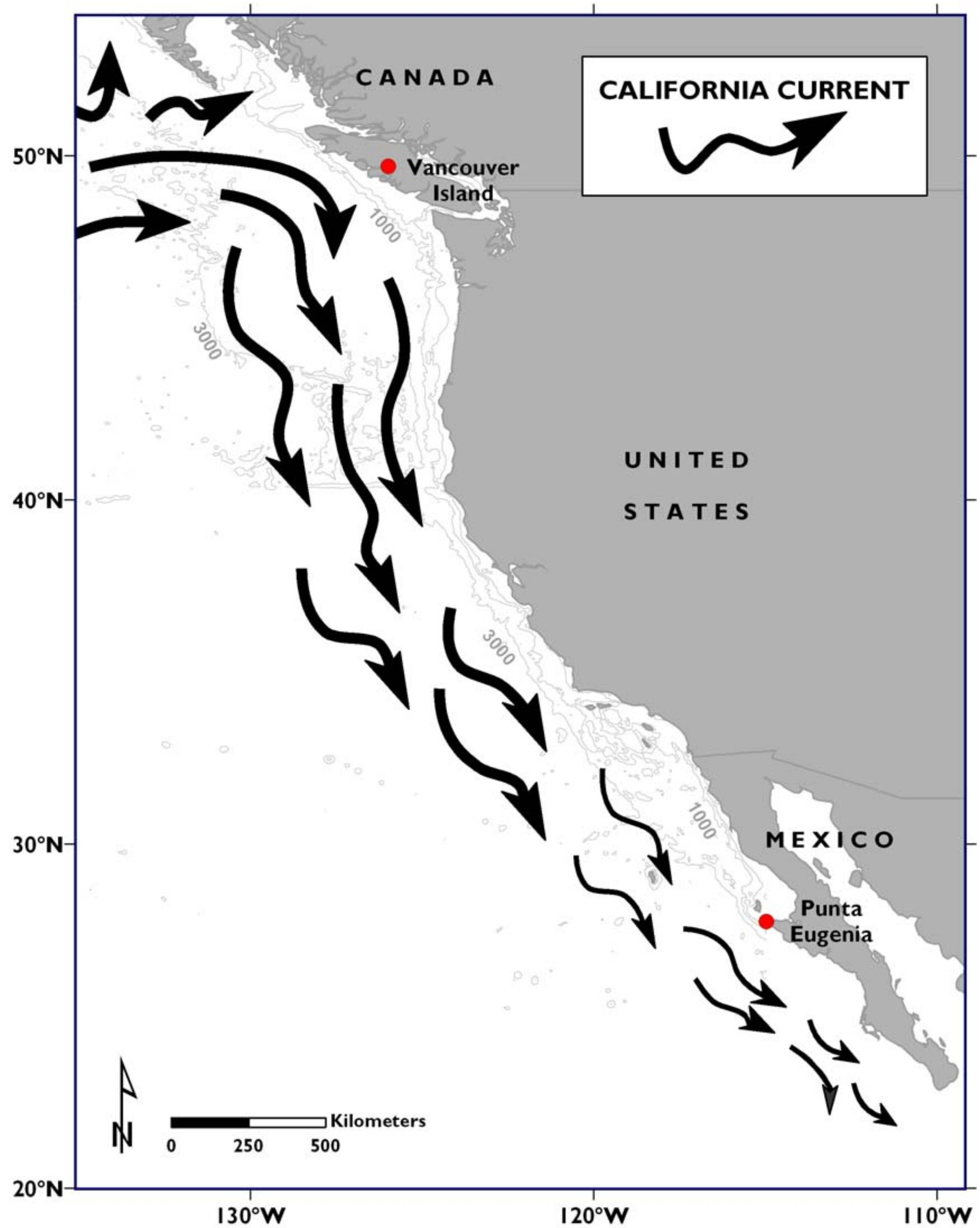

Figure 2. North Pacific Gyre Oscillation (NPGO), 1950-2008. Dashed lines reflect 1 s.d. above and below the long-term mean (0-line). Data courtesy Manu Di Lorenzo/Georgia Tech.

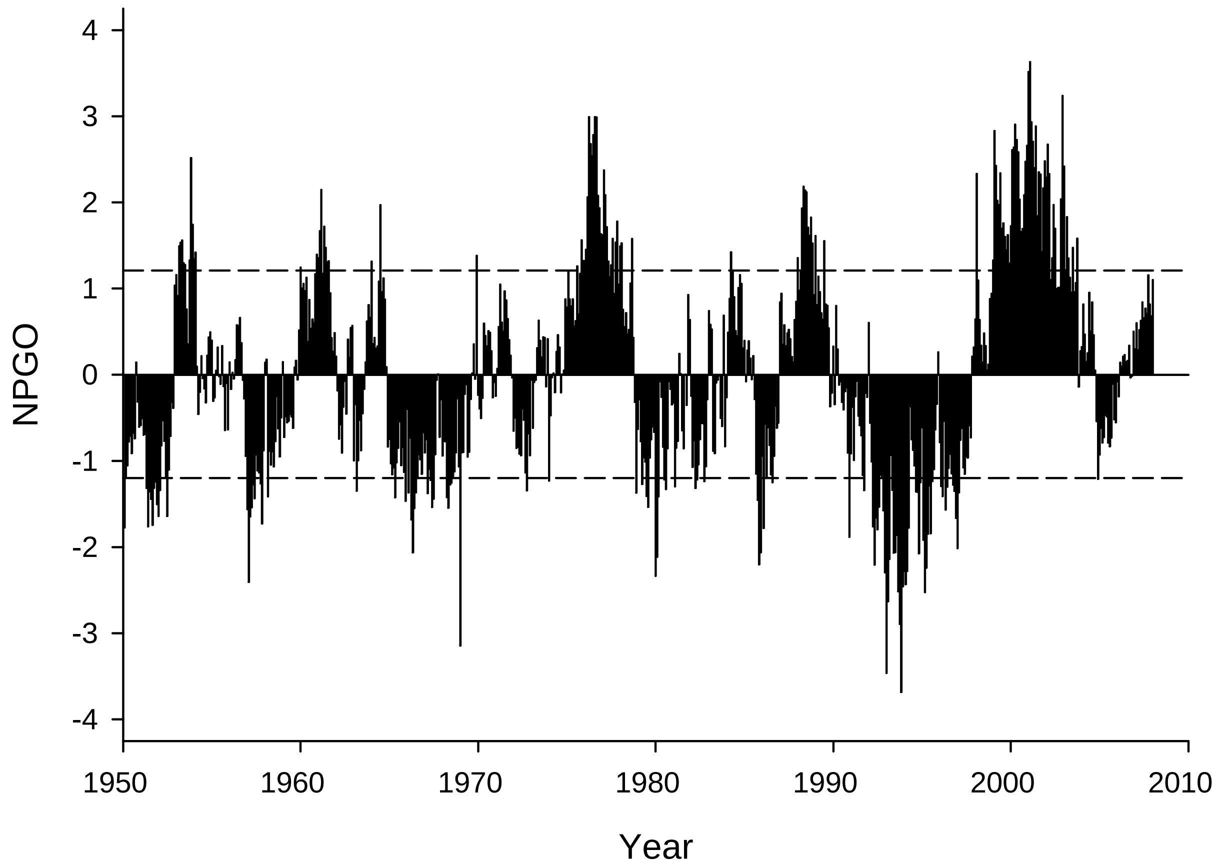

Figure 3. Multivariate ENSO Index (MEI), 1950-2008. Dashed lines reflect 1 s.d. above and below the long-term mean (0-line). Positive values reflect El Niño events whereas negative values indicate La Niña. Data courtesy Klaus Wolter/NOAA.

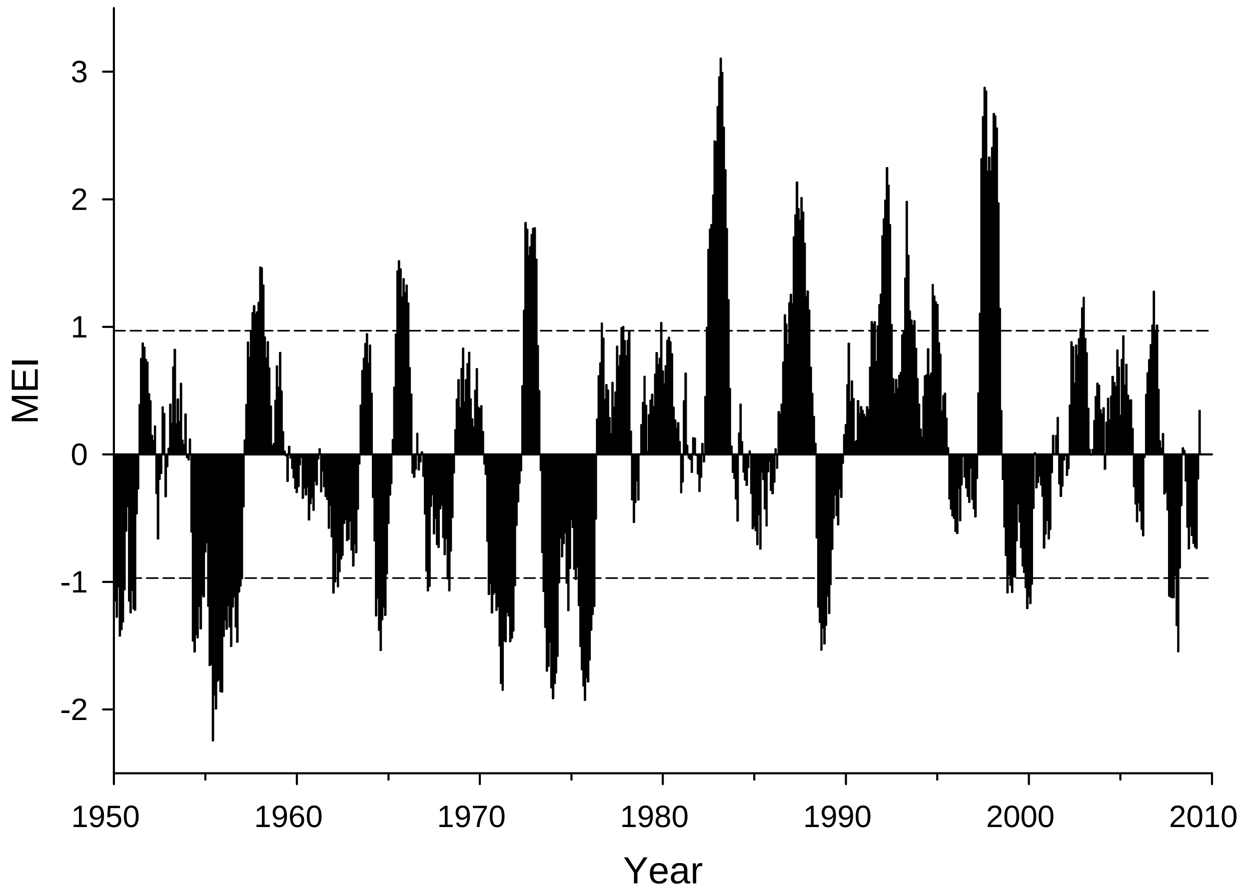

Figure 4. Current Flow in the North Pacific, 2002-2007. Dashed lines reflect 1 s.d. above and below the long-term residual mean (0-line). Positive values indicate stronger current flows. Data courtesy Howard Freeland/DFO Canada.

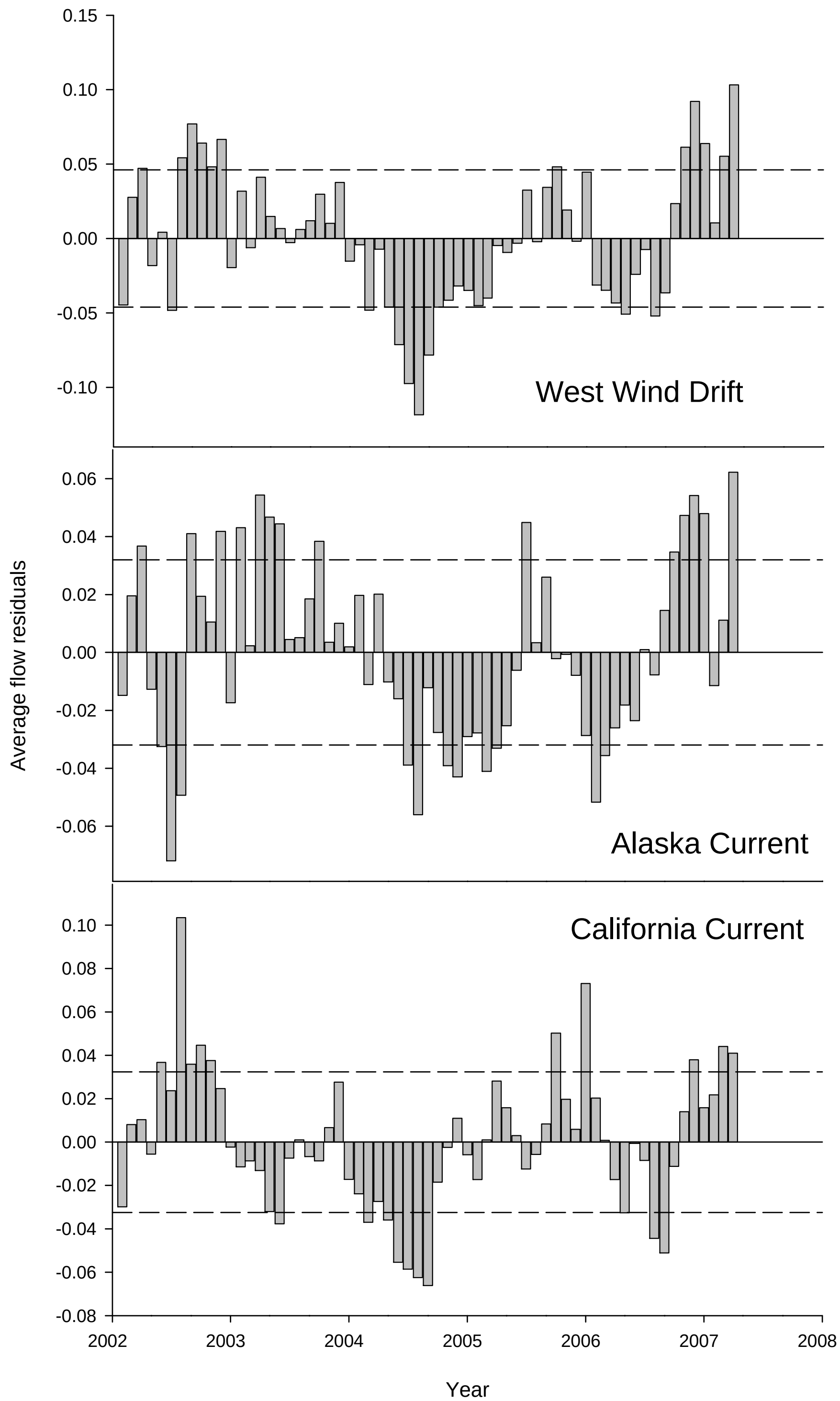

Figure 5. Upwelling Index for Point Arena, California (39°N 125°W), 1946-2008. The dark line is a Loess smoothing line (sampling proportion 0.8). Data courtesy ERD/NOAA.

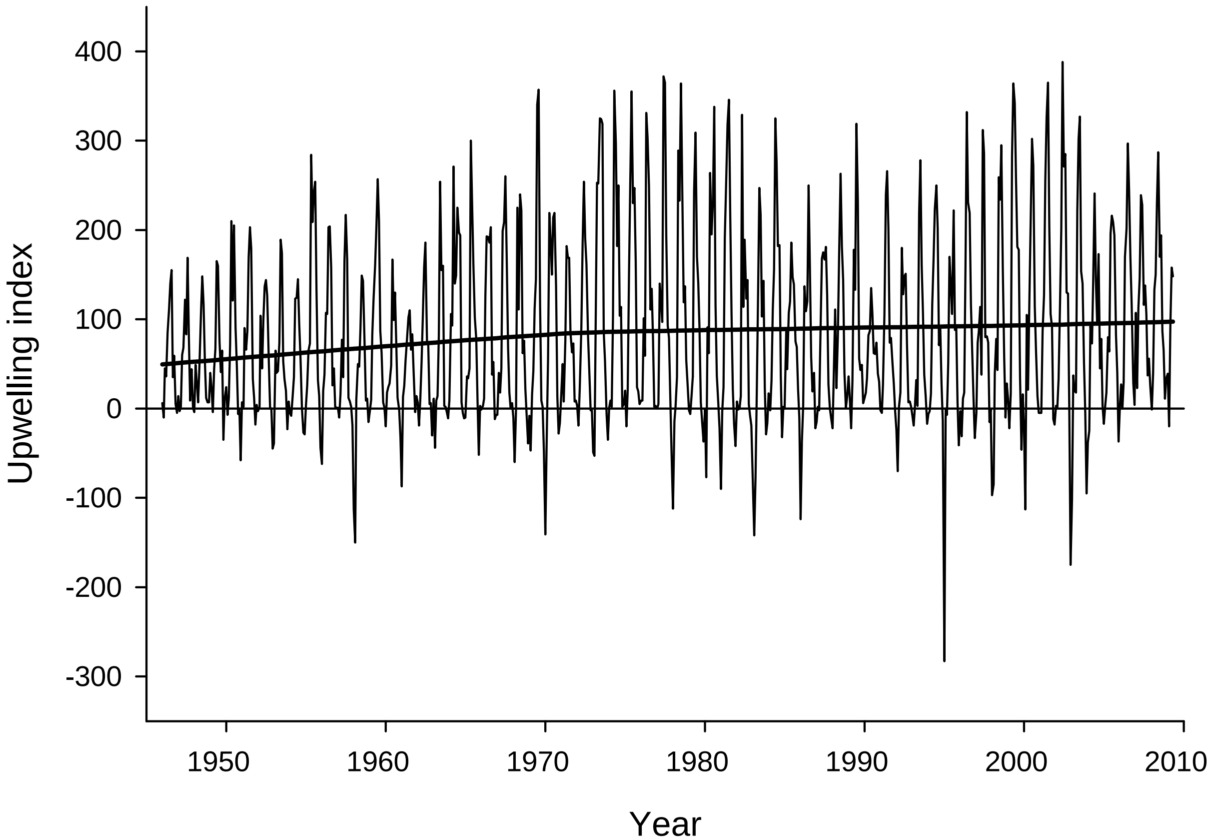

Figure 6. Pacific Decadal Oscillation (PDO) Index, 1900-2008. Positive values indicate warm eastern North Pacific SST, whereas negative values indicate cool temperatures. Note: the long-term ocean warming signal has been removed to illustrate interannual and interdecadal variation. Data courtesy Nate Mantua/UW.

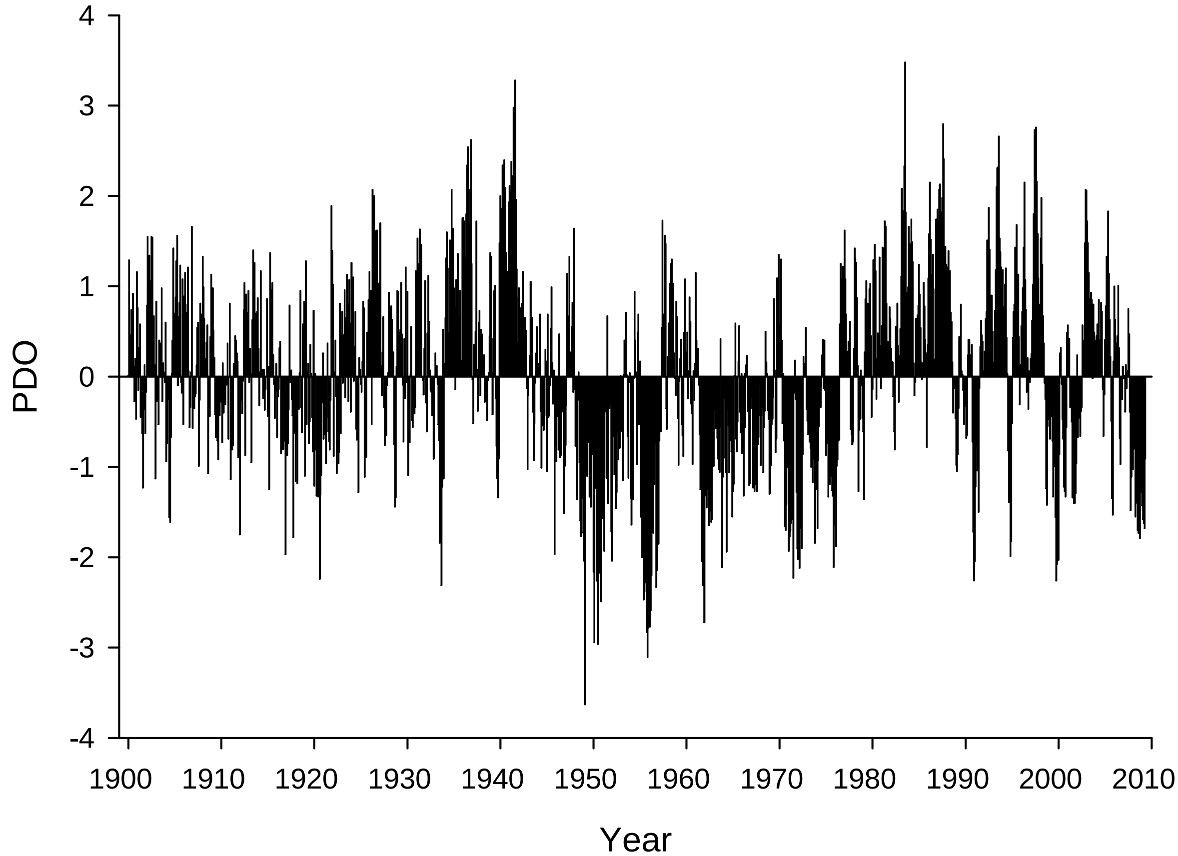

Figure 7. Sea Surface Temperature for Hopkins Marine Station, Pacific Grove, California, 1919-2008. Top: Data with Loess smoothing line (sampling proportion 0.8). Bottom: Residuals of sea surface temperature. Dashed lines reflect 1 s.d. above and below the long-term residual mean (0-line). Data courtesy Scripps Institution of Oceanography.

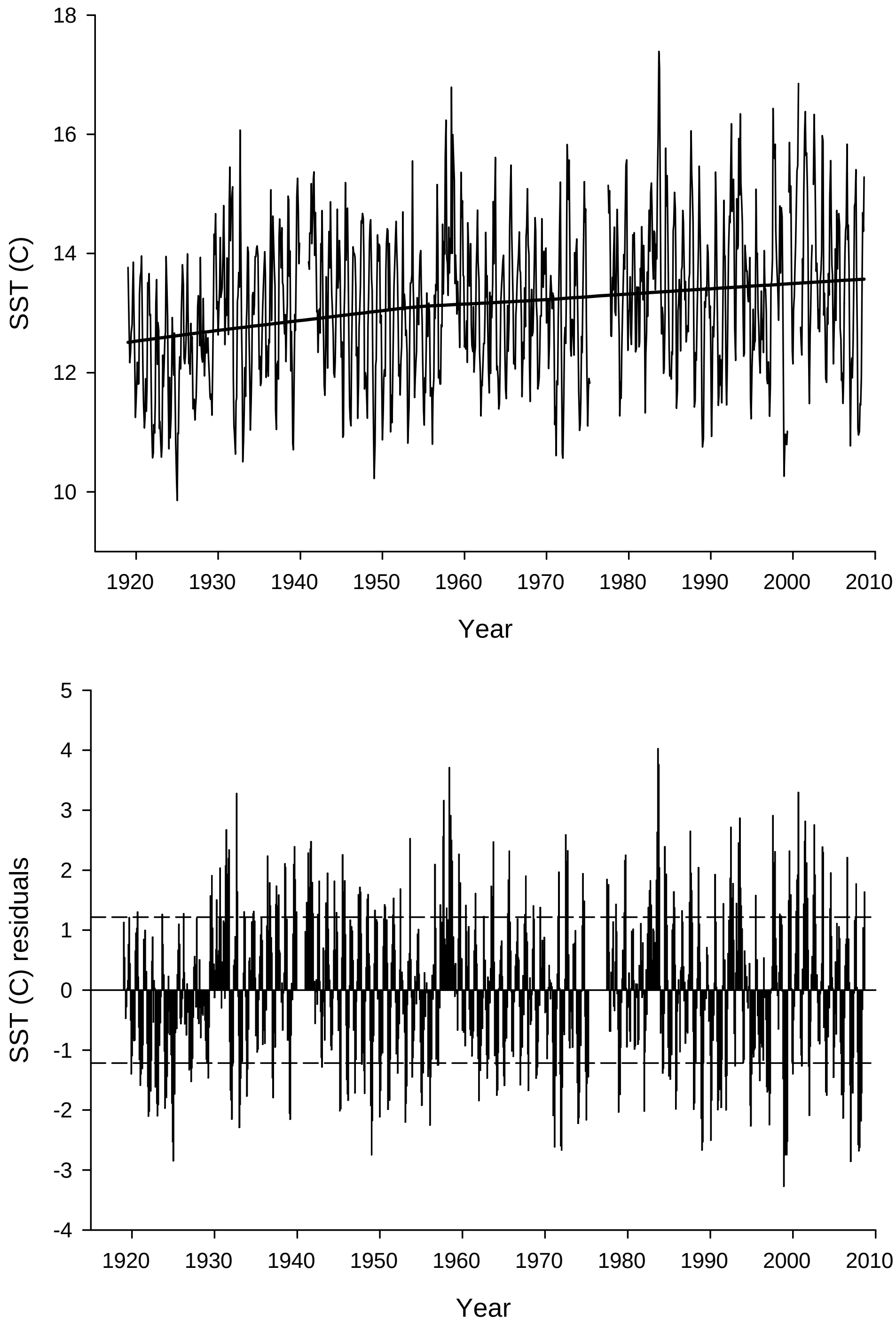

Figure 8. Sea Level for San Francisco, 1901-2008. Top: Data with Loess smoothing line (sampling proportion 0.8). Bottom: Sea level residuals. Dashed lines reflect 1 s.d. above and below the long-term residual mean (0-line). Data courtesy University of Hawaii Sea Level Center.

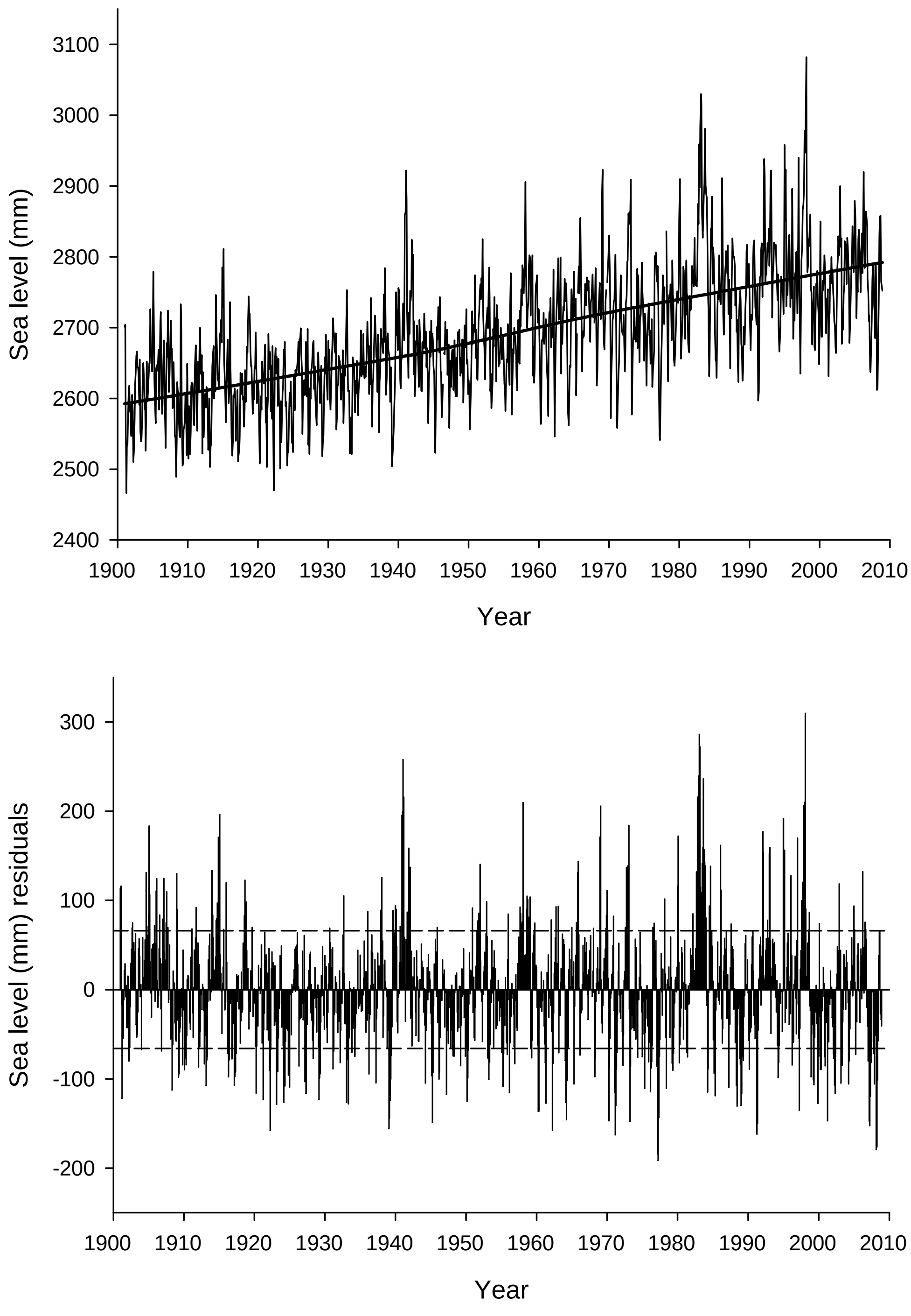

Figure 9. Chlorophyll concentrations for Farallon Islands, 1998-2006. Top: Data with Loess smoothing line (sampling proportion 0.8). Bottom: Chlorophyll concentrations residuals. Dashed lines reflect 1 s.d. above and below the long-term residual mean (0-line). Data courtesy Rob Suryan/Oregon State University.

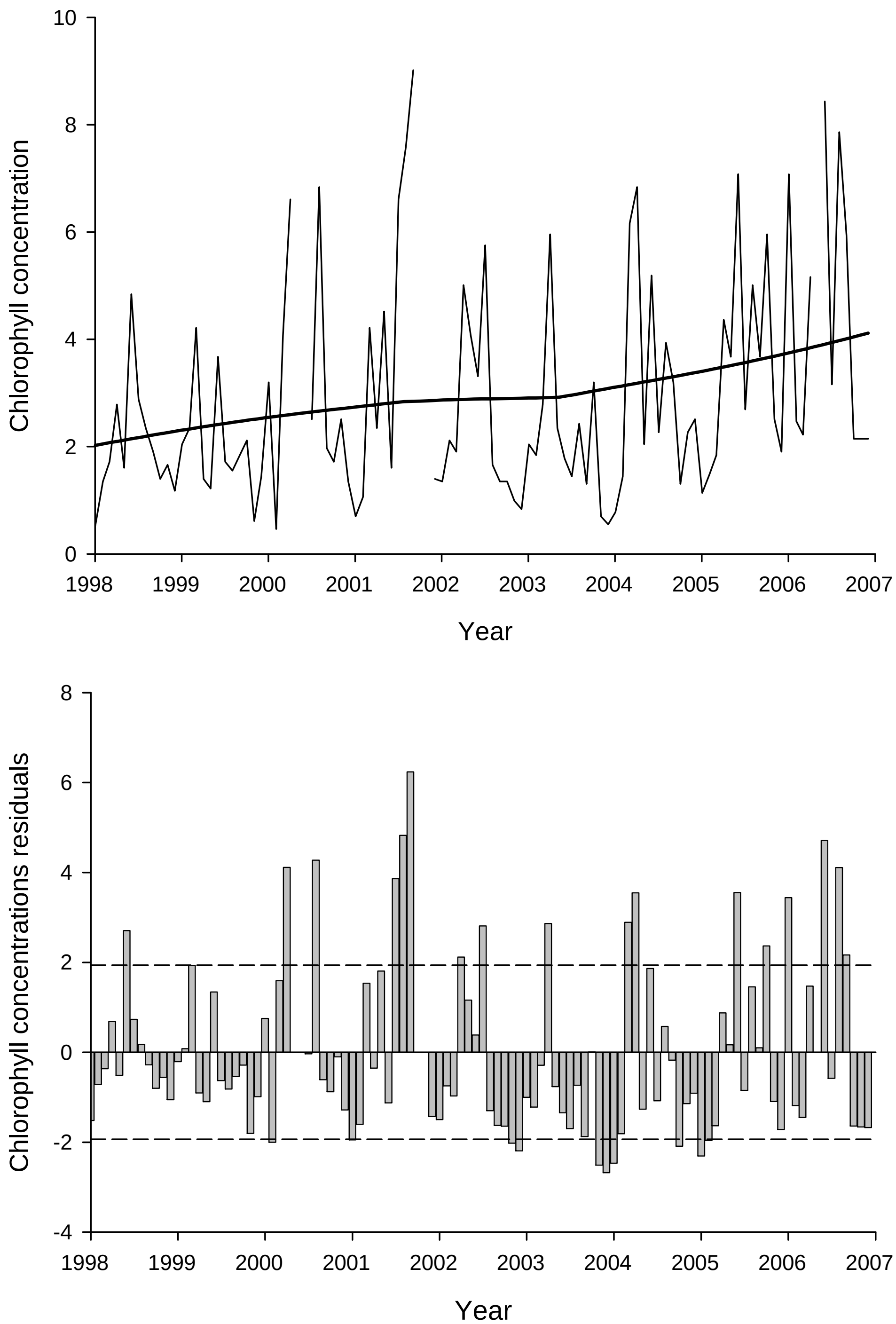

Figure 10. Small plankton volume from CalCOFI survey lines, July-September, 1951-2007. Top: Data with Loess smoothing line (sampling proportion 0.8). Bottom: Average small plankton volume residuals. Dashed lines reflect 1 s.d. above and below the long-term residual mean (0-line). Data courtesy the CalCOFI program.
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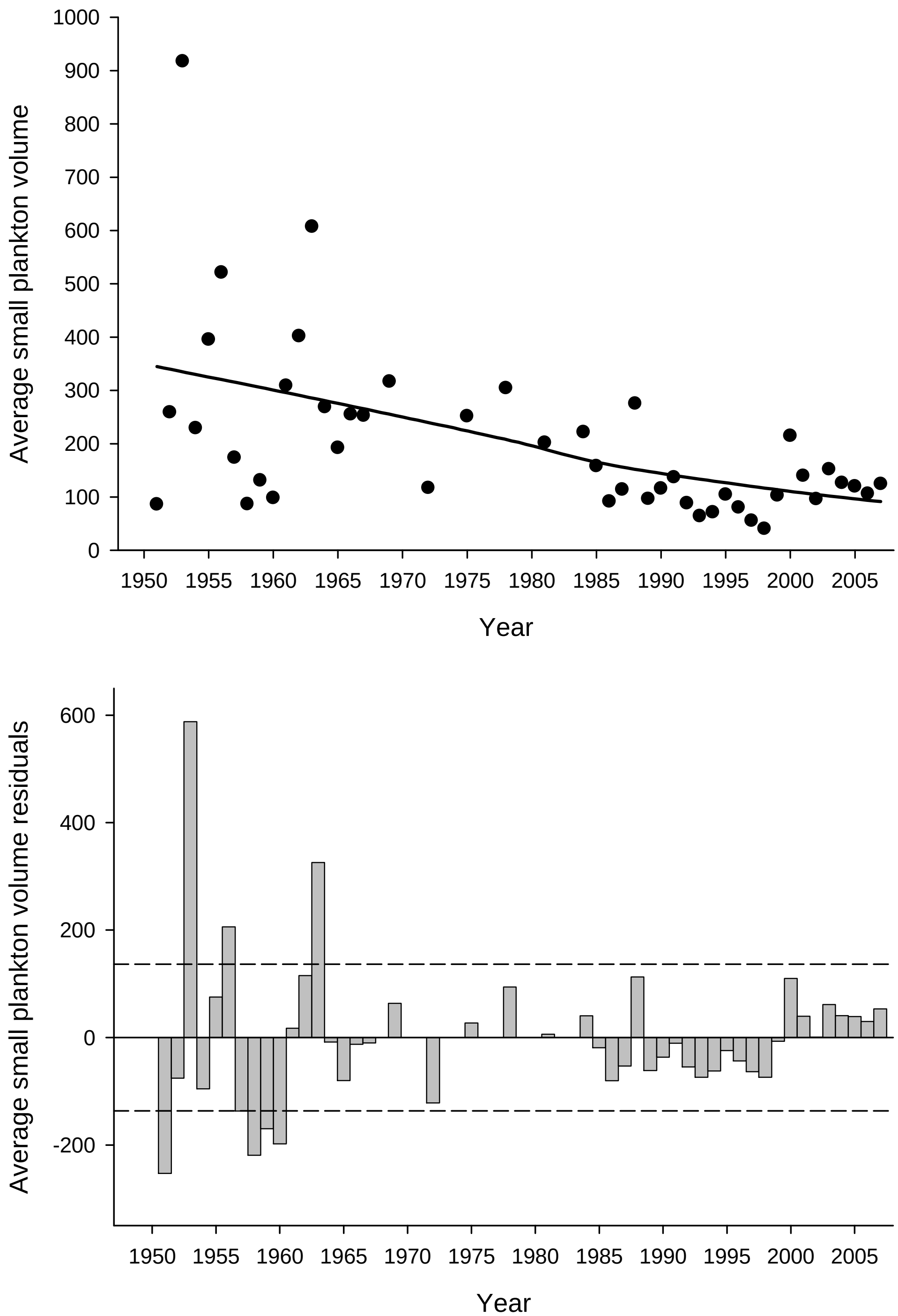

Figure 11. The Northern Copepod Index, 1996-2007. Top: Data with Loess smoothing line (sampling proportion 0.8). Bottom: Anomaly residuals. Dashed lines reflect 1 s.d. above and below the long-term residual mean (0-line). Data courtesy Bill Peterson/NOAA.

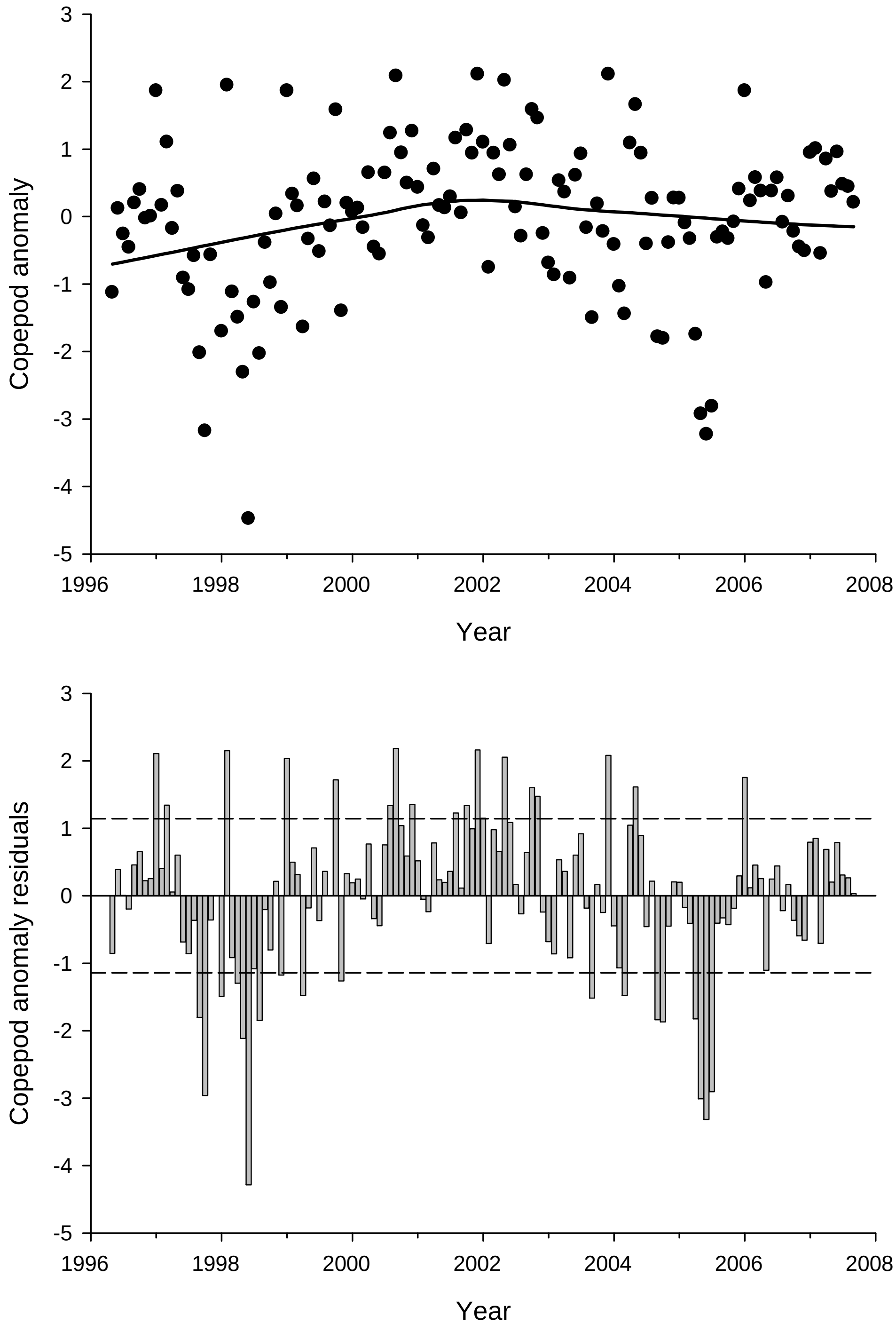

Figure 12. Euphausiid (*T. spinifera*) larval biomass in Barkley Sound, British Columbia, 1991-2005. Top: Data with Loess smoothing line (sampling proportion 0.8). Bottom: Biomass residuals. Dashed lines reflect 1 s.d. above and below the long-term residual mean (0-line). Data courtesy Ron Tanasichuk/DFO Canada.

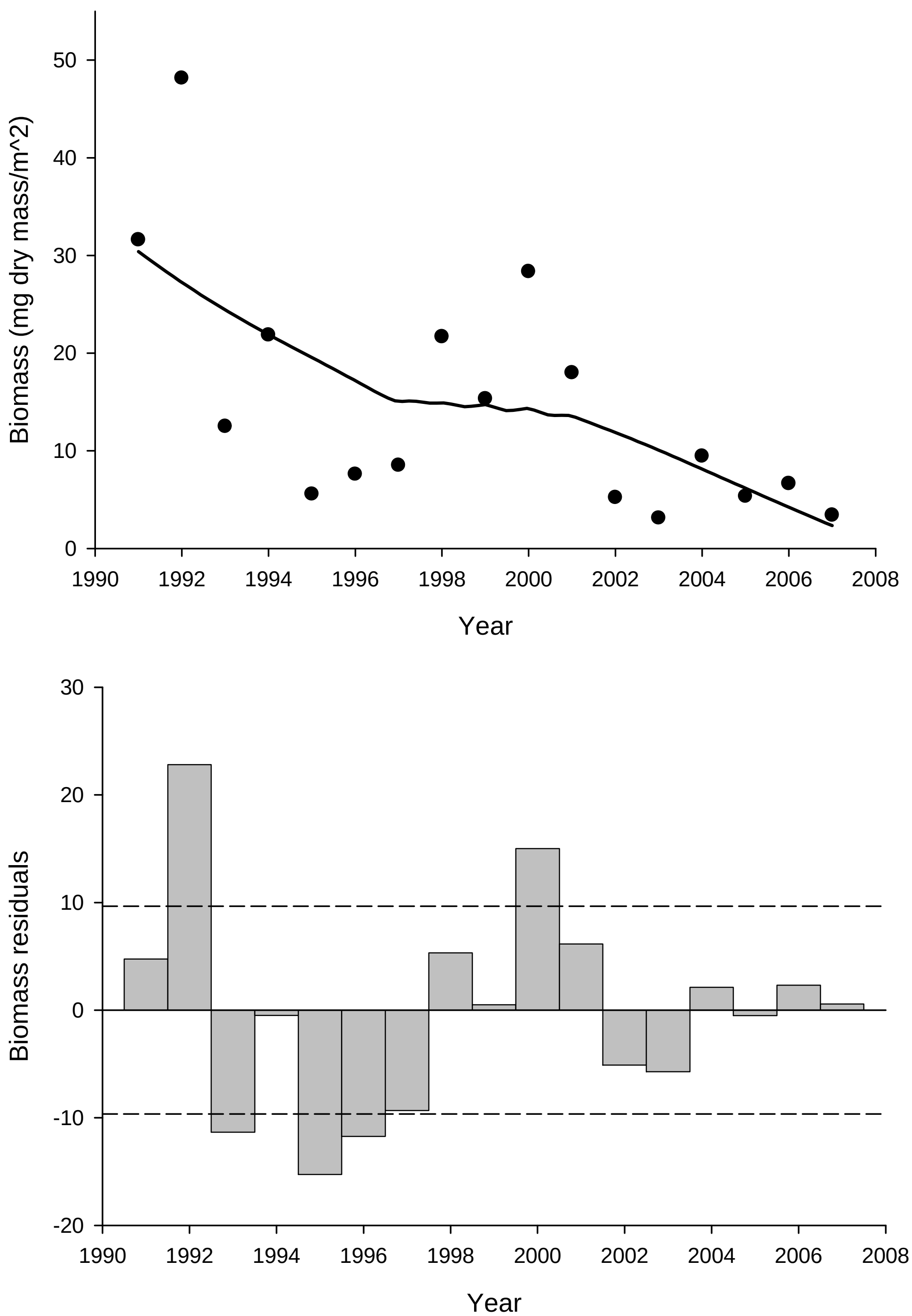

Figure 13. Juvenile rockfish relative abundance (Juvenile Rockfish Index), 1983-2007. Top: Data with Loess smoothing line (sampling proportion 0.8). Bottom: Abundance residuals. Dashed lines reflect 1 s.d. above and below the long-term residual mean (0-line). Data courtesy John Field/NOAA.
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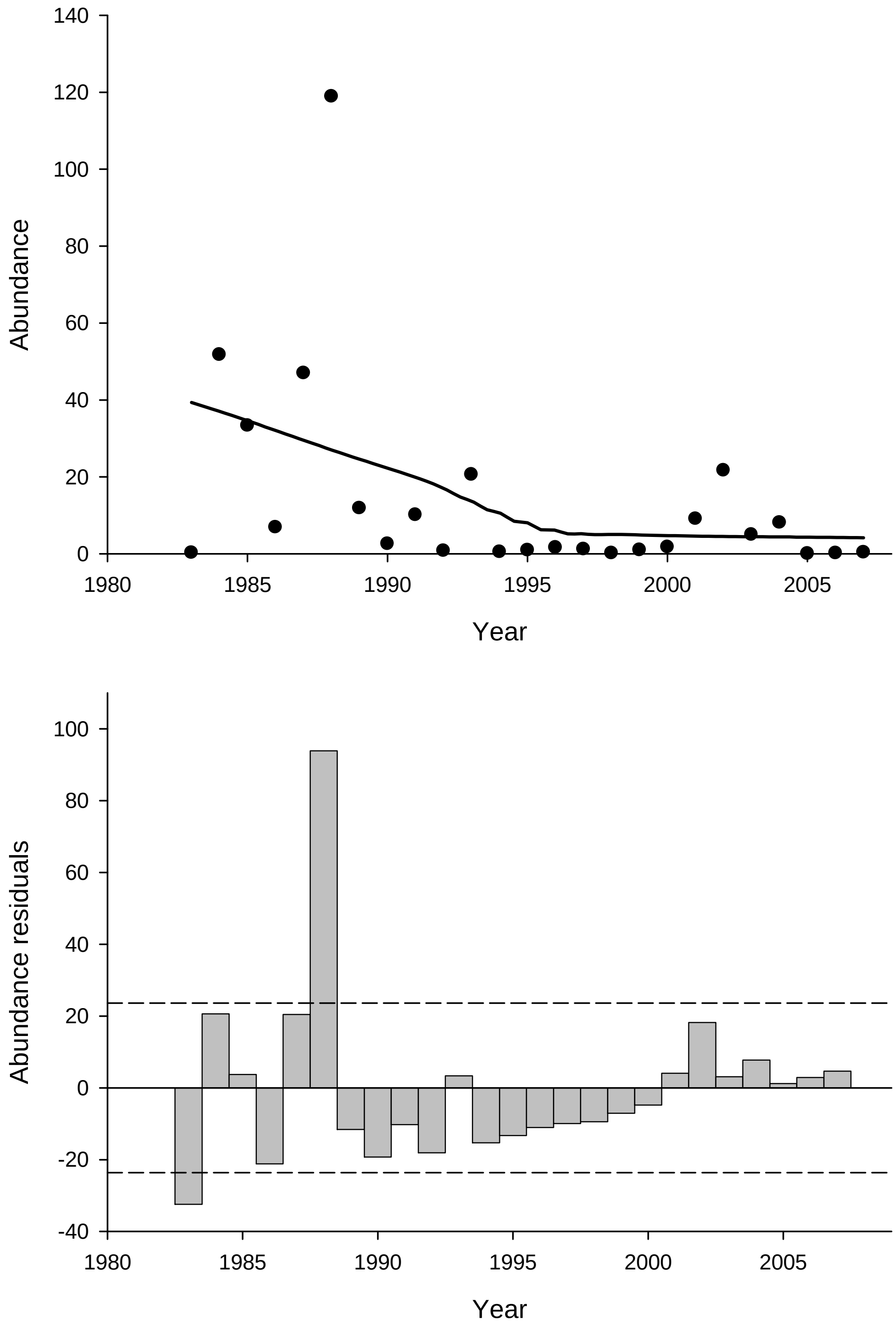

Figure 14. Proportion rockfish in seabird (Common murre) chick diet at the Farallon Islands, 1975-2007. Top: Data with Loess smoothing line (sampling proportion 0.8). Bottom: Proportion residuals. Dashed lines reflect 1 s.d. above and below the long-term residual mean (0-line). Data courtesy PRBO Conservation Science.
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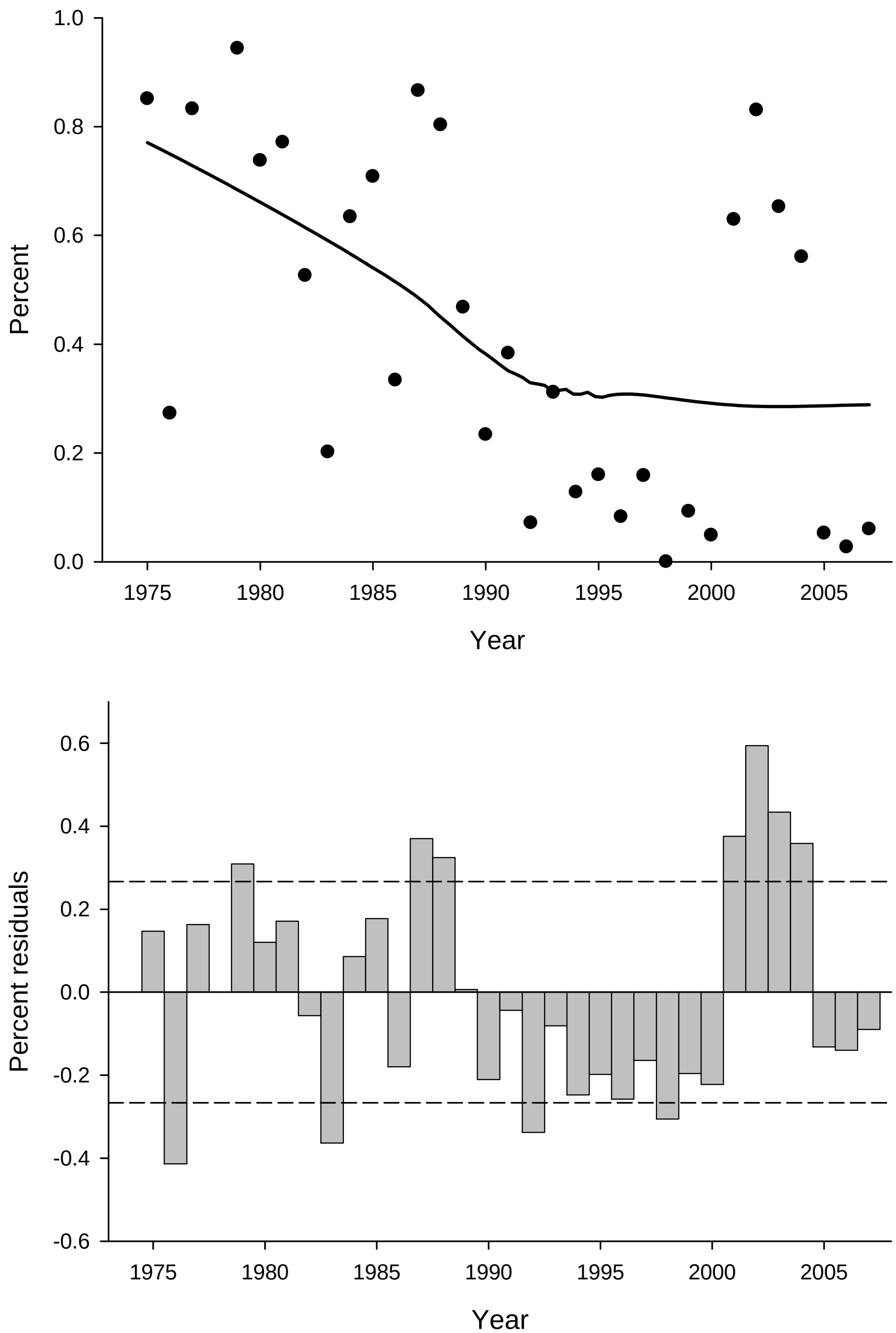

Figure 15. Juvenile hake abundance (log(number pre-recruits)), 1986-2006. Data with Loess smoothing line (sampling proportion 0.8). Bottom: Abundance residuals. Dashed lines reflect 1 s.d. above and below the long-term mean residual (0-line). Data courtesy NOAA/DFO Canada.
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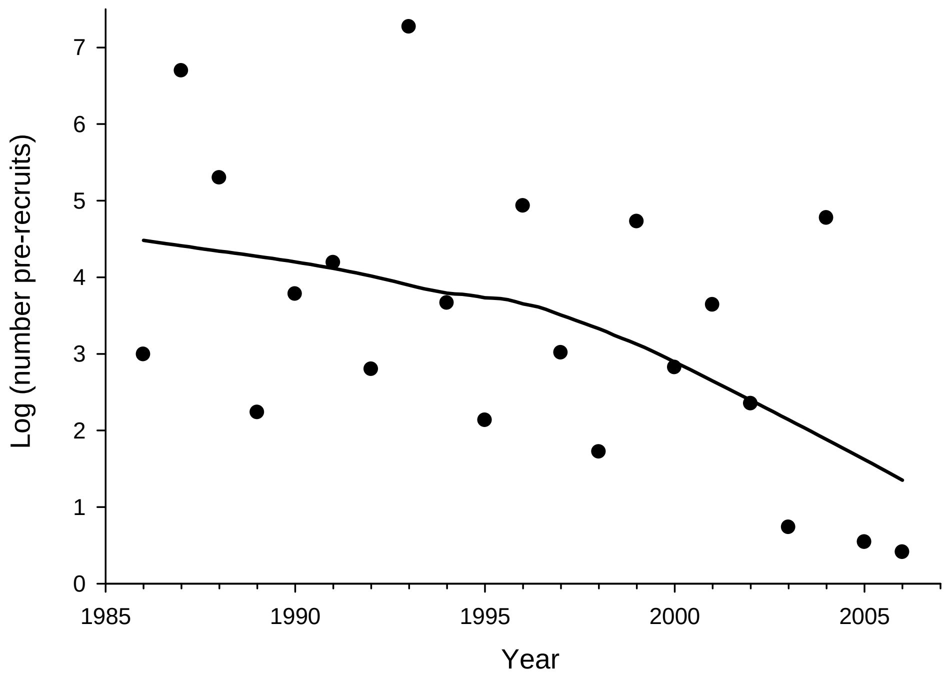


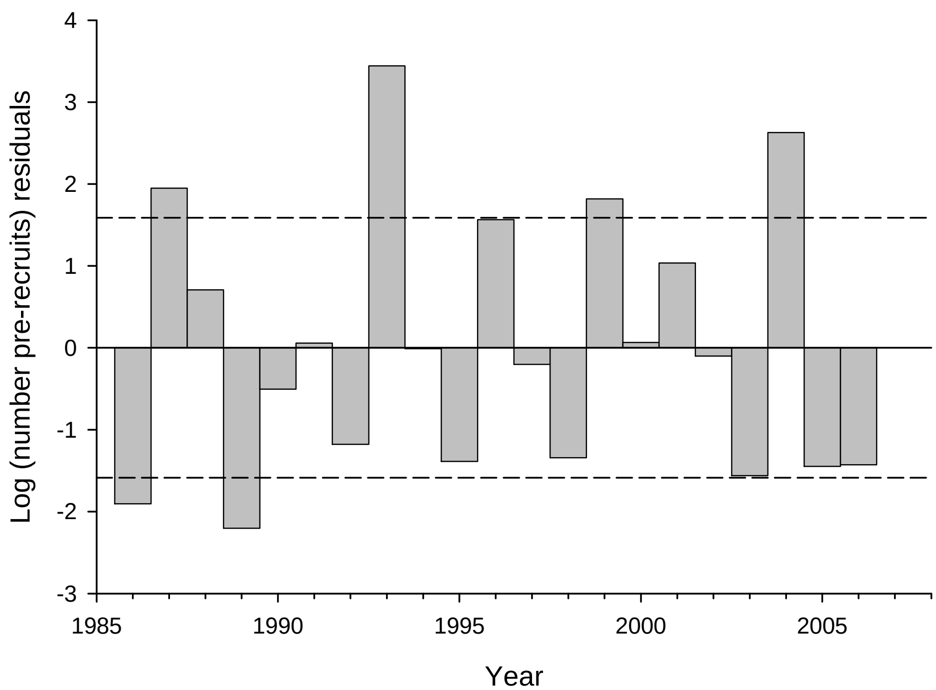
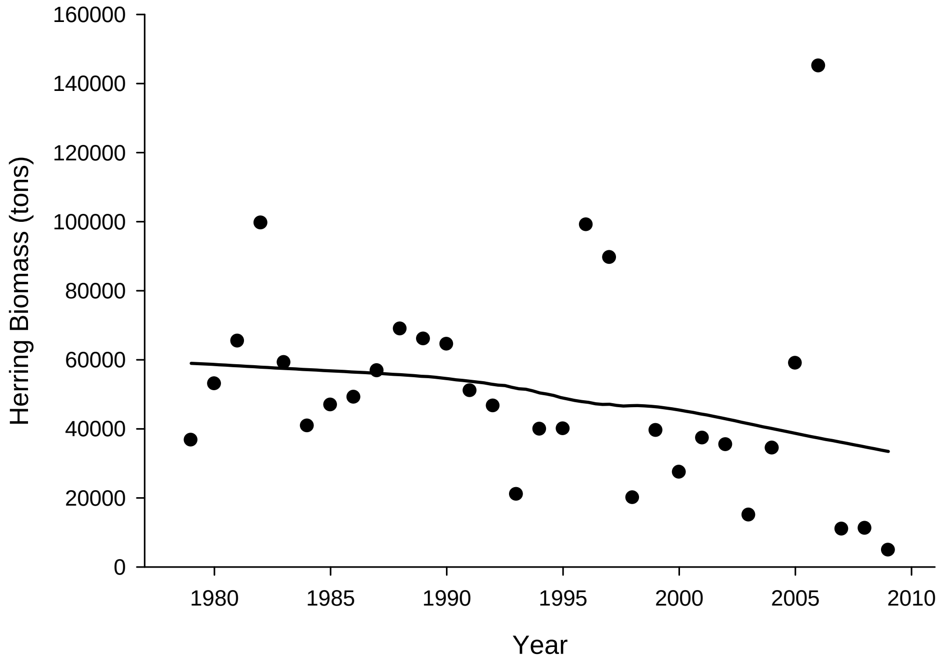


Figure 16. Herring estimated spawning biomass in California (San Francisco Bay), 1979-2009. Top: Data with Loess smoothing line (sampling proportion 0.8). Bottom: Landings residuals. Dashed lines reflect 1 s.d. above and below the long-term residual mean (0-line). Data courtesy CDFG.



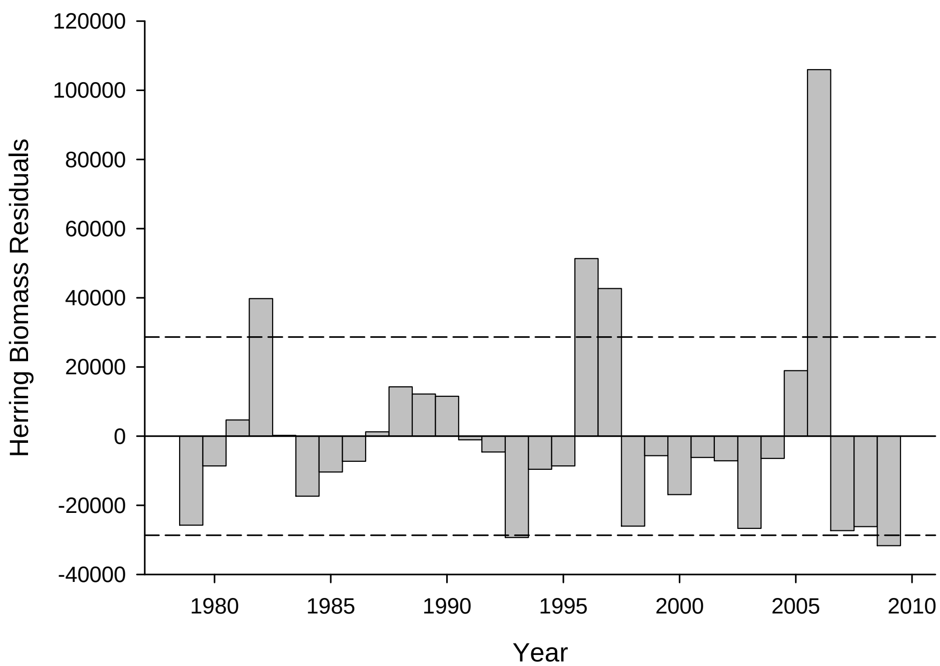


Figure 17. Herring landings in California (mostly San Francisco Bay), 1977-2006. Top: Data with Loess smoothing line (sampling proportion 0.8). Bottom: Landings residuals. Dashed lines reflect 1 s.d. above and below the long-term residual mean (0-line). Data courtesy CDFG.

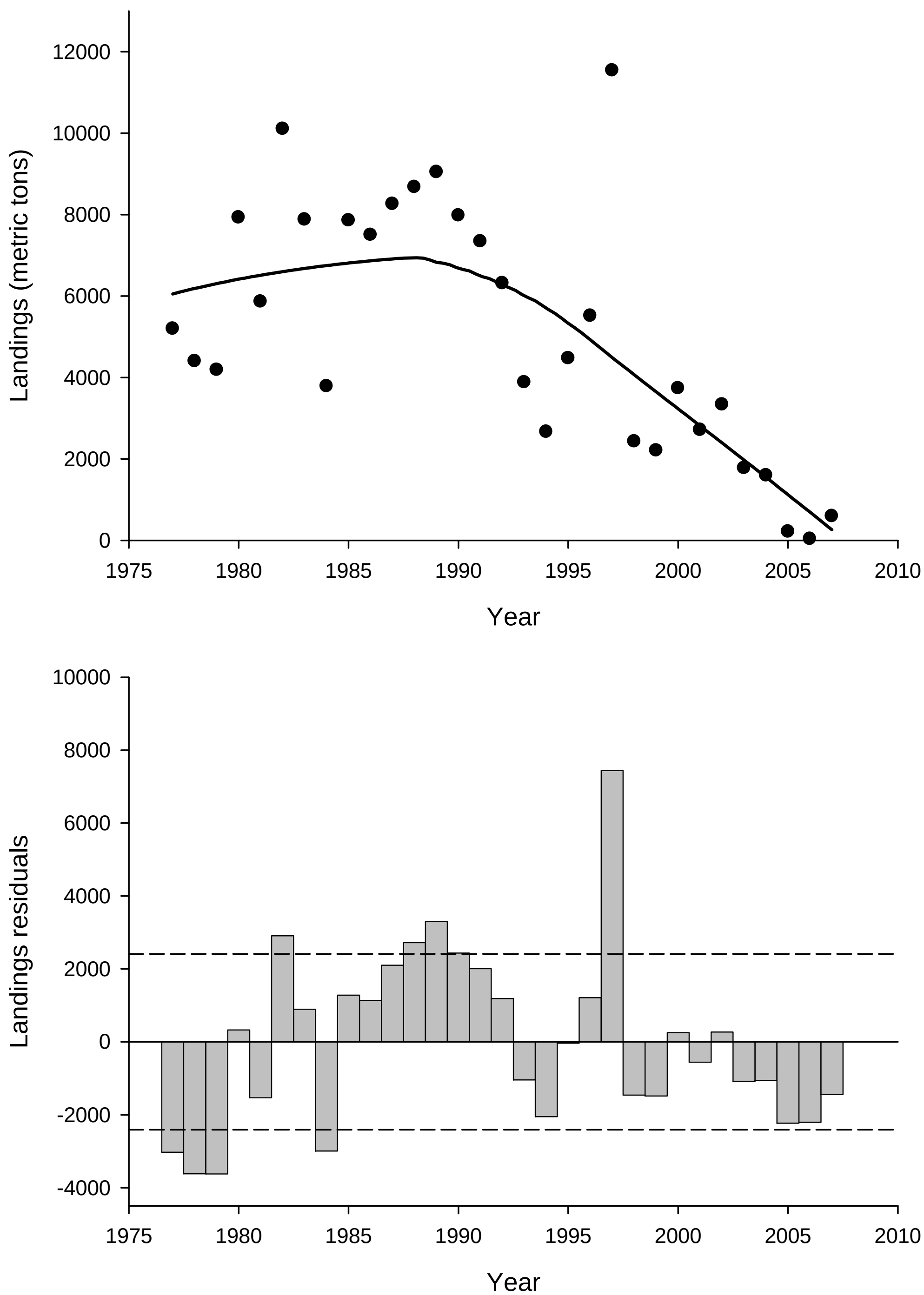


Figure 18. Oregon Production Index: Coho salmon percent smolt-adult return, 1970-2007. Top: Data with Loess smoothing line (sampling proportion 0.8). Bottom: Percent return residuals. Dashed lines reflect 1 s.d. above and below the long-term residual mean (0-line). Data courtesy NOAA.

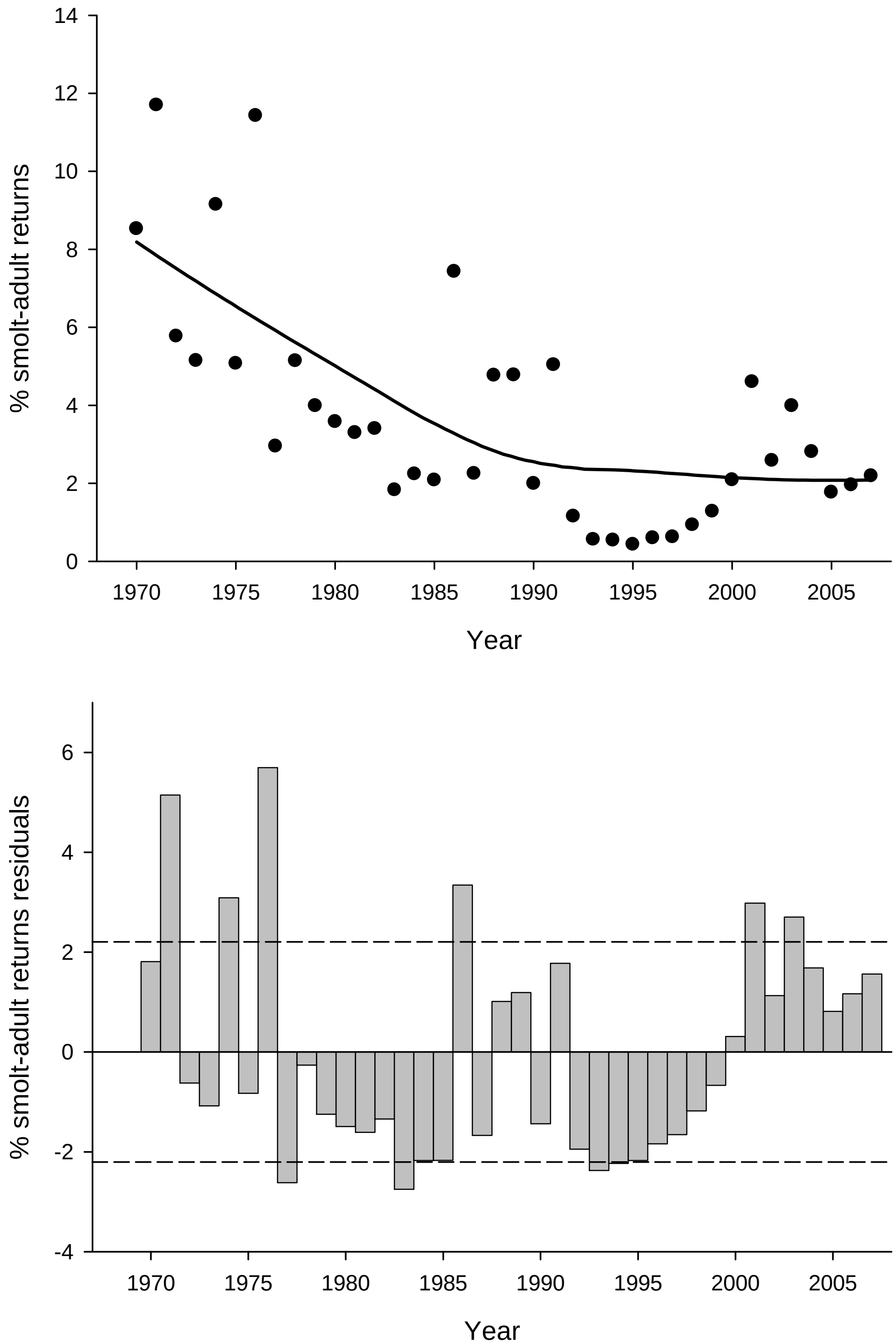


Figure 19. Chinook salmon fall escapement in the Central Valley, California, 1970-2008. Points 1970-2007 are from the Chinook Valley Index, while 2008 is from the Sacramento Index. The Central Valley Index is no longer being produced. Top: Data with Loess smoothing line (sampling proportion 0.8). Bottom: Abundance residuals. Dashed lines reflect 1 s.d. above and below the long-term residual mean (0-line). Data courtesy NOAA and CDFG.

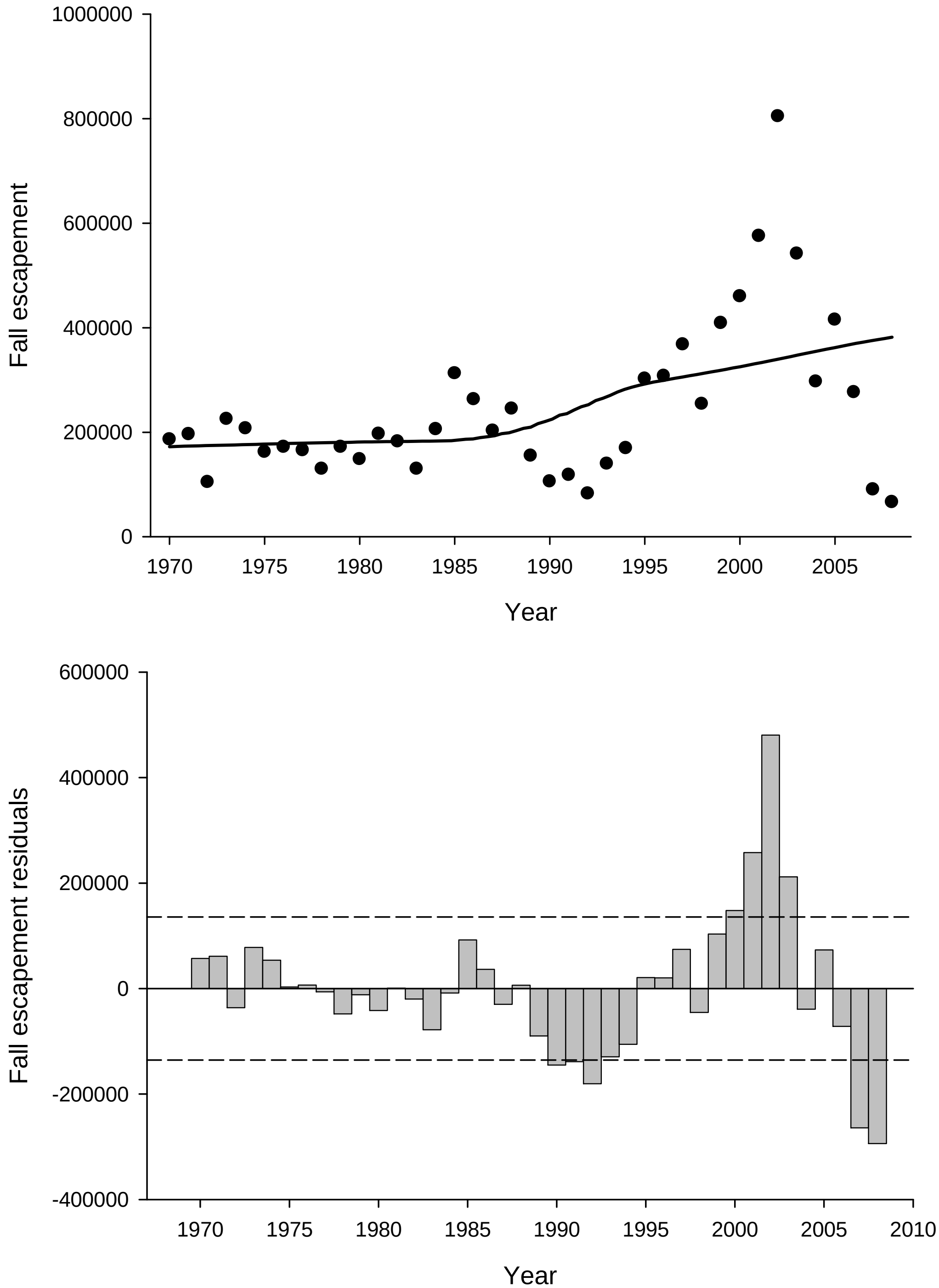


Figure 20. Cassin's auklet reproductive success at the Farallon Islands, 1972-2007. Top: Data with Loess smoothing line (sampling proportion 0.8). Bottom: Reproductive success residuals. Dashed lines reflect 1 s.d. above and below the long-term residual mean (0-line). Data courtesy USFWS and PRBO Conservation Science.

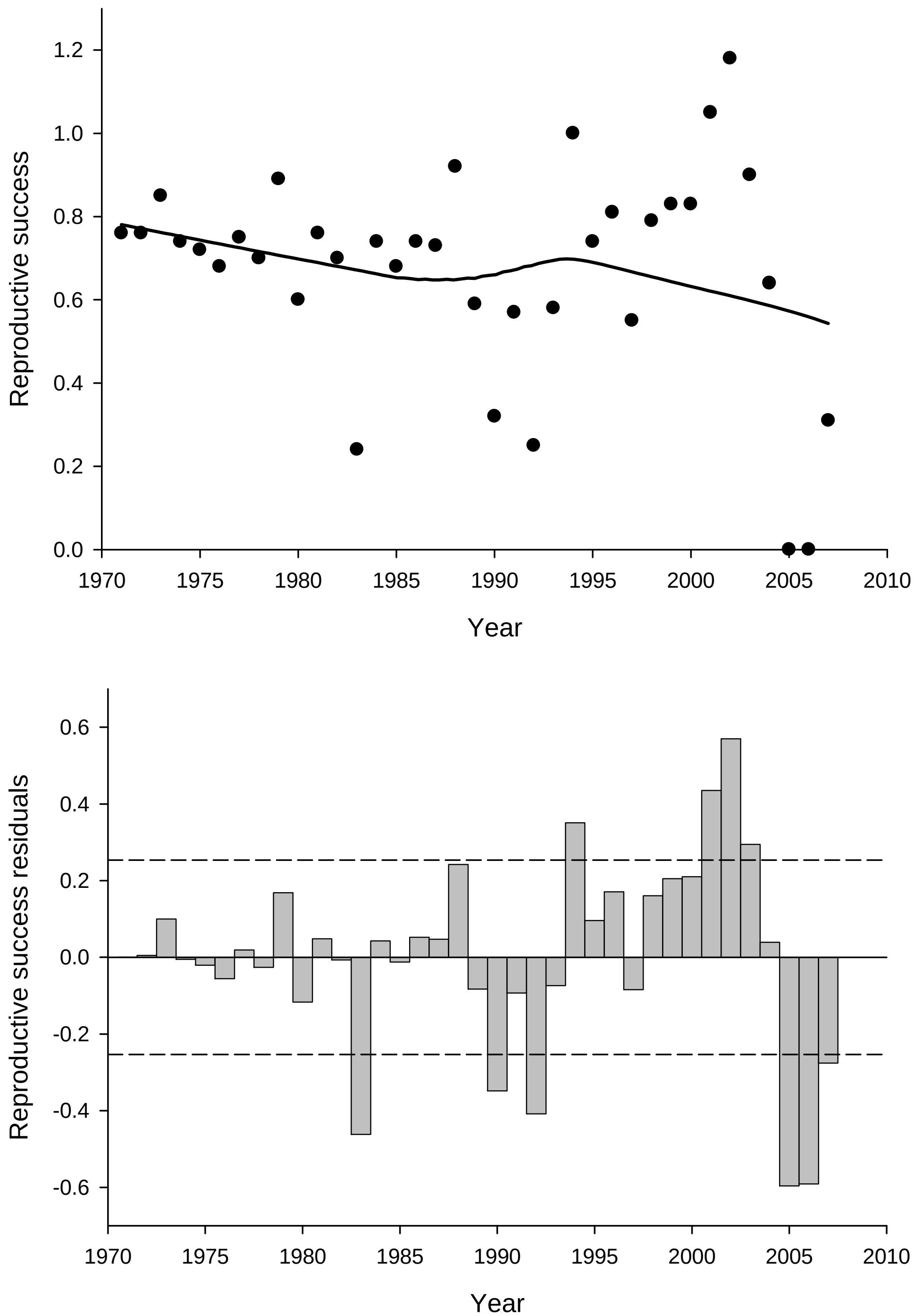
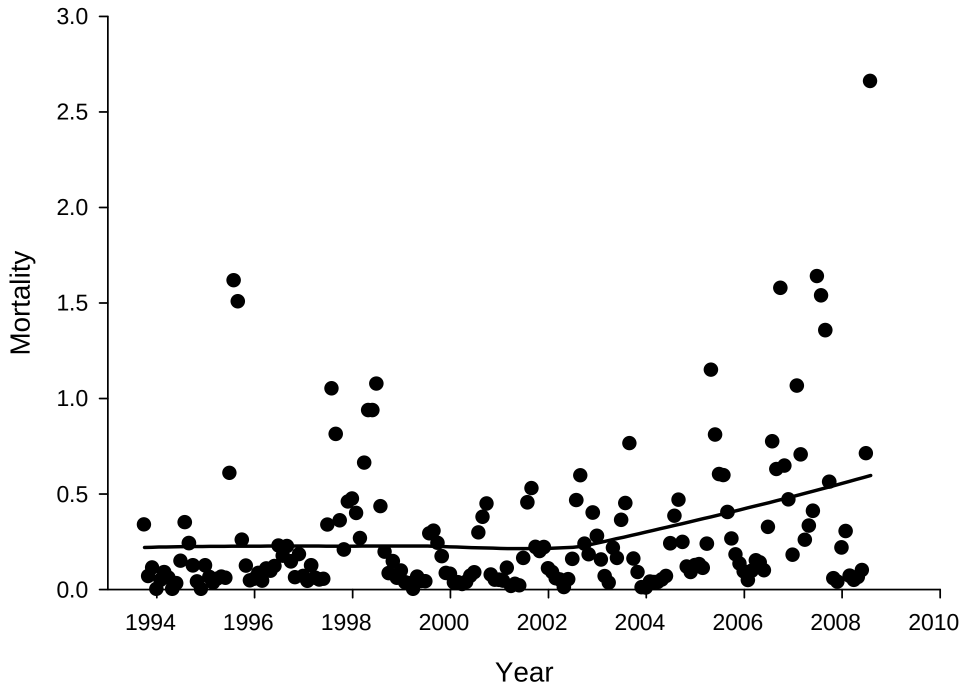


Figure 21. Common murre mortality from beached bird surveys in central California, 1993-2008. Top: Data with Loess smoothing line (sampling proportion 0.8). Bottom: Mortality residuals. Dashed lines reflect 1 s.d. above and below the long-term mean (0-line). Data courtesy Jan Roletto/NOAA.



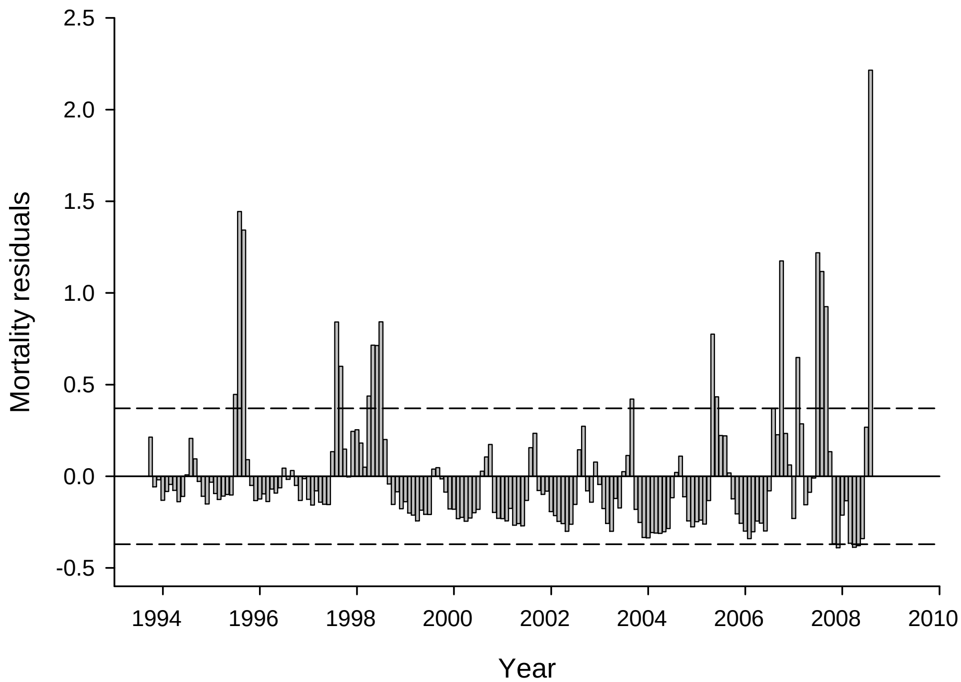


Figure 22. California sea lion pup production in southern California, 1975-2007. Top: Data with Loess smoothing line (sampling proportion 0.8). Bottom: Abundance residuals. Dashed lines reflect 1 s.d. above and below the long-term residual mean (0-line). Data courtesy Mark Lowry/NOAA.

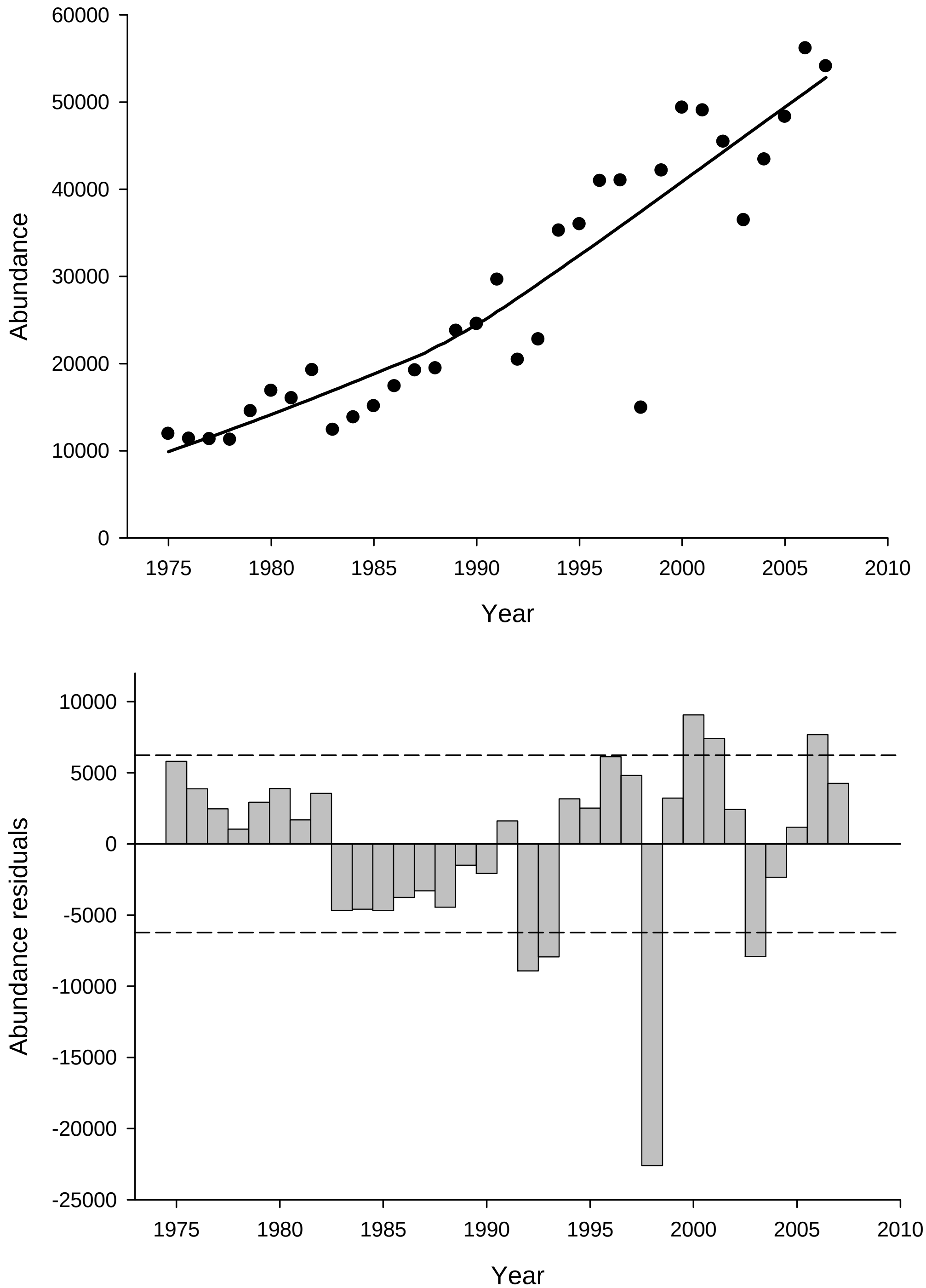
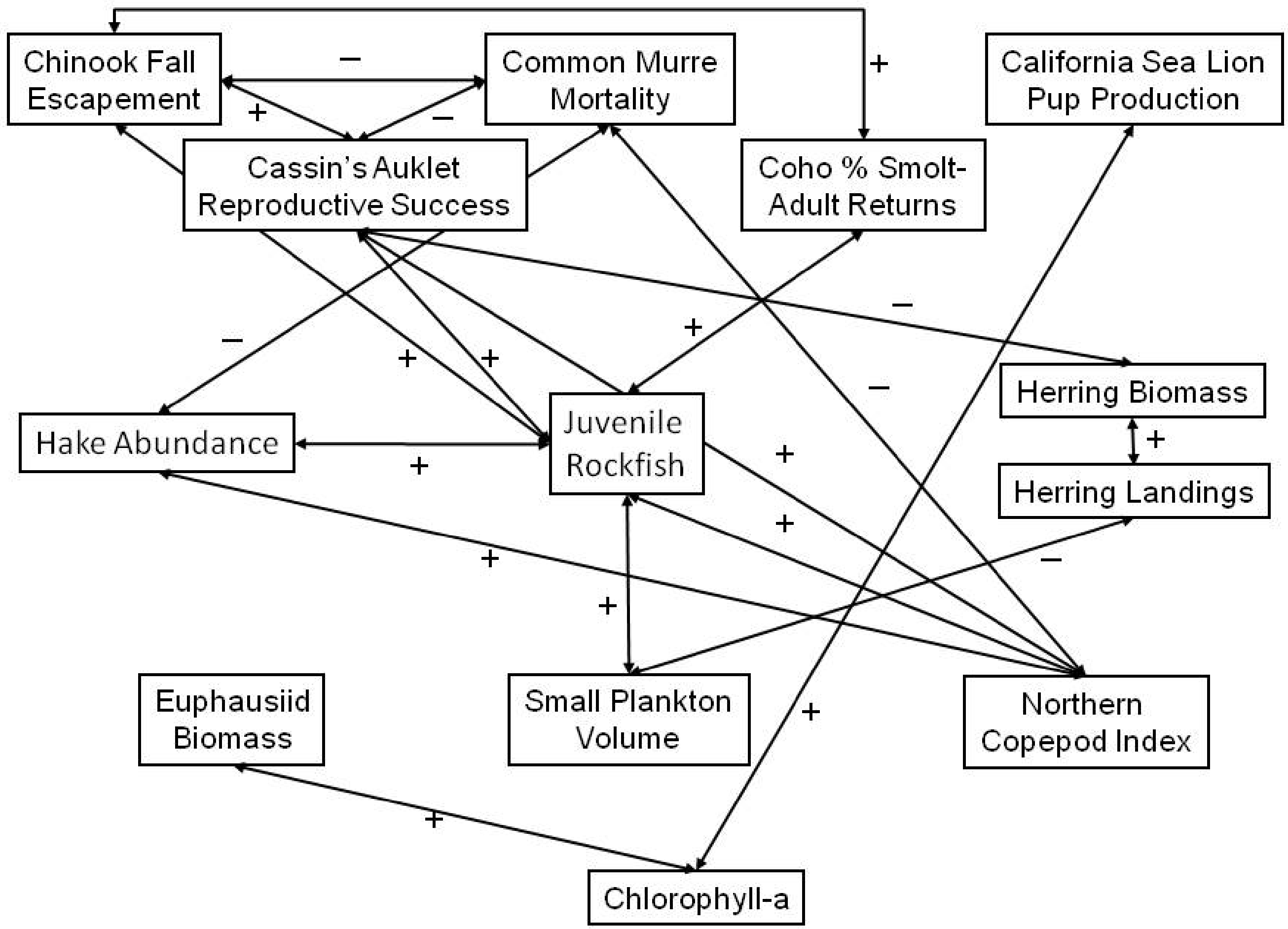


Figure 23. Interrelationships between biological variables as determined by Spearman rank cross-correlation analysis (see Table 9 for details). Arrows (direction non-specific) indicate significance of p<0.1.



Appendix 1. Data contributors and contact information.

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Petaluma, CA 94975
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Dataset	**Argo Current Flow**
Contributor	Howard Freeland
Organization	Fisheries and Oceans Canada Institute of Ocean Sciences
URL	http://www.pac.dfo-mpo.gc.ca/SCI/osap/projects/argo/default_e.htm

Dataset	**California Sea Lion Pup Abundance**
Contributor	Mark Lowry
Organization	NOAA National Fisheries Service Southwest Fisheries Science Center
URL	http://swfsc.noaa.gov/prd-eez.aspx

Dataset	**Cassin's Auklet Reproductive Success**
Contributor	William Sydeman
Contact	Sarah Ann Thompson
Associated Party	PRBO Conservation Science
URL	http://www.prbo.org/cms/index.php

Dataset	**Central Valley Chinook Salmon Fall Escapement**
Contributor	Pacific Fishery Management Council
URL	http://www.pcouncil.org
Contact	Kyra Mills
Organization	Farallon Institute for Advanced Ecosystem Research

Dataset	**Coho Salmon Oregon Production Index**
Contact	Cheryl Morgan
Organization	Cooperative Institute for Marine Resource Studies Oregon State University
URL	http://oregonstate.edu/groups/cimrs/

Dataset	**Common Murre Mortality**
Contributor	Gulf of the Farallones National Marine Sanctuary
URL	http://farallones.noaa.gov
Contact	Jan Roletto

Dataset	**Euphausiid Biomass**
Contributor	Ronald Tanasichuk
Organization	Fisheries and Oceans Canada Pacific Biological Station
URL	http://www.pac.dfo-mpo.gc.ca/science/facilities-installations/pbs-sbp/index-eng.htm

Dataset	**Hake Abundance**
Contributor	Thomas E. Helser
Organization	Northwest Fisheries Science Center National Marine Fisheries Service NOAA
Contributor	Steve Martell
Organization	University of British Columbia, Fisheries Center

Dataset	**Herring Estimated Spawning Biomass**
Contributor	California Department of Fish and Game
URL	http://www.dfg.ca.gov/marine/herring/ceqa.asp

Dataset	**Herring Landings**
Contributor	California Department of Fish and Game
URL	http://www.dfg.ca.gov/

Dataset	**Juvenile Rockfish Index (JRI)**
Contributor	John Field
Organization	NOAA Southwest Fisheries Science Center Fisheries Ecology Division
URL	http://swfsc.noaa.gov/fed.aspx

Dataset	**Multivariate ENSO Index (MEI)**
Contributor	NOAA Earth System Research Laboratory Physical Sciences Division
URL	http://www.esrl.noaa.gov/psd/
Contact	Cathy Smith

Dataset	**North Pacific Gyre Oscillation Index (NPGO)**
Contributor	Emanuele Di Lorenzo
Organization	School of Earth and Atmospheric Sciences Georgia Institute of Technology
URL	http://eros.eas.gatech.edu/manu/

Dataset	**Northern Copepod Index**
Contributor	Bill Peterson
Organization	NOAA Fisheries Science Center, Fisheries Science

Dataset	**Pacific Decadal Oscillation Index (PDO)**

Contributor	Joint Institute for the Study of the Atmosphere and Ocean
URL	http://jisao.washington.edu/
Contact	Nathan Mantua

Dataset	**Rockfish in Common Murre Diet**
Contributor	William Sydeman
Contact	Sarah Ann Thompson
Associated Party	PRBO Conservation Science
URL	http://www.prbo.org/cms/index.php

Dataset	**Sea Level**
Contributor	Center for Operational Oceanographic Products and Services National Ocean Service NOAA
URL	http://co-ops.nos.noaa.gov/index.shtml
Associated Party	University of Hawaii Sea Level Center
URL	http://ilikai.soest.hawaii.edu

Dataset	**Sea Surface Temperature**
Contributor	Scripps Institution of Oceanography, Shore Stations Program University of California, San Diego
URL	http://shorestation.ucsd.edu

Dataset	**Small Plankton Volume**
Contributor	California Cooperative Oceanic Fisheries Investigations (CalCOFI)
URL	http://www.calcofi.org/newhome/index.htm
Contact	Jennifer Rodgers-Wolgast

Dataset	**Upwelling Index**
Contributor	NOAA Pacific Fisheries Environmental Laboratory
URL	http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/NA/data_download.html

Appendix 2. Complete and detailed methods.

Atmospheric and Oceanographic Indicators

Pacific Decadal Oscillation Index (PDO)

Computation of the Pacific Decadal Oscillation Index (PDO) was developed by Zhang et al. (1997). The PDO is derived from monthly sea surface temperatures on a 5x5 degree grid provided by the Hadley Center. Monthly anomaly fields were created for all grid points, and a monthly mean global sea surface temperature anomaly time series was then created for all months. Residual SST anomalies for the North Pacific were calculated by subtracting out the global mean anomaly from each North Pacific grid point from 20^o-65^o N (only in the Pacific Basin). Empirical Orthogonal Functions (EOFs) of the North Pacific residual SST anomaly fields were computed and all missing data points were ignored (set to zero). The PDO index is the leading principal component (EOF) from this analysis. To calculate PDO index values after 1993, observed North Pacific residual SST anomalies were projected onto the leading eigenvector from the EOF analysis. Data were downloaded from the Joint Institute for the Study of the Atmosphere and Ocean at the University of Washington, in cooperation with NOAA, at http://jisao.washington.edu/pdo/PDO.latest.

North Pacific Gyre Oscillation Index (NPGO)

The North Pacific Gyre Oscillation Index (NPGO) was downloaded from http://eros.eas.gatech.edu/npgo/data/NPGO.txt. The NPGO modes of climate variability emerge from analyses of Northeast Pacific sea-surface temperature anomalies (SSTa) and sea-surface height anomalies (SSHa) over the region (180^oW–110^oW; 25^oN–62^oN) (Di Lorenzo et al. 2008). Using empirical orthogonal function (EOF) analysis, fields are decomposed into a set of independent/uncorrelated spatial modes (the EOFs) whose temporal fluctuations are given by the corresponding Principal Components (PCs). The Pacific Decadal Oscillation (PDO) pattern emerges as the first EOF/PC of both SSTa and SSHa, while the NPGO represents the second EOF/PC.

Multivariate ENSO Index (MEI)

The Multivariate ENSO Index (MEI) is based on the six main observed variables over the tropical Pacific, including sea-level pressure (P), zonal (U) and meridional (V) components of the surface winds, sea surface temperature (S), surface air temperature (A), and total cloudiness fraction of the sky (C). These observations have been collected and published in the Comprehensive Ocean-Atmosphere Data Set (COADS) for many years. The MEI is computed separately for each of twelve sliding bi-monthly seasons (Dec/Jan, Jan/Feb,...Nov/Dec). After spatially filtering the individual fields (Wolter 1987), the MEI is calculated as the first unrotated Principal Component (PC) of all six variables (Wolter and Timlin 1993). Negative values of the MEI represent the cold ENSO phase, a.k.a. La Niña, while positive MEI values represent the warm ENSO phase (El Niño). Data were obtained at http://www.cdc.noaa.gov/people/klaus.wolter/MEI/table.html, from NOAA's Earth System Research Laboratory. Methods from http://www.cdc.noaa.gov/people/klaus.wolter/MEI/mei.html.

Argo current flow

Flow in the North Pacific, Alaska, and California Currents were calculated by Howard Freeland, Fisheries and Oceans Canada, from data collected by ARGO profiling floats. These floats are programmed to spend 10 days at 1000 m, followed by a profiling time dive to 2000 m and subsequent return to the surface to transmit data. Currents were computed by assessing dynamic surface height relative to 1000 m; flow was estimated from gradients in dynamic height. We calculated the standard deviation as well as residuals of the flow data by subtracting the mean from each value. Positive values indicate stronger than average flow, while negative values indicate weaker than average flow.

Upwelling Index (UI)

The Upwelling Index (UI) is calculated by NOAA's Pacific Fisheries Environmental Laboratory, available on ERDDAP. The index is calculated from estimates of the magnitude of the offshore component of the Ekman transport driven by geostrophic wind stress. Positive values indicate upwelling while negative values indicate downwelling. Geostrophic winds are calculated from 6-hourly and monthly mean surface atmospheric pressure fields that are provided by the U.S. Navy Fleet Numerical Meteorological and

Oceanographic Center (FNMOC). Methods and data from http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/NA/how_computed.html.

Sea surface temperature (SST)
Sea surface temperature (SST) data were collected from shore stations operated by the Shore Stations Program of Scripps Institution of Oceanography using precision ingraved stem mercury immersion thermometers manufactured by Kahl Scientific Instruments Corporation. Thermometers read in degrees Celsius, with 0.1 °C divisions, and though they are calibrated against certified primary standards during the manufacturing process, upon receipt, they are recalibrated by the Oceanic Data Facility at SIO to 0.01 °C accuracy. Methods and data from http://shorestation.ucsd.edu/methods/index_methods.html.

Sea level
Sea level measurements were compiled by the National Water Level Observation Network (NWLON), which is managed by the Center for Operational Oceanographic Products and Services (CO-OPS) (NOS 2008). Water levels have been recorded by a variety of instruments over the time series with continuing improvements in instrument accuracy and with occasional small shifts in instrument location (NOAA and Sanctuary 1997). Earliest water levels were observed and recorded by tide staff, but following technological innovations, water levels have been recorded (from 1975-1990) by analog-to-digital recorders, and (since 1991) by Aquatrek acoustic gauge. Verified products, such as monthly means for sea level, are made available over the Internet within one to four weeks after data collection (NOS 2008). Monthly data are an average of all daily values and were calculated if there were fewer than 7 days of missing values in the month. Sea level data used in this report were downloaded from the University of Hawaii Sea Level Center (http://uhslc.soest.hawaii.edu/), and methods described here for instrumentation and data averaging can be found in the station info at that site.

Lower Trophic Level Indicators

Chlorophyll-a
Satellite remotely-sensed chlorophyll concentration (mg m^{-3}) data were obtained from the Sea-viewing Wide Field-of-View Sensor (SeaWiFS; http://oceancolor.gsfc.nasa.gov/SeaWiFS/). Monthly Level 3 mapped 9 km resolution data were provided by the NASA Goddard Space Flight Center (http://oceancolor.gsfc.nasa.gov/). Instrument bands for the SeaWiFS sensor are 402-885 nm wavelengths, primarily within the visible light spectrum and, therefore, affected by cloud cover. We used monthly composites of 9x9 km pixels to assess changes in chlorophyll a; monthly composites minimized data loss while permitting seasonal comparisons.

Small plankton volume
Small plankton volume was measured from spatially averaged displacement volume of zooplankton sampled on the California Cooperative Oceanic Fisheries Investigation surveys. Zooplankton was sampled with various devices, but most recently with 71 cm diameter paired bongo nets, equipped with 0.505 mm mesh. Bottom depth permitting, the nets were towed obliquely from 210 meters to the surface for a standard tow time of ~ 21 minutes. The bio-volume filtered was standardized by flowmeter readings and the area of the net opening. One codend was preserved with buffered formalin and the other was alcohol preserved or frozen. Biomass, as wet displacement volume, after removal of large (>5 ml) organisms, was determined in the laboratory. These procedures were summarized by Kramer et al. (1972). Methods and data from http://www.calcofi.org. Data were summarized for the "core" area off southern California.

Northern Copepod Index
NOAA's Northwest Fisheries Science Center samples zooplankton (with a focus on copepods) along the Newport Hydrographic Line biweekly during the upwelling season and monthly during winter; this time series has been continuous since May 1996. Plankton were sampled with a vertically-towed 0.5 m, 0.202 mm net. Zooplankton were processed in the laboratory by subsampling with a Stempel pipette. Species and developmental stage of copepods were enumerated with the aid of a dissecting microscope. Counts were converted to number of individuals per m^3 of water using appropriate conversion factors. Biomass

was estimated by multiplying the number of individuals per m³ by the dry weight of the taxa (using values from either literature or laboratory measurements). The "northern/boreal" copepod index was calculated for three species with cold-water affinities: *Pseudocalanus mimus*, *Acartia longiremis*, and *Calanus marshallae.* The index was calculated after log-transforming biomass values, finding average biomass for each month, and subtracting monthly values from the long-term mean for each month. Methods from http://www.nwfsc.noaa.gov/research/divisions/fed/oeip/ka-hydrography-zoo-ichthyoplankton.cfm.

Euphausiid biomass
Biomass of larvae of the euphausiid *Thysanoessa spinifera* was estimated from samples collected from four stations in Barkley Sound (Vancouver Island, British Columbia) in January and then monthly from March through November each year; in 1994-1997, samples were collected in January, March, June, August and October only. Sampling was conducted at night using obliquely towed bongo nets (60 cm 0.33 mm mesh) to within 10 m of the bottom. The entire sample from one codend was preserved in 5% formalin, then size-fractionated using 250, 500 and 1700 µm sieves to separate adults and sub-adults. Calyptopis and furcilia larvae were identified to species and stage, then counted and measured. Larvae were identified using the descriptions presented by Summers (1993). Median annual biomass was estimated from March to the following February to reflect the "biological year" on the basis of the beginning of spawning events.

Mid and Upper Trophic Level Indicators

Fish
Juvenile Rockfish Index (JRI)
Abundance data of age-0 pelagic juvenile rockfish (*Sebastes spp.*) were collected in annual trawl surveys conducted by the National Marine Fisheries Service in May and early June from 1983-2007. For the first twenty years (1983-2003), the survey covered the central California coastal region from Bodega Bay (38"20'N) to Cypress Point (36"35'N). Samples were taken at night with a 14 x 14-m modified Cobb trawl with a 9.5 mm stretched mesh codend liner (Wyllie-Echeverria et al. 1990). Standard trawling depth was 30 m, except at near-shore shallow-water stations (bottom depths less than 60 m), where the standard trawling depth was 10 m. Trawling lasted 15 minutes at depth, and all trawls were completed between the hours of 2100 and 0600. Since 2004 the area surveyed has been extended from approximately the U.S./Mexico border to a survey line just south of Cape Mendocino, California. As ongoing efforts suggest that mesoscale patterns of rockfish abundance differ throughout this larger region from year to year, only the index developed from the core stations monitored consistently throughout the duration of the survey are presented here. The Juvenile Rockfish Index (JRI) was calculated after the raw catch was adjusted to a common age of 100 days to account for interannual differences in age structure. To develop a relative annual index of abundance for each species, tow-specific catches and a Delta-GLM approach, which combines a binomial model for presence/absence information (using a logit link) with a model of catch per unit effort for positive tows to remove spatial (station) and seasonal (ten-day period) effects on catch rate, was used. Specification of the error distribution for the positive observations was determined based on Akaike Information Criteria, and the product of the year effects of the two models (binomial and positive models) was used as the final index of abundance.

Hake abundance
The juvenile hake index was obtained from Helser and Martell (2007, table 11a). Juvenile hake (longer than 30 mm) were collected as part of the NMFS Southwest Fisheries Science Center mid-water trawl survey (Sakuma and Ralston 1997). Catches of juvenile hake were transformed by $\log_e$(number/trawl+ 1). The index was base CPUE from the Monterey outside stratum only.

Rockfish in Common murre diet
PRBO Conservation Science (formerly Point Reyes Bird Observatory) has conducted studies of seabird food habits on Southeast Farallon Island since 1972 (Ainley et al. 1990, Mills et al. 2007). Common murres (*Uria aalge*) provision young with single prey items brought to the colony and forage fish are identified by observers ~10 m from feeding parents. Because it is difficult to identify juvenile rockfish to the species level when not in hand, information on which rockfish species comprise the diet of murre is

limited, although most are likely *Sebastes jordani*, *S. entomelas*, and *S. flavidus*. The percentage of the diet composed of juvenile rockfish was estimated by dividing the number of rockfish observed/collected by the total number of forage fish identified in the diet each year. The long-term mean take of juvenile rockfish was calculated, and the annual data was expressed as an anomaly (annual – long-term mean) statistic.

Herring Spawning Biomass

Herring spawning biomass was estimated by the California Fish and Game Commission, and is reported each year in an annual "Final Supplemental Environmental Document for Pacific Herring Commercial Fishing Regulations" (http://www.dfg.ca.gov/marine/herring/ceqa.asp). From 1979-1989 and 2003-present, the spawning biomass estimate was derived from spawning deposition surveys in spawning grounds in San Francisco Bay. From 1990-2002, the estimate was derived from a combination of the results of the spawning deposition surveys and hydroacoustic surveys.

Herring landings

Data for herring fisheries landings were compiled by the California Department of Fish and Game (DFG) from the weight of the catch brought to shore for sale (landings) recorded by fish buyers, markets, and canneries (Mason 2004), and are published annually in the CalCOFI report. Landings data were de-trended to account for changing fishing effort through time.

Coho Oregon Production Index

The Oregon Production Index (OPI) is the percent of smolt-to-adult returns for Coho salmon in Oregon. Data used in these calculations were obtained from tables in the Pacific Fishery Management Council's Preseason Reports (http://www.pcouncil.org/salmon/salpre.html). The percent smolt-adult returns were calculated by the formula SAR=a/(b*1000)*100, where SAR is the percent smolt-adult return, a is the adult OPIH (thousands), and b is the total public hatchery smolts OPI (millions).

Chinook fall escapement

Several indices of Chinook salmon abundance are calculated and reported by the Pacific Fishery Management Council (PFMC) each year. The Central Valley Index (CVI) is a measure of the overall abundance that includes the ocean harvest south of Point Arena and the total escapement into the Central Valley. The fall escapement represents the salmon that "escape" the fishery and return to spawn in the Central Valley. The CVI was not produced after 2008 (i.e. 2007 data), and was replaced with a similar Sacramento Index. Because the two indices are highly correlated, we use a dataset compiled of fall escapement values from the CVI from 1970-2007, and the fall escapement value from the Sacramento Index for 2008.

Seabirds

Cassin's auklet reproductive success

To determine the reproductive success of seabird species, a sample of focal breeding pairs was studied by PRBO Conservation Science throughout each nesting season at the breeding colony to determine reproductive performance (Sydeman et al. 2001). Cassin's auklets (*Ptychoramphus aleuticus*) were monitored at Southeast Farallon Island. Individual nest sites were monitored (n=15–500 nests per year) at 1–7 day intervals for breeding activity. Fledging was assumed with departure of young from the colony. Reproductive performance was defined as the number of fledged offspring per breeding pair per year.

Common murre mortality

Data on Common murre mortality were collected from 32 beach segments between Bodega Head (38° 18.492' N, -123° 4.024' E), in Sonoma County, south to Año Nuevo in San Mateo County (37° 6.422' N, 122° 17.589' E) (Roletto et al. 2003). Surveys for each beach were conducted at either two- or four-week intervals. Teams of 1-4 people surveyed beaches in a zigzag fashion and scanned the edges of any upper dunes, recording the species and number of dead birds and presence or absence of oil. Each carcass encountered was photographed for additional species, age and sex verification by an expert ornithologist. Numbers of birds recorded were quantified as monthly encounter rates (i.e. number of birds per kilometer of beach surveyed). More than 21,000 kilometers of beach were surveyed between October 1993 and August 2008, with an average of 118 kilometers surveyed each month.

Marine Mammals

California sea lion pup abundance

Abundance of California sea lion pups was measured in Southern California at multiple rookeries, including locations on Santa Barbara Island, San Nicolas Island, and San Miguel Island. Prior to 1981, abundance data were obtained from the literature and are a combination of ground counts and 35 mm format aerial photographic counts. Pup abundance data were obtained by ground counts between 1981 and 1987. From 1987-1997, 126 mm format aerial photography was used along with ground counts to census California sea lion pups. Since 1998, 126 mm format aerial photography has been used to count sea lion pups (with a ground count at one small rookery island to compare with the photo count or as a backup when the aerial survey did not go as planned). Methods for data collection can be found in Lowry (1999). With the color transparency photograph illuminated on a light table, pups were counted through a 7-70 X zoom binocular microscope. Non-decomposed dead pups were not distinguishable from live pups and were included in the counts. Carcasses of decomposed pups were tallied but were not included in the counts. Pups were marked by pen on a clear acetate plastic overlay as each was counted. Marks on the acetate were compared and verified with overlapping photographs (allowing the counter to view each pup from two additional angles to verify the marked pup counted). After completing the confirmation procedure, the acetate was placed on another photograph at the exact position of the coastline where the count ended previously and the count resumed on the uncounted portion. Pups were counted in this manner for each aerial photographic census until the entire coastline was examined. High-altitude (1,400 m) photographs and knowledge of geographical features on the ground were used to orient the low-altitude photographs. For ground counts, live pups were tallied with mechanical hand-counters as animals were viewed by naked eye or through binoculars. Although each ground observer could make several counts of the same group of pups, only the count judged by the observer to be best was recorded.