

ENVIRONMENTAL INFLUENCES ON SPECIES COMPOSITION OF THE COMMERCIAL HARVEST OF FINFISH AND INVERTEBRATES OFF CALIFORNIA

JERROLD G. NORTON AND JANET E. MASON

Pacific Fisheries Environmental Laboratory
Southwest Fisheries Science Center
National Marine Fisheries Service, NOAA
1352 Lighthouse Avenue
Pacific Grove, California 93950-2097
jnorton@pfeg.noaa.gov

ABSTRACT

California commercial finfish and invertebrate landings from catches made in waters off California were examined to evaluate the relationship of fluctuations in species composition to environmental influences during 1930–2000. We considered empirical orthogonal function (EOF) analysis on \log_e -transformed annual weight for species and species groups. We developed ocean process indexes by accumulating monthly anomalies of central California sea surface temperature (SST) and southward wind stress (SWS), SST from La Jolla, California, and the Pacific Decadal Oscillation (PDO). Time variation of the first EOF, which explains more than 25% of the variance, is significantly correlated with the La Jolla SST and the PDO indexes. Time variation of the second EOF, which accounts for 20% of the variance, is significantly correlated with the SWS index, and its variability is similar to concurrent ecosystem changes. Individual landings series were not adjusted for fishing effort, so we estimated annual effort using the number of boats in the fishery as a proxy. Correlation of the species composition to the effort proxy and to inflation-adjusted total ex-vessel value indicates that fishery factors have acted together with environmental events and fisheries management regulations to produce nearly continuous change in the species composition of commercial finfish and invertebrate landings from 1930 to 2000.

INTRODUCTION

Changes in the species composition of fish and invertebrates in the ocean off California represent inter- and intraspecies adjustment to harvest and to environmental changes (Ryther 1969; McGowan 1990; McGowan et al. 1998; Stenseth et al. 2002). We have examined and compared annual landings of more than 43 species of commercially harvested fish and invertebrates for indications of environmental forcing. The landings records were compiled by the California Department of Fish and Game and have been available in annual publications dating from 1928 (Bureau of Marine Fisheries 1951; Oliphant 1979; Oliphant et al. 1990; Eres 2002). The

Pacific Fisheries Environmental Laboratory of the Southwest Fisheries Science Center has assembled these data and converted them to computer accessible formats (CACom).¹ CACom contains primarily those California landings harvested within about 400 km west of the California coast. Catch-locations were provided by fishers and recorded on landings receipts, which are the source of the CACom data (Bureau of Marine Fisheries 1951; Oliphant 1979; Oliphant et al. 1990; Eres 2002).

Parrish et al. (2000), in their study of environmental variability in the northeastern Pacific Ocean, developed climate indexes consisting of 3-year running means of sea surface temperature (SST) and southward wind stress (SWS). They summarized the Comprehensive Ocean-Atmosphere Data Set (COADS) for a well-sampled coastal area extending 200 km seaward off central California (fig. 1). Their 3-year means (fig. 2) are useful in delineating environmental events that may impact commercial landings. Year-to-year environmental events may be smoothed by market factors, the longevity of harvested species, migrations, and harvest regulation, but longer-lasting events are expected to be evident by changes in the species composition of the landings. Multi-year events extend over larger areas (McGowan 1990) and would be more likely to affect statewide landings.

The central hypothesis of this study is that temporal changes in the proportion of species and species groups in the landings will correspond to the environmental patterns discussed by Parrish et al. (2000) and illustrated in Figure 2. First, central California SST and SWS have fluctuating covariability that may be found in the patterns of change among CACom species. Second, Parrish et al. (2000) found that some of the highest SST means of the twentieth century occurred during the 1957–62 period (fig. 2). CACom variation in species composition may respond to this anomalous event. Third, Figure 2 illustrates a well-documented northeastern Pacific climate change during 1973–82 (Norton et al. 1985; Ebbesmeyer et al. 1991; Miller et al. 1994; Chavez et al. 2003) that may be indicated by persisting shifts in

[Manuscript received 18 April 2003.]

¹Mason, J. E. 2003. Historical patterns from 74 years of commercial landings from California waters.

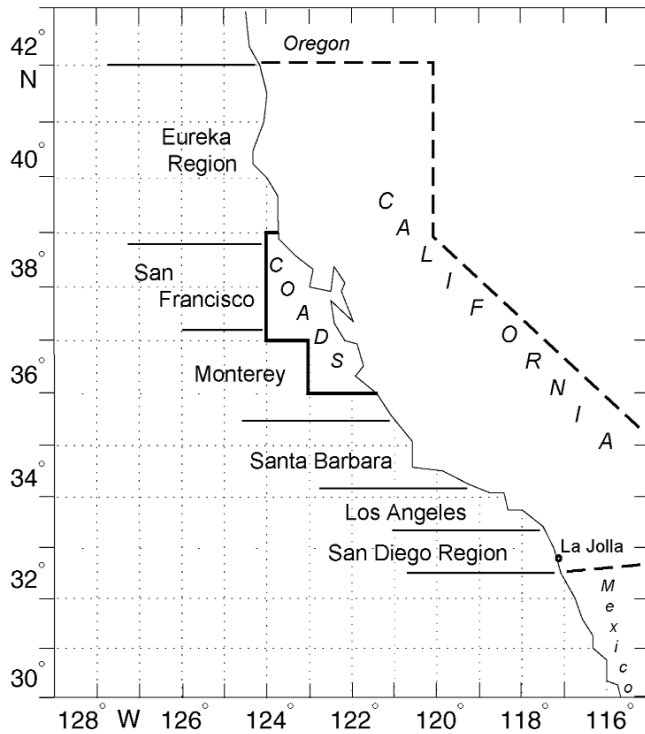


Figure 1. Statistical areas used in the California commercial landings of fish and invertebrates (CACom) data. Weight of catch for the statistical areas was combined for each market group and summed for each year. Region labeled "COADS" indicates central California coastal areas where data from Comprehensive Ocean-Atmosphere Data Set was summarized by Parrish et al. (2000) and for this study.

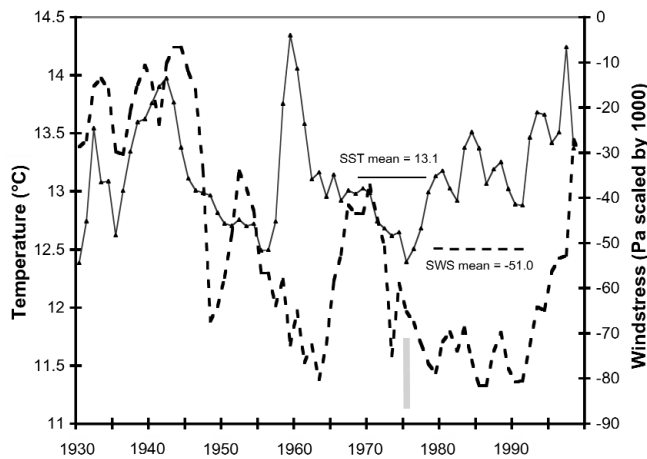


Figure 2. Fluctuations in 3-year seasonally corrected running means of sea surface temperature (SST) in °C and southward wind stress (SWS) in Pa $\times 1,000$ from the central California area (fig. 1). SWS increases downward (right-hand scale); solid line shows SST, and dashed line shows SWS; horizontal lines show the 1930–2000 overall means (revised from Parrish et al. 2000).

CACom species composition. Finally, SST and SWS have similar trends in the late 1990s after a 20-year period of dissimilar trends, suggesting a fourth significant environmental shift (fig. 2) that may have affected the composition of species in the landings.

Previous studies have addressed the fluctuation of certain CACom species over various periods (Godsil 1938; Sund and Norton 1990; Kalvass and Hendrix 1997; Norton 1999; Leet et al. 2001). This is the first examination of temporal variation in the composition of market group ensembles representing more than 85% of the CACom total landings weight from 1930 to 2000.

METHODS

The CACom data were derived from thousands of reports received from hundreds of fish dealers purchasing the catch from fishers in dozens of ports throughout California (fig. 1). CACom data are cataloged as market groups that represent either a single species or a mixture of species caught and sold together. Time series representing ensembles of CACom market groups, environmental indexes, and fishery indicators were developed and compared visually and by simple correlation to evaluate relationships. We limited the analyses to 43 market groups that have landing records throughout the 1930–2000 period and examined two subsets of the 43-group ensemble: (1) all market groups representing a single species (29 species), and (2) all single-species groups that were recorded in the landings in every year from 1930 to 2000 (25 species). Common species names used throughout this report are those of Miller and Lea (1972) and Leet et al. (2001).

Empirical Orthogonal Functions and Their Time Variation

First, the three market group ensembles were assembled into three data matrixes where each market group is represented by a column in the data matrix and the variation in annual landing weight over 71 years is presented as rows. Second, corresponding correlation matrices were formed after \log_e -transformation of each of the three data matrixes. Third, the eigenvalues and corresponding eigenvectors (empirical orthogonal functions or EOFs) of each correlation matrix were computed. Reviews and examples of these procedures are given by Kutzbach (1967), Davis (1976), and Cloern and Jassby (1995).

The eigenvalues give estimates of the data matrix variance explained (extracted) by each corresponding empirical orthogonal function (EOF). By convention, EOF1 has the largest eigenvalue, EOF2 the second largest, and so forth. Of the 25–43 possible EOFs, only EOF1 and EOF2, which are significant at less than the 0.05 level (North et al. 1982), are discussed in this report. The products of the EOFs and the corresponding \log_e -transformed data matrixes give the time-variable coefficients (C) and indicate the unique variation of each EOF through the 1930–2000 period (Kutzbach 1967). The time-variable coefficients series (C) are also called "principal components."

TABLE 1
 Loading Values for First Empirical Orthogonal Function (EOF1)

N = 43, all species and groups	N = 29, all species	N = 25, local species
0.90 California barracuda	0.90 California barracuda	0.88 California barracuda
0.85 Pacific halibut	0.87 Pacific halibut	0.83 Pacific sardine
0.83 Pacific sardine	0.87 Pacific sardine	0.64 giant sea bass
0.64 white seabass	0.71 ocean whitefish	0.53 white seabass
0.63 giant sea bass	0.60 giant sea bass	0.51 yellowtail
0.61 ocean whitefish	0.54 California sheephead	0.50 California sheephead
0.52 California scorpionfish	0.53 California scorpionfish	0.50 California scorpionfish
0.46 bluefin tuna	0.53 white seabass	0.47 bluefin tuna
0.42 turbot ¹	0.45 bluefin tuna	0.34 Pacific mackerel
0.39 California sheephead	0.45 yellowtail	0.20 California halibut
0.37 yellowtail	0.38 Pacific mackerel	-0.09 spiny lobster
0.29 Pacific mackerel	0.22 California halibut	-0.12 Pacific bonito
0.23 smelt ¹	0.00 spiny lobster	-0.26 swordfish
0.20 flounder ¹	-0.18 skipjack tuna	-0.29 white croaker
0.19 abalone ¹	-0.20 Pacific bonito	-0.44 Pacific hake
0.10 California halibut	-0.26 white croaker	-0.44 Dungeness crab
0.08 salmon ¹	-0.27 yellowfin tuna	-0.50 albacore
0.07 sharks ¹	-0.28 swordfish	-0.51 cabezone
0.03 octopus ¹	-0.40 Dungeness crab	-0.56 lingcod
0.03 flyingfish ¹	-0.43 Pacific hake	-0.57 Pacific herring
0.02 perch ¹	-0.47 cabezone	-0.58 Pacific butterfish
-0.03 skates ¹	-0.48 albacore	-0.61 jack mackerel
-0.07 spiny lobster	-0.54 Pacific herring	-0.68 California market squid
-0.21 Pacific bonito	-0.57 Pacific butterfish	-0.78 northern anchovy
-0.21 white croaker	-0.57 lingcod	-0.84 sablefish
-0.27 skipjack tuna	-0.58 jack mackerel	
-0.34 albacore	-0.64 California market squid	
-0.39 Dungeness crab	-0.79 northern anchovy	
-0.41 yellowfin tuna	-0.85 sablefish	
-0.41 Pacific butterfish		
-0.42 swordfish		
-0.42 jack mackerel		
-0.52 lingcod		
-0.59 cabezone		
-0.59 sanddab ¹		
-0.60 Pacific hake		
-0.66 Pacific herring		
-0.69 northern anchovy		
-0.70 California market squid		
-0.77 rock crab ¹		
-0.84 soles ¹		
-0.87 rockfish ¹		
-0.87 sablefish		

¹Multispecies CACom market group.

The EOFs are vectors or series of loading values that represent unique patterns of species variation. Each column (market group) has a loading value within the EOF. The loading values and their order within the EOF make the EOF series unique. Tables 1 and 2 give EOF1 and EOF2, respectively, for each of the three data matrices. Loading values are also measures of the similarity (or correlation) of temporal variation in that market group to temporal variation in the corresponding C-series. Negative loading values (loadings) indicate negative correlation.

The C-series shown in Figure 3 are time series of species composition in the landings. Positive trends or slopes of the C-series (up and to the right of the graph) show that positively loaded species (tabs. 1 and 2) are becoming more abundant in the landings (relative to their range of abundance). Each market group series has

distinct autocorrelation, which is dependent on the life cycle of the fishes as well as the fishery. This autocorrelation is evident in the C-series (fig. 3), but the C-series are not accumulated or integrated over time.

Accumulated Physical and Environmental Indexes

Environmental time series were examined as monthly anomalies accumulated over the 1930–2000 period. Accumulation (integration through time) adds persistence (autocorrelation) to the physical series, making them similar to the C-series. Anomaly accumulation also emphasizes continuity in the processes that produce the anomaly (Norton and McLain 1985; Klyashtorin 2001). In addition to central California time series derived from the same data as those presented by Parrish et al. (2000),

TABLE 2
 Loading Values for Second Empirical Orthogonal Function (EOF2)

N = 43, all species and groups	N = 29, all species	N = 25, local species
0.71 jack mackerel	0.63 white seabass	0.61 white seabass
0.68 Pacific butterfish	0.57 Pacific butterfish	0.58 Pacific butterfish
0.65 albacore	0.56 jack mackerel	0.50 jack mackerel
0.60 abalone ¹	0.41 albacore	0.40 northern anchovy
0.58 northern anchovy	0.40 northern anchovy	0.37 albacore
0.56 soles ¹	0.25 giant sea bass	0.34 giant sea bass
0.56 flyingfish ¹	0.16 lingcod	0.26 lingcod
0.52 flounder ¹	0.12 California scorpionfish	0.19 Pacific bonito
0.47 lingcod	0.11 white croaker	0.06 white croaker
0.42 Pacific bonito	0.04 bluefin tuna	0.04 California scorpionfish
0.41 perch ¹	0.02 California barracuda	0.03 bluefin tuna
0.36 salmon ¹	0.01 Pacific bonito	-0.04 California barracuda
0.35 Dungeness crab	0.00 Pacific halibut	-0.08 yellowtail
0.30 white croaker	-0.08 Dungeness crab	-0.13 Dungeness crab
0.28 turbot ¹	-0.08 Pacific sardine	-0.17 Pacific sardine
0.21 white seabass	-0.22 yellowtail	-0.23 sablefish
0.19 sablefish	-0.28 spiny lobster	-0.35 California market squid
0.03 octopus ¹	-0.29 sablefish	-0.45 spiny lobster
-0.02 rockfish ¹	-0.32 California market squid	-0.61 Pacific mackerel
-0.10 rock crab ¹	-0.41 ocean whitefish	-0.61 swordfish
-0.15 spiny lobster	-0.55 Pacific mackerel	-0.62 cabezone
-0.15 yellowfin tuna	-0.57 cabezone	-0.63 Pacific herring
-0.19 Pacific herring	-0.58 skipjack tuna	-0.63 California halibut
-0.19 California scorpionfish	-0.61 Pacific herring	-0.69 Pacific hake
-0.26 sharks ¹	-0.61 California halibut	-0.71 California sheephead
-0.26 bluefin tuna	-0.67 California sheephead	
-0.27 skipjack tuna	-0.68 Pacific hake	
-0.28 swordfish	-0.71 yellowfin tuna	
-0.30 giant sea bass	-0.72 swordfish	
-0.36 yellowtail		
-0.36 sanddab ¹		
-0.41 Pacific halibut		
-0.43 California market squid		
-0.43 Pacific sardine		
-0.46 California barracuda		
-0.46 smelt ¹		
-0.47 Pacific mackerel		
-0.48 Pacific hake		
-0.49 cabezone		
-0.50 ocean whitefish		
-0.50 skates ¹		
-0.55 California halibut		
-0.78 California sheephead		

¹Multispecies CACom market group.

we examined two other physical data sets: the SST from Scripps Institution of Oceanography at La Jolla and the Pacific Decadal Oscillation (Mantua et al. 1997). The Pacific Decadal Oscillation (PDO) series, derived from fields of extratropical North Pacific SST anomalies was accumulated from monthly values. For the central California series and the La Jolla SST, the mean of the 1930–2000 period was determined for each month and the corresponding monthly anomalies from those means accumulated. Accumulated SST, SWS, and PDO anomaly series are indicated as A-SST, A-SWS, and A-PDO.

Accumulation filters most seasonal and many inter-annual events from the record. Accumulated series are interpreted in terms of processes that together cause negative or positive anomalies. If a series trends in a positive (negative) direction, processes that lead to positive

(negative) anomalies dominate the interval. A steady or horizontal tendency (trend or slope $\cong 0$) indicates a period of average temperatures. Changes in trend sign indicate change in anomaly sign and probably changes in ecological effects. If these accumulated anomaly series match the C-series, it suggests physical environmental processes have affects lasting from years to decades on species abundance in the CACom landings.

Fishery Variables

We assembled two variable series to describe fishery affects: the total number of boats reporting catch each year and the total dollar value of California landings adjusted to base year 2000.

The 43 market groups with landings reported throughout the 1930–2000 period represent more than 85% of

TABLE 3
**Correlation Between Time-variable Coefficients (C_n)
 and Accumulated Environmental and Fisheries Indexes**

Index	C_n	
	EOF1	EOF2
CC A-SST ¹	0.72	0.44
A-SWS ¹	0.08	0.84*
La Jolla A-SST	0.95**	0.04
A-PDO	0.85**	0.01
Boats ²	-0.59**	0.47**
Value ²	-0.27*	0.05

¹Summarized from the central California COADS area (see fig. 1).

²Adjusted numbers of boats and adjusted total value.

** $p < 0.01$. Significance levels were corrected for effective degrees of freedom.

* $p < 0.05$.

the California commercial landings throughout 1930–2000. The major fishery not represented in the 43-group ensemble is the red sea urchin fishery that began in about 1975. The numbers of boats used by the urchin fishery (Kalvass and Hendrix 1997; Thomson 2001; P. E. Kalvass, pers. comm.) were subtracted from the total-boats time series, and the percentage of total value contributed by urchin landings was subtracted from the total-value time series. The total-boats index was also adjusted to remove boats that engaged primarily in tropical tuna harvests (Godsil 1938; Herrick 1981; E. Everett, pers. comm.), since the landings from waters south of California were excluded from the CACom data.

Each correlation has an effective number of degrees of freedom, determined by the long-lag correlation method using lags of 20–30% (Chelton 1983). Table 3 summarizes the correlations and significance levels.

RESULTS

The time variations of EOF1 and EOF2, C1 and C2, respectively, represent two independent patterns of variation in the ensembles of CACom market groups. Corresponding patterns of variation are apparent in the environmental and fishery variables.

Patterns of Species Variation

Patterns of species variation represented by EOF1₄₃ account for 26% of the variance in the 43-group data matrix (fig. 3). When the time-variable coefficients for EOF1₄₃ (C1₄₃) had higher values, as at the left in figure 3a, there were higher landings of barracuda, Pacific halibut, sardine, and white seabass (positively loaded species, tab. 1) and lower landings of sablefish, rockfish, soles, and rock crab (negatively loaded species), relative to their landings ranges. C1₄₃ has a generally negative trend through the 1930–82 period (fig. 3). The negative trend is followed by a generally positive trend from 1983 until 1998, indicating a moderate resurgence of positively loaded species (tab. 1). EOF1₄₃ species-composition pat-

terns (C1₄₃) had low trend during 1976–82, indicating relative stability during this period.

The EOF2₄₃-species composition pattern explains 20% of the CACom data variability (tab. 2). C2₄₃ has little trend during 1930–44, suggesting stable EOF2₄₃-species composition pattern in the landings (figure 3d). A sharp increase in C2₄₃ occurs in 1946–47 followed by a general increase until 1970, indicating shifts toward positively loaded species, such as white seabass, jack mackerel, and northern anchovy (fig. 3d). After 1977, sharp decreases occurred in C2₄₃ until 1997, indicating shifts to negatively loaded EOF2₄₃ species, including California sheephead, Pacific mackerel, and California market squid (tab. 2). A minor C2₄₃-trend reversal occurs in 1998. C2₄₃ undergoes large changes during the 1973–82 period when C1₄₃ becomes most stable. These two temporal patterns, C1₄₃ and C2₄₃, indicate two modes of change in species composition. The species contributing most strongly to each mode are those with the largest positive or negative loading values (tabs. 1 and 2).

To examine EOF₄₃ and C₄₃-series robustness, we limited the input data matrices to the 29 single-species market groups and to the 25 single-species market groups with landings recorded in each of the 71 years. A minor difference in C-series between the 43-group and the 29-group ensembles (fig. 3b) is a 1975 minimum in C1₂₉ corresponding to the minimum in central California mean SST (fig. 2). The minimum in C1₄₃ occurs in 1982 and the minimum in C1₂₅ is indistinct within the 1975–82 period. C1₂₅ and C2₂₅ have less interannual variability, but long-term trends remain (figs. 3c,f). In addition to the overall trends, two shorter events are apparent in the C-series from each data ensemble: (1) there is a transient increase in C1 beginning in 1958 and lasting until 1962 that is similar to increases in SST and SWS (fig. 2), and (2) C1 and C2 have trend reversals involving the last three years of the record.

Correlation of EOF1 and EOF2 with Environmental Variables

Time variation of EOF1 and EOF2 calculated from the ensemble of 29 single-species groups (C1₂₉ and C2₂₉) have the greatest variability (fig. 3) and are used in the correlation to environmental indexes because these correlations have more degrees of freedom (4–15).

Significant correlation (correlation coefficient $r = 0.95$, $p < 0.01$) is found between C1₂₉ and accumulated La Jolla SST anomalies (A-SST). Both series have discontinuities during the 1930–33 and the 1957–62 anomalous events (fig. 4). There is a general decline in positively loaded species and an accumulation of negative SST anomaly from 1930 to 1976. From 1976 to 1982, there is a transitional period when La Jolla SST anomalies were small and the EOF1₂₉-species compo-

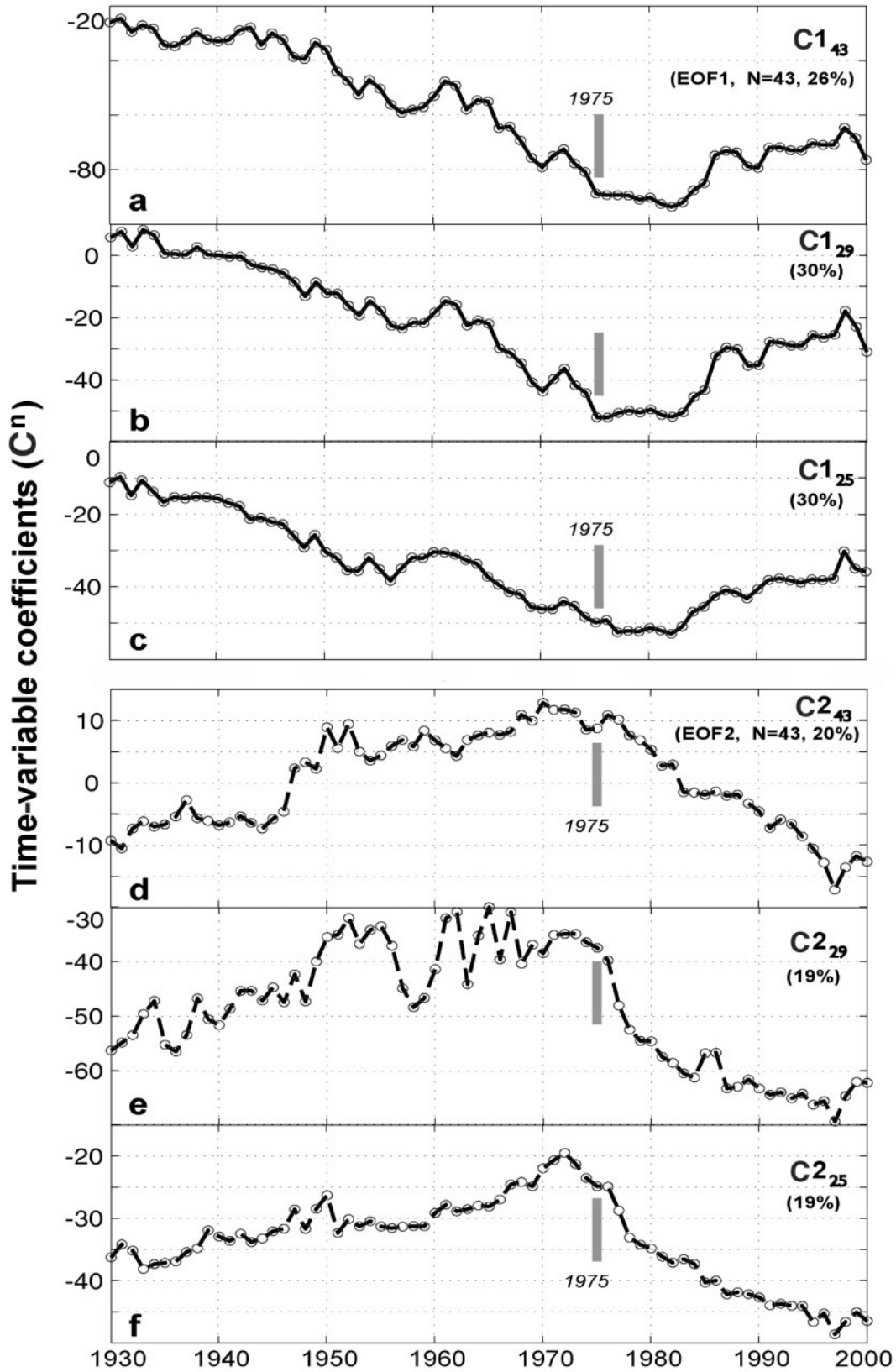


Figure 3. Time-variable coefficients (C) for the ensemble of the 43, 29, and 25 market groups having landings throughout 1930–2000. Time-variable coefficients for EOF1 ($C1$, solid line) are at the top (a, b, c). Panels d, e, and f give the time-variable coefficients for EOF2 ($C2$, dashed line). Circles indicate C -values for each year; only the connecting lines are used in Figures 4–7.

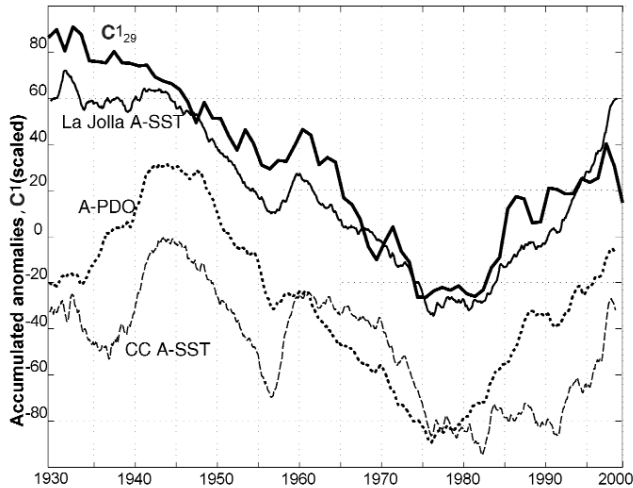


Figure 4. Accumulated monthly anomalies of the environmental indexes discussed in the text and annual $C1_{29}$ values for EOF1₂₉ (thick solid line) are scaled to show similarities. Accumulated SST anomaly from the La Jolla shore station (La Jolla A-SST, thin solid line); accumulated Pacific Decadal Oscillation (A-PDO, dotted line); and accumulated SST anomaly from the central California area (CC A-SST, dashed line).

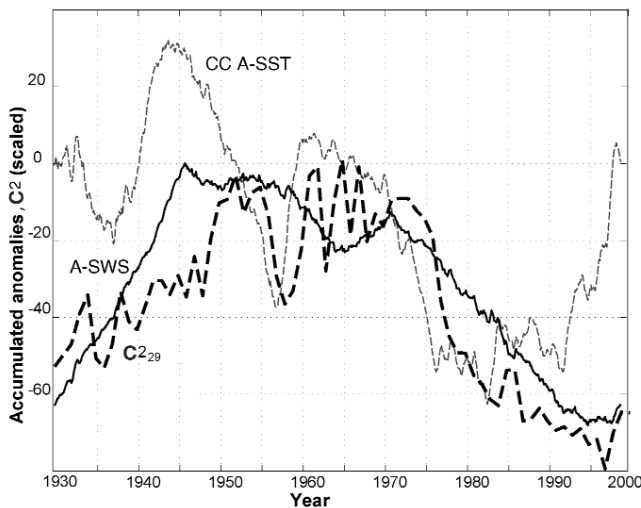


Figure 5. Accumulated monthly anomalies of the environmental indexes discussed in the text and annual time-variable coefficients ($C2_{29}$) values for EOF2₂₉ (thick dashed line) are scaled to show similarities. Accumulated central California SWS anomaly (A-SWS, thin solid line); accumulated SST anomaly for the central California area (CC A-SST, dashed line). Scaling and offsets are as follows: $C2_{29} \times 2$, $+60^\circ\text{C}$; A-SWS $\times 10$ Pa; CC A-SST, axis.

sition pattern was more stable (fig. 4). After 1982, the EOF1₂₉-species composition pattern trends of 1930–75 are reversed along with the trend in La Jolla A-SST and the A-PDO. The A-PDO, which shows the same trends and discontinuities as the La Jolla A-SST during 1944–2000, is also significantly correlated to $C1_{29}$ ($r = 0.85$, $p < 0.01$), suggesting continuity between EOF1₂₉-species composition pattern changes and North Pacific basinwide forcing. La Jolla SST has variability similar to that found throughout much of the northeastern Pacific Ocean (McGowan et al. 1998).

Significant correlation ($r = 0.84$, $p < 0.05$) is found between $C2_{29}$ and central California A-SWS (tab. 3, fig. 5). $C2_{29}$ and central California A-SWS have positive trends from 1930 until 1945 in A-SWS and until 1952 in $C2_{29}$ (fig. 5). By convention southward stress is given a negative sign, therefore larger SWS values indicate periods of less intense SWS. During the 1950–70 period there is high variability in $C2_{29}$ but little overall trend in A-SWS and $C2_{29}$. In 1970 A-SWS starts a period of decline (greater SWS) until 1994. After a 3-year period of essentially no change in EOF2-species composition pattern from 1971 to 1973, $C2_{29}$ trends sharply negative from 1974 to 1977 and continues this generally negative trend until 1997 (fig. 5). A trend reversal is indicated during 1998–2000. Major trend changes in A-SWS precede the $C2_{29}$ -trend changes by 3 to 8 years (fig. 5), suggesting fishery responses to physical environmental influences.

The patterns discussed by Parrish et al. (2000) and illustrated in Figure 2 correspond to changes in landings patterns in the CACom data. First, dissimilar temporal patterns in C1 and C2 series are consistent with their apparently unique correlation to La Jolla A-SST and A-SWS, respectively. Second, some of the highest central California SST means of the twentieth century occurred during the 1957–62 period (fig. 2), a period marked by a trend in C1 to more positively loaded species. Third, the northeastern Pacific climate change of 1973–82 is indicated by a negative trend in C1 during the early 1970s, followed by a relatively stable period. C2 shows the 1973–82 climate shift by continuous change to more negatively loaded species (fig. 3). Finally, C1 and C2 have robust changes during the cooler ocean climate following the 1997–98 California El Niño period.

Fisheries Variation

The numbers of boats reporting landings and the annual ex-vessel value of California landings series (see “Methods” section) indicate year-to-year changes in the fishery. These indexes separate 1930–2000 into three fisheries intervals (figs. 6 and 7). First, the 1930–52 period includes the rise and fall of the great sardine fishery that contributed more than 50% of the value and about 80% of the landings weight. Second, there is a more stable interval in the numbers of boats and total value of the landings from 1953 to 1972. During the third fisheries interval (1973–2000), there was a rapid rise in the number of boats and the value of landings from 1973 to the 1977–80 maxima followed by a 20-year decline in each variable back to pre-1970s levels (figs. 6 and 7).

Significant correlation is found between $C1_{43}$ and both boats and total annual ex-vessel value (tab. 3). These relationships are stronger during the last two fisheries intervals (fig. 6). The sign of EOF1₄₃ has been reversed

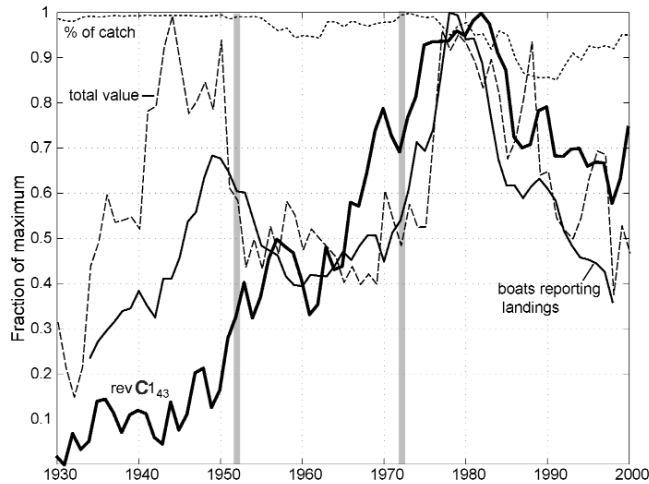


Figure 6. Time-variable coefficients ($C1_{43}$) for EOF1₄₃ computed from an ensemble of 43 species (*thick solid line*) plotted with reverse sign (*revC1₄₃*) to show relation to total value adjusted to year-2000 dollars (*dashed line*) and adjusted numbers of boats (*thin solid line*). Fraction of total catch taken by the 43 market groups is indicated by the dotted line (*top*). Fishery variables are plotted as the fraction of the maximum values: 7,189 boats and \$233,399,911. Vertical lines separate fishery intervals discussed in the text.

in Figure 6 (*revC1₄₃*) to show similarities in trends. Negative trend in *revC1₄₃* indicates species composition shifts to positively loaded species (tab. 1). Trends in (*revC1₄₃*) from 1949, the year of maximum boats in the first fisheries interval, to 1955 represent changes in fisheries to alternate species as the sardine fishery declined.

Total boats reporting landings and $C2_{43}$ are significantly correlated ($r = 0.47, p < 0.01$). $C2_{43}$ follows the number of boats in the first fisheries interval, again indicating that the increase in boats after 1945 was not due to increased investment in the sardine fishery (fig. 7). In the second fisheries interval (1953–72) the trend to positively loaded EOF2₄₃-fishes persists (fig. 7). Jack mackerel, anchovy, albacore, and salmon are positively loaded EOF2₄₃-species that supported the fishery in the 1960s and 1970s.² During the third fisheries interval, the number of boats appears to be lagging $C2_{43}$ by about 8 years, suggesting that the change in the number of boats may have been partially a response to changes in species composition reflected in EOF2₄₃ (tab. 2).

The 1997–98 California El Niño (Schwing et al. 2000) and the subsequent cooler period changed the trend in $C1$ and $C2$ (fig. 3) and in the total value (fig. 6). Much of the 20% drop in total value was due to the failure of the market squid fishery in 1998 (fig. 6). The squid fishery has since rebounded to near record levels, but the catch of Pacific herring, market crab, bluefin tuna, yellowfin tuna, and skipjack has declined since the 1997–98 event.³

²Mason, Historical patterns.

³Mason, Historical patterns.

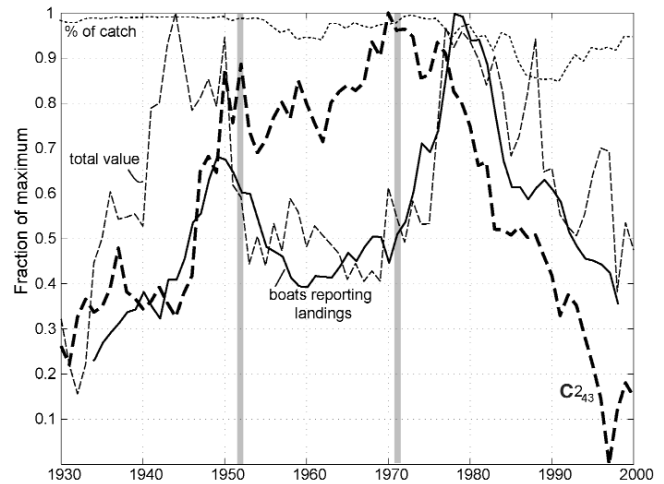


Figure 7. Time-variable coefficients ($C2_{43}$) for EOF2 computed from an ensemble of 43 species (*thick dashed line*) compared to corrected total landings value (*thin dashed line*) and corrected numbers of boats (*solid line*). Dotted line indicates fraction of the total catch taken by the 43 market groups. Fishery variables are plotted as the fraction of the maximum values: 7,189 boats and \$233,399,911. Vertical lines separate the fishery intervals discussed in the text.

DISCUSSION

The CACom data have two distinct patterns of variation in species composition that explain more than 45% of the variance through the 1930–2000 period. These patterns, defined by EOF1 and EOF2, appear robust to changes in CACom species ensembles (fig. 3). EOF1 and EOF2 variation through the 71-year period ($C1$ and $C2$) are close fits to physical environmental variables (tab. 3). Association of trends in fisheries variables to trends in $C1$ and $C2$ during parts of the record suggests that the fishery—alert to profitable opportunities, expanding markets, and changes in species availability—readily altered the species composition of the landings. The flexibility of the fishery combined with a changing environment and changing species availability produced nearly continuous change in the species composition of the landings from 1930 to 2000.

Trends in $C1$ and $C2$ match trends in physical environmental variables more closely than they match variation in fisheries variables (tab. 3). This suggests that the changes found in species composition begin as changes in the physical environment that cascade through the food web and create changes in species abundance and availability in the California Current system.

Changes in the physical and biological environment during the 1957–62, 1973–82, and 1998–2000 periods are documented in detail by Norton (1999), Parrish et al. (2000), Bograd et al. (2000), and Lea and Rosenblatt (2000), and in the present study. Sampling by California Cooperative Oceanic Fisheries Investigations (CalCOFI) off Southern California has shown changes in temperature, salinity, and sea level during 1957–62, 1973–82,

and 1998–2000 to be well-correlated to changes in zooplankton biomass (Sette and Isaacs 1960; Chelton et al. 1982; Roemmich 1992; Roemmich and McGowan 1995; McGowan et al. 1998; Hayward 2000; Schwing et al. 2002). McGowan et al. (1998) present a time series of \log_e -zooplankton biomass concentration in the CalCOFI region that is similar to the $C2_{29}$ series (fig. 3). Zooplankton biomass concentration and $C2_{29}$ rose to a relative maximum in the early 1950s, then dipped to a local minimum during 1957–60. Both continuously declined from the early 1970s to the early 1990s, with the sharpest decline occurring from 1973 to 1982 (fig. 3, and McGowan et al. 1998). The relative concentration of dominant euphausiid species also changed during 1973–77 (Brinton 1981), the period of greatest decline in $C2_{29}$ (fig. 3). During the 1998–2000 trend reversal in $C2$ (fig. 3), the CalCOFI zooplankton biomass concentration off southern California exceeded average concentrations of the previous six years (Hayward 2000; Schwing et al. 2002). These changes in zooplankton concentration during 1957–62, 1973–82, and 1998–2000, concomitant with same-sense $C2$ changes, link the commercial landings to lower trophic-level events that are not directly influenced by California fisheries.

Sea birds feed on larger zooplankton and fish, and their reproductive success within the central California sampling area (shown in fig. 1) appears tied to the same environmental processes that affect EOF1-species composition patterns. During 1971–91, seasons of poor sea bird reproduction increased after 1981 (Ainley et al. 1995), when there was a clear rebound of positively loaded EOF1 species and a decline in negatively loaded EOF1 species (fig. 3). Juvenile rockfish and anchovies, which are negatively loaded EOF1 species (tab. 1), are important in the diets of central California sea birds (Ainley et al. 1995). The decline of negatively loaded EOF1 species, indicated by the positive trend $C1$ after 1982 (fig. 3), may have causal relationship to low levels of sea bird reproductive success. The $C1$ -trend reversal toward more negatively loaded species in 1998–2000 had a corresponding response in seabird reproductive success. Seabird reproductive success was below average in 1998, but in the following 3 years reproductive success was above average for the six central California species monitored (Schwing et al. 2002).

These relationships of sea bird reproductive success and zooplankton biomass to the same physical events that are linked to trend changes in $C1$ and $C2$ support the hypothesis that $C1$ and $C2$ trends are the result of environmental events and are not solely artifacts of directed harvest. Instead, the trend changes observed during 1957–62, 1973–82, and 1998–2000 in $C1$ and $C2$ appear to be indicating changes in the physical and biological environment of the California Current system.

The orthogonal property of EOF1 and EOF2 requires that changes in species composition will not be in phase throughout the 71-year series. If changes in the species composition of the California commercial landings, indicated by EOF1 and EOF2, are forced by the physical environment, then at least two modes of physical variability, as suggested by fig. 2, are likely. These modes may be related to combinations of (1) local atmospheric forcing (Parrish et al. 1981; Parrish et al. 1983; Norton and McLain 1994; Schwing et al. 2000); (2) basin-scale forcing that causes variations in input of higher nutrient, cooler water from the north (Chelton et al. 1982; Norton 1999; Parrish et al. 2000); and (3) locally and remotely forced changes in California Current pycnocline and nutricline depth (Norton et al. 1985; Roemmich and McGowan 1995; McGowan et al. 1998). Our results do not detail how these factors interact with seasonal and longer cycles and with California fisheries to produce the two modes of change in species composition patterns. However, the significant correlation of $C1$ with Pacific Decadal Oscillation (A-PDO), a physical variable related to the extra-tropical North Pacific Ocean, and the significant correlation of $C2$ with central California southward wind stress (A-SWS) suggest basinwide forcing of $C1$ and relatively local forcing of $C2$.

$C1$ and $C2$ have changed continuously throughout the 71-year period, with general trends maintaining the same sign over intervals lasting from 6 to 36 years. Effort in the California fishery, proxied by the number of boats reporting landings, appears related to $C1$ and $C2$ trends. Effort increased with total ex-vessel value by about 100% in the late 1970s, after enactment of the Fishery Management and Conservation Act (P.L. 94-265) and reached maxima of about 7,200 boats and \$233,000,000 during 1977–80. These increases in effort and in value of the landings probably both affected and were affected by rapid changes in species composition that occurred during the mid- and late 1970s. Following the 1977–80 maxima, effort and value of the landings declined to pre-1970s levels. Present results suggest that the dynamics between species composition in the landings, the environment, harvest effort, market factors, and regulation have varied during the 71-year period as species composition in the California Current environment has changed.

CONCLUSION

This is the first analysis of environmental influences on interspecies variability in a 71-year time series from the California commercial fishery landings (CACom) data. Large-scale, long-lasting environmental events in 1957–62, 1973–82, and 1998–2000 are clearly evidenced by changes in species composition. EOF1 and EOF2 account for more than 45% of the variance and indicate

two modes of variability among species and market groups. The time-variable coefficients, C1 and C2, derived from EOF1 and EOF2, and the CACom catch data provide uncorrelated time series that describe species composition as it varied through the 1930–2000 period. The correspondence of C1 and C2 and the temporal variation of unharvested species during 1957–62, 1973–82, and 1998–2000 suggest that C1 and C2 indicate changes in the physical and biological environment of the California Current system. Correlation of C1 with Pacific Decadal Oscillation (A-PDO) and the correlation of C2 with the central California southward wind stress (A-SWS) suggest basinwide forcing of C1 and relatively local forcing of C2.

Comparison of C1 and C2 with fisheries variables—numbers of boats reporting landings and total ex-vessel value of the landings—shows close correspondence during specific periods. This suggests that different dynamics involving environmental forcing, investment in boat operation, evolving markets, and species composition were operating at various intervals over the 1930–2000 period.

ACKNOWLEDGMENTS

We thank Pete Kalvass of CDFG for providing information on the red sea urchin fishery. Ed Everett and Dan Fuller of the Inter-American Tropical Tuna Commission provided information on tropical tuna fisheries. Michael Laurs, director of the Pacific Fisheries Environmental Laboratory (PFEL), and Cindy Thomson of the Southwest Fisheries Science Center (SWFSC), Santa Cruz Laboratory provided guidance on interpreting fisheries effects. Michael Laurs, Richard Parrish, Frank Schwing, and Steven Bograd, of PFEL, SWFSC, provided many useful suggestions. Gary Sharp and Paul Reilly were particularly helpful in improving the manuscript. We thank all these people and the editors of *CalCOFI Reports* for their insightful contributions.

LITERATURE CITED

- Ainley, D. G., W. J. Sydeman, and J. Norton. 1995. Upper trophic level predators indicate interannual negative and positive anomalies in the California Current food web. *Mar. Ecol. Prog. Ser.* 118:70–79.
- Bograd, S. J., P. M. Digiacomo, R. Durazo, T. L. Hayward, K. D. Hyrenbach, R. J. Lynn, A. W. Mantyla, F. B. Schwing, W. J. Sydeman, T. Baumgartner, B. Lavanigos, and C. S. Moore. 2000. The state of the California Current, 1999–2000: forward to a new regime? *Calif. Coop. Oceanic Fish. Invest. Rep.* 41:26–52.
- Brinton, E. 1981. Euphausiid distributions in the California Current during the warm-water spring of 1977–78, in the context of a 1949–66 time series. *Calif. Coop. Oceanic Fish. Invest. Rep.* 22:135–154.
- Bureau of Marine Fisheries. 1951. California Department of Natural Resources, Division of Fish and Game, *Fish Bull.* 80, 87 p.
- Chavez, F. P., J. Ryan, S. E. Lluch-Cota, and M. Niquen. 2003. From anchovies to sardines and back: Multidecadal change in the Pacific Ocean. *Science* 299:217–221.
- Chelton, D. B. 1983. Effects of sampling errors in statistical estimation. *Deep-Sea Res.* 30:1083–1103.
- Chelton, D. B., P. A. Bernal, and J. A. McGowan. 1982. Large-scale interannual physical and biological interaction in the California current. *J. Mar. Res.* 40:1095–1125.
- Cloern, J. E., and A. D. Jassby. 1995. Year-to-year fluctuation of the spring phytoplankton bloom in south San Francisco Bay: an example of ecological variability at the land-sea interface. *In* Ecological time series, T. M. Powell and J. H. Steele, eds. New York: Chapman and Hall. Pp. 139–149.
- Davis, R. E. 1976. Predictability of sea surface temperature and sea level pressure anomalies over the North Pacific. *J. Phys. Oceanogr.* 6:249–266.
- Ebbesmeyer, C. C., D. R. Cayan, D. R. McLain, F. H. Nichols, D. H. Peterson, and K. T. Redmond. 1991. 1976 Step in the Pacific climate: forty environmental changes between 1968–1975 and 1977–1984. *In* Proceedings of the seventh annual Pacific climate (PACLIM) workshop, J. L. Betancourt and V. L. Tharp, eds. *Calif. Dep. Water Res. Interagency Ecol. Stud. Prog. Tech. Rep.* 26:115–126.
- Eres, J. E., ed. 2002. Final California commercial landings for 2001. Los Alamitos: Calif. Dep. Fish Game, Marine Region. 90 p.
- Godsil, H. C. 1938. The high seas tuna fishery of California. *Calif. Dep. Fish Game Fish Bull.* 51, 61 p.
- Hayward, T. L. 2000. El Niño 1997–98 in the coastal waters of southern California: a timeline of events. *Calif. Coop. Oceanic Fish. Invest. Rep.* 41:98–116.
- Herrick, S. F. 1981. Status report: eastern tropical Pacific yellowfin tuna. *In* Status reports on world tuna and billfish stocks, NOAA-TM-NMFS-SWFSC-15, pp. 143–162.
- Kalvass, P. E., and J. M. Hendrix. 1997. The California Red Sea Urchin, *Strongylocentrotus franciscanus*, fishery: catch, effort, and management trends. *Mar. Fish. Rev.* 59:1–17.
- Klyashtorin, L. B. 2001. Climate change and long-term fluctuations of commercial catches. *FAO Fish. Tech. Pap.* 410, 86 p.
- Kutzbach, J. E. 1967. Empirical eigenvectors on sea-level pressure, surface temperature and precipitation complexes over North America. *J. Appl. Meteorol.* 6:791–802.
- Lea, R. N., and R. H. Rosenblatt. 2000. Observations of fishes associated with 1997–98 El Niño off California. *Calif. Coop. Oceanic Fish. Invest. Rep.* 41:117–131.
- Leet, W. S., C. M. Dewees, R. Klingbeil, and E. J. Larson, eds. 2001. California's living marine resources: A status report. *Univ. Calif. Agricul. Nat. Res.* SG01-11, 492 p.
- Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. *Bull. Am. Meteorol. Soc.* 78:1069–1079.
- McGowan, J. A. 1990. Climate and change in oceanic ecosystems: The value of time-series data. *Trends Ecol. Evol.* 5:293–299.
- McGowan, J. A., D. R. Cayan, and L. M. Dorman. 1998. Climate-ocean variability and ecosystem response in the northeast Pacific. *Science* 281:210–217.
- Miller, A. J., D. R. Cayan, T. P. Barnett, N. E. Graham, and J. M. Oberhuber. 1994. The 1976–77 climate shift of the Pacific Ocean. *Oceanography* 7:21–26.
- Miller, D. J., and R. N. Lea. 1972. Guide to the coastal marine fishes of California. *Calif. Dep. Fish Game Fish Bull.* 157, 235 p.
- North, G. R., T. L. Bell, R. F. Cahalan, and F. J. Moeng. 1982. Sampling errors in the estimation of empirical orthogonal functions. *Mon. Weath. Rev.* 110:699–706.
- Norton, J. G. 1999. Apparent habitat extensions of dolphinfish (*Coryphaena hippurus*) in response to climate transients in the California Current. *Scientia Marina*. 63:239–260.
- Norton, J. G., and D. R. McLain. 1985. Coastal ocean monitoring using daily sea surface temperatures from shore stations. *EOS, Trans. Am. Geophys. Union.* 66:923.
- . 1994. Diagnostic patterns of seasonal and interannual temperature variation off the west coast of the United States: local and remote large-scale atmospheric forcing. *J. Geophys. Res.* 99:16,019–16,030.
- Norton, J. G., D. R. McLain, R. E. Brainard, and D. M. Husby. 1985. El Niño event off Baja and Alta California and its ocean climate context. *In* Niño effects in the eastern subarctic Pacific Ocean, W. S. Wooster and D. L. Fluharty, eds. Seattle: Washington Sea Grant Program, University of Washington. Pp. 44–72.

- Oliphant, M. S. 1979. California marine fish landings for 1976. Calif. Dep. Fish Game Fish Bull. 170, 56 p.
- Oliphant, M. S., P. A. Gregory, B. J. Ingle, and R. Madrid. 1990. California marine fish landings for 1977–1986. Calif. Dep. Fish Game Fish Bull. 173, 52 p.
- Parrish, R., C. Nelson, and A. Bakun. 1981. Transport mechanisms and reproductive success of fishes in the California current. Biol. Oceanogr. 1:175–203.
- Parrish, R. H., A. Bakun, D. M. Husby, and C. S. Nelson. 1983. Comparative climatology of selected environmental processes in relation to eastern boundary current pelagic fish reproduction. *In* Proceedings of the expert consultation to examine changes in abundance and species composition of neritic fish resources, G. D. Sharp and J. Csirke, eds. FAO Fish. Rep. 291(3):731–777.
- Parrish, R. H., F. B. Schwing, and R. Mendelsohn. 2000. Mid-latitude wind stress: the energy source for climatic shifts in the North Pacific Ocean. Fish. Oceanogr. 9:224–238.
- Roemmich, D. 1992. Ocean warming and sea level rise along the southwest U.S. coast. Science 257:373–375.
- Roemmich, D., and J. McGowan. 1995. Climatic warming and the decline of zooplankton in the California Current. Science 267:1324–1326.
- Ryther, J. H. 1969. Photosynthesis and fish production in the sea. Science 166:72–80.
- Schwing, F. B., C. S. Moore, S. Ralston, and K. A. Sakuma. 2000. Record coastal upwelling in the California Current in 1999. Calif. Coop. Oceanic Fish. Invest. Rep. 41:148–160.
- Schwing, F. B., S. J. Bograd, C. A. Collins, G. Gaxiola-Castro, J. García, R. Goericke, J. Gómez-Valdéz, A. Huyer, K. D. Hyrenbach, P. M. Kosro, B. E. Lavaniegos, R. J. Lynn, A. W. Mantyla, M. D. Ohman, W. T. Peterson, R. L. Smith, W. J. Sydeman, E. Venrick, and P. A. Wheeler. 2002. The state of the California Current, 2001–2002: will the CCS keep its cool, or is El Niño looming? Calif. Coop. Oceanic Fish. Invest. Rep. 43:31–68.
- Sette, O. E., and J. D. Isaacs, eds. 1960. The changing Pacific Ocean in 1957 and 1958. Calif. Coop. Oceanic Fish. Invest. Rep. 7:14–217.
- Stenseth, N. C., A. Mysterud, G. Ottersen, J. W. Hurrell, K.-Sik Chan, and M. Lima. 2002. Ecological effects of climate fluctuations. Science 297:1292–1296.
- Sund, P. N., and J. G. Norton. 1990. Interpreting long-term fish landings records: environment and/or exploitation? *In* Proceedings of the sixth annual Pacific climate (PACCLIM) workshop, April 1990. J. I. Betancourt and A. M. MacKay, eds. Calif. Dep. Water Res. Interagency Ecol. Stud. Prog. Tech. Rep. 23:71–76.
- Thomson, C. J. 2001. Human ecosystem dimension. *In* California's living marine resources: a status report, W. S. Leet, C. M. Dewees, R. Klingbeil, and E. J. Larson, eds. Univ. Calif. Agricul. Nat. Res. SG01-11, pp. 47–66.