

LOCALLY AND REMOTELY FORCED ENVIRONMENTAL INFLUENCES ON CALIFORNIA COMMERCIAL FISH AND INVERTEBRATE LANDINGS

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ABSTRACT

This study extends the investigations of Norton and Mason (2003), who used empirical orthogonal function (EOF) analysis of the California commercial fish and invertebrate landings data (CACom database) to find two patterns of variability (EOF1 and EOF2) that describe major changes in species composition from 1930 through 2000. Temporal variations in EOF1 and EOF2 are closely correlated to climate-scale physical processes of the equatorial Pacific (remote) and the North Pacific (local) atmosphere and oceans, respectively. These findings suggest that changes in species composition of California landings begin as remote and local physical processes that are transmitted through the ecosystem to target species. Log_e-transformed sardine landings history is similar to the time variations in EOF1. As fish and invertebrate resources become fully utilized, variations in their landings become better indicators of environmental climate change off California; however, conservative resource management and fluctuating market demand may disrupt this close relationship. Consistent temporal associations of species groups with recurrent physical environmental conditions may allow timely detection of climate changes and thereby provide opportunities for proactive ecosystem management.

INTRODUCTION

Studies by Norton and Mason (2003) used empirical orthogonal functions (EOFs) to examine California commercial fish landings from 1930 through 2000. They found two modes of variability, EOF1 and EOF2, that explain more than 45% of the variance in composition of species making up more than 95% of the total landings. When time-varying coefficients or principal components of these EOFs, C1 and C2, were compared to indexes of physical change in the California fisher's harvest environment (CFHE) and to time series representing fishing effort and market factors, it was found that C1 and C2 are more closely correlated to the environmental indexes (correlation coefficient magnitude, $|r| > 0.8$) than to the effort and market indexes ($|r| < 0.6$).

Variation in C1 and C2 show that the species composition of the landings changed continuously from 1930 to 2000, indicating that the California fishing industry adapted to profitable opportunities of changing CFHE conditions and expanding markets (Norton and Mason 2003). The purpose of this study is to extend investigations into how major changes in the species composition of California landings relate to the primary physical forcing of the CFHE.

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 C1 and C2, are forced by the physical environment, then at least two modes of physical variability are likely. These modes may be related to combinations of (1) local atmospheric effects, such as wind forcing of the CFHE (Parrish et al. 1983; Norton and McLain 1994); (2) basin-scale forcing that causes variations in input of higher nutrient content, cooler water from the north (Chelton et al. 1982; Norton 1999; Parrish et al. 2000); and (3) locally and remotely forced changes in CFHE pycnocline and nutricline depth (Norton et al. 1985; Roemmich and McGowan 1995; McGowan et al. 1998). Norton and Mason (2003) found that the uncorrelated temporal patterns in C1 and C2 are uniquely correlated to indexes of southern California sea-surface temperature (SST, $r = 0.92$) and central California southward wind stress (SWS, $r = 0.85$), respectively. C1 species composition changes were also found to have significant correlation to the Pacific Decadal Oscillation (PDO; $r = 0.85$) index (Mantua et al. 1997). The dependence of the PDO index on both direct and indirect forcing from the equatorial ocean and atmosphere (Newman et al. 2003) suggests a connection of C1 to equatorial processes.

Temporal patterns in the California commercial landings shown by C1 and C2 correspond to patterns of variation in species not directly affected by California fisheries. Zooplankton biomass is affected by the same physical events in 1957–1962, 1973–1982, and 1998–2000 (McGowan et al. 1998) that are evident in C1 and C2. Reproductive success of central California seabirds (Ainley et al. 1995) also corresponds to C1 and

C2 variation. These examples suggest that EOF1 and EOF2 temporal patterns reflect variation of many non-commercial species of the California Current ecosystem and that EOF1 and EOF2 are not solely artifacts of directed harvest and fluctuating market demand (Norton and Mason 2003).

The California Current flows equatorward and extends up to 900 km seaward off the west coast of temperate North America. The offshore California Current environment, westward of 50–150 km, is separated from the coastal zone by an undulating transition band of maximum equatorward velocity. Shoreward of the transition zone, flow in the upper 500 m becomes increasingly poleward, except during frequent wind-forced upwelling events when surface currents in the upper 50–150 m flow equatorward over the poleward subsurface currents (Lynn and Simpson 1987; Strub et al. 1987). These three currents are the main components of the California Current system (CCS). The CFHE is that part of the CCS extending from the coast to 400–600 km offshore.

Remote forcing from the equatorial Pacific will affect the CCS by anomalous transmission of coastal long-waves, with wave length much greater than water depth, trapped by the eastern boundary (Shriver et al. 1991; Ramp et al. 1997) and by atmospheric teleconnections (Horel and Wallace 1981; Alexander 1992). As coastal-trapped waves propagate poleward through the CFHE, they lose energy to offshore propagating Rossby waves, which spread effects 300–400 km offshore (Fu and Qui 2002). In the case of downwelling long-waves, geostrophic adjustment depresses isotherms and isopycnals along the coast. This favors increased poleward transport, which leads to warming and increased sea level in the CFHE. Anomalous ocean-to-atmosphere heat transfer associated with SST anomalies in the equatorial Pacific Ocean teleconnect through the atmosphere to increase or decrease cyclogenesis over the northeastern Pacific Ocean (Alexander 1992). The teleconnection affects local North Pacific atmospheric forcing primarily during winter. Consequently, time series of surface oceanic and atmospheric variables from the North Pacific and from the equatorial Pacific may have considerable common variability.

Local large-scale forcing will have a different spatial pattern of effects than will remote forcing (Chelton et al. 1982; Enfield and Allen 1980; Parrish et al. 1983; Norton and McLain 1994; Miller et al. 1997; King et al. 1998; McGowan et al. 1998; Fu and Qui 2002), and it acts continuously and simultaneously on the entire northeastern Pacific Ocean. Variations in strength and duration of wind-field effects and the exchange of heat and mass between the North Pacific Ocean and atmosphere are the primary local forcing processes. Local atmospheric forcing thousands of kilometers distant may

affect temperature and sea level in the CCS at lags of weeks to months. Because remote equatorial forcing of the North Pacific through the atmospheric teleconnection and local North Pacific forcing thousands of kilometers distant may lead to similar changes in the CCS, it is often difficult to distinguish remote from local forcing effects in CCS data sets. However, it appears from our analysis of the CACom data set of commercial fish landings that two forcing modes are detectable in our measures of CFHS biological variability.

METHODS

Time series of change in species composition over the 1930–2000 period are derived from the California commercial landings data by extracting the time-varying coefficients or principal components of the two empirical orthogonal functions (EOFs) explaining the most variance (C1, C2). These are compared to environmental climate indexes.

Commercial Landings

Summarized landings records were compiled from landing receipts by the California Department of Fish and Game. The Pacific Fisheries Environmental Laboratory of the Southwest Fisheries Science Center (Norton and Mason 2003; Mason 2004) has converted these summarized records to a computer-accessible database (CACom), available at <http://www.pfeg.noaa.gov>; it is the source of all landings data used in this report.

The effects of local biases in the landings data are reduced by the aggregation of the large number of landings transactions. By 1950, there were more than 100 locations where trip tickets had been completed and filed with the California Department of Fish and Game (tab. 1). During the 1930–2000 period, the number of boats reporting landings has varied from about 1,600 to 7,300 (Norton and Mason 2003). The large number of boats and the alternative markets for landing (selling) the catch have probably led to fewer systematic recording biases in averaged data.

EOF Analysis and Time-variable Coefficients

Let the data matrix [D] consist of columns of market groups with annual catch for 1930–2000 in 71 rows (years). All columns are log-transformed,

$$\log_e [D'] = [D]. \quad (1)$$

Then find correlation matrix [R] of [D] using matrix manipulations

$$[R] = k[D]^{-1}[D], \quad (2)$$

where k depends on the dimensions of [D], and [D]^T is the transpose of [D].

TABLE 1
 Number of Locations Reporting Landings in 1950 and Before

CDFG statistical area	Northern limit	Southern limit	Number reporting, by weight of landings		
			> 500 kg	> 5,000 kg	> 500,000 kg
Eureka	42.0°N (Del Norte County)	38.75°N (Mendocino County)	8	3	4
San Francisco	38.75°N (Sonoma County)	37.08°N (San Mateo County)	24	7	12
Monterey	37.08°N (Santa Cruz County)	35.78°N (Monterey County)	2	0	3
Santa Barbara	35.78°N (San Luis Obispo County)	34.03°N (Ventura County)	6	3	3
Los Angeles	34.03°N (Los Angeles County)	33.22°N (Orange County)	10	3	5
San Diego	33.22°N (San Diego County)	32.5°N (San Diego County)	7	0	2
Total			57	16	29

Source: From Scofield 1954.

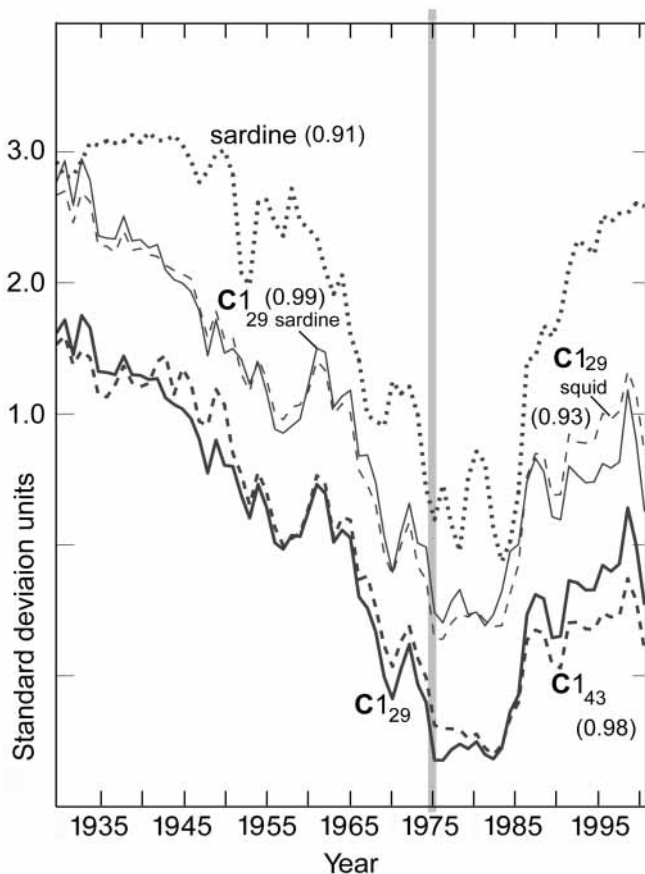


Figure 1. Time-varying coefficients, C1, for EOF1 computed from various landing data sets and \log_e -transformed sardine landings (dotted line). All series are standardized and offset in standard deviation increments for comparison. Bottom two lines show C1 computed from 29 (C1₂₉, thick solid line) and 43 (C1₄₃, thick dashed line) market group computation matrices. The middle series are C1₂₉ with either sardine (thin solid line) or squid (thin dashed line) landing series omitted from the 29 single-species market-group matrix. EOF1₂₉ and EOF1₄₃ explain 30% and 26% of the variance in their respective computation matrixes, [D₂₉'] and [D₄₃']. Correlation to C1₂₉ is given in parentheses. \log_e -transformed sardine series and C1₂₉ computed without sardines are the least similar ($r = 0.86, p < 0.05$) of these series. C1₂₉ is closely related to the sardine series ($r = 0.91, p < 0.01$).

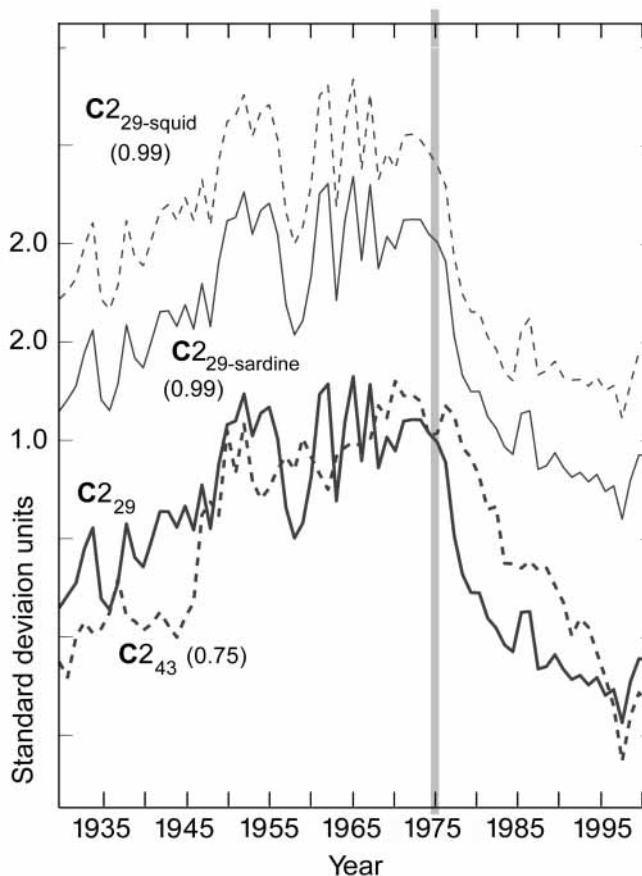


Figure 2. Time-varying coefficients, C2, for EOF2 computed from various landing data sets. All series are standardized and offset in standard deviation increments for comparison. Lower lines show C2 computed from 29 (D₂₉, thick solid line) and 43 (D₄₃, thick dashed line) market group computation matrixes. Upper series are C2 computed from the 29 single-species market-group ensembles, omitting sardine (thin solid line) and squid (thin dashed line) landing series. EOF2₂₉ and EOF2₄₃ explain 20% and 19% of the variance in their respective computation matrixes. Correlations with C2₂₉ are given in parentheses. C2₂₉ and C2₂₉ computed without the sardine series are correlated to the C2₄₃ series, with $r = 0.75, p < 0.10$. C2₄₃ series and C2₂₉ computed without the squid series are the least alike ($r = 0.68$) of the series shown.

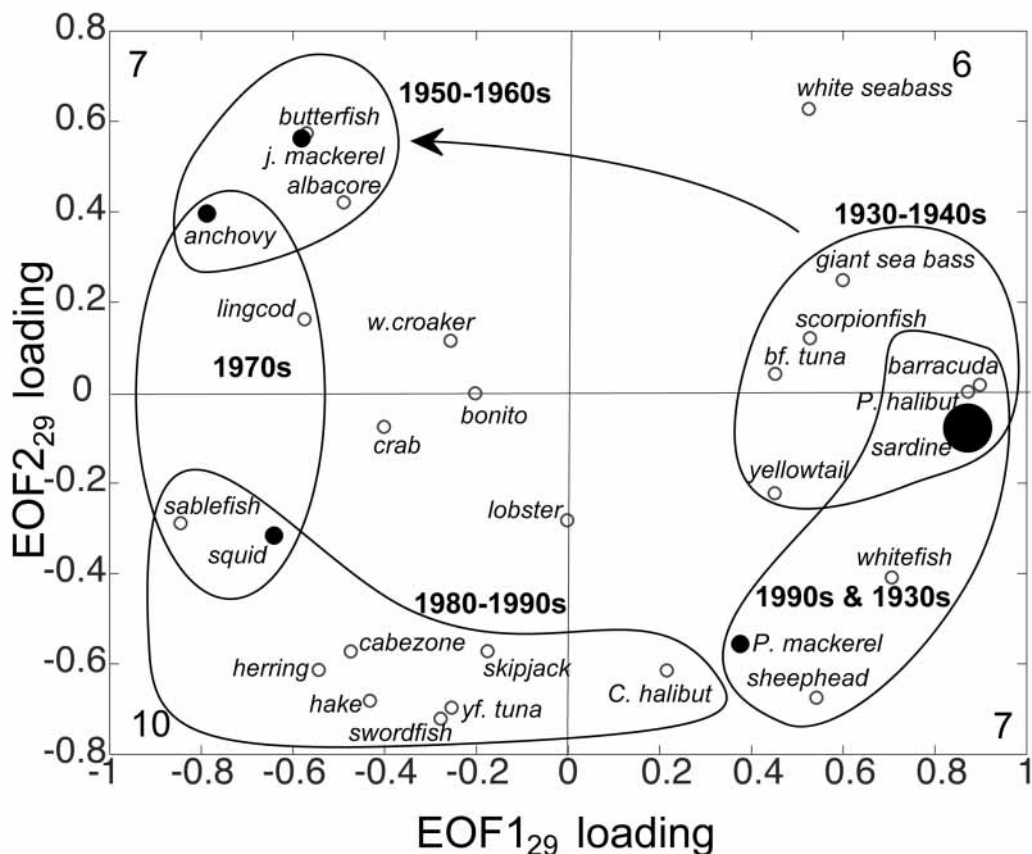


Figure 3. Species EOF loading values are plotted, with EOF1 on the horizontal and EOF2 on the vertical axes. The arrow and the enclosed species groups show the counterclockwise progression of species groups having landings maxima. Filled circles show species that have had total landings exceeding 10^9 metric tons; size of the filled circles indicates relative total catch among those species. Number of species in each quadrant is shown in the corners. Abbreviated common names for the 29 single-species market groups are albacore (*Thunnus alalunga*), anchovy (*Engraulis mordax*), barracuda (*Sphyræna argentea*), bluefin (bf.) tuna (*Thunnus thynnus*), bonito (*Sarda chiliensis*), butterfish (*Peprilus simillimus*), California (C.) halibut (*Paralichthys californicus*), cabezon (*Scorpaenichthys marmoratus*), crab (*Cancer magister*), croaker (*Genyonemus lineatus*), giant seabass (*Stereolepis gigas*), hake (*Merluccius productus*), herring (*Clupea pallasii*), jack (j.) mackerel (*Trachurus symmetricus*), lingcod (*Ophiodon elongatus*), lobster (*Panulirus interruptus*), Pacific (P.) halibut (*Hippoglossus stenolepis*), Pacific (P.) mackerel (*Scomber japonicus*), sablefish (*Anoplopoma fimbria*), sardine (*Sardinops sagax*), scorpionfish (*Scorpeaena guttata*), sheephead (*Semicossyphus pulcher*), skipjack (*Euthynnus pelamis*), squid (*Loligo opalescens*), swordfish (*Xiphias gladius*), white seabass (*Atractoscion nobilis*), whitefish (*Caulolatilus princeps*), yellowtail (*Seriola dorsalis*), and yellowfin (yf.) tuna (*Thunnus albacares*).

Then the eigenvectors $[E]$ and eigenvalues are derived from

$$[R][E] = [L][E]. \quad (3)$$

The diagonal elements of $[L]$ are eigenvalues (l_n) that correspond to the column eigenvectors of $[E]$. EOF loadings (one value for each of n columns in $[D']$) are given by

$$EOF_n = (l_n)^{1/2} [E_n], \quad (4)$$

where l_n gives the variance explained by EOF_n . The first EOF, EOF1, has the largest l_n , EOF2 has the second largest l_n , and so forth. We use the method of North et al. (1982) to find that EOF1 and EOF2 are significant below the 0.05 probability level ($p < 0.05$). The

time variation of EOF_n over the sampling interval (time-varying coefficients) is given by

$$[Cn] = [D][EOF_n] \quad (5)$$

The following analyses focus on two data matrixes. The first data matrix, $[D_{43}]$, has 43 columns corresponding to 43 market groups that are recorded consistently throughout the 71-year record. A market group may contain several species that have similar market characteristics. The 43-market-group matrix, $[D_{43}]$, represents more than 85% of the total catch throughout the 71-year period, more than 90% of the catch during 65 years, less than 90% from 1980 through 1994, and more than 95% of the catch during 61 years. The second data matrix, $[D_{29}]$, has 29 columns of annual landing totals for 29 single-species market groups (Norton and Mason

2003). Differences in the time-varying coefficients, C1 and C2, derived from $[D_{43}]'$ and $[D_{29}]'$ are shown in Figures 1 and 2. EOF1 and EOF2 loadings for $[D_{29}]'$ are plotted as abscissa and ordinate, respectively, in Figure 3. EOF143, EOF243, EOF129, and EOF229 account for 26%, 20%, 30%, and 19% of the variance in $[D_{43}]$ and $[D_{29}]$, respectively. All loading values listed are from Norton and Mason (2003).

Physical Time Series

Because trends in the time variation of the EOFs persist over periods of 5–30 years, indexes showing persistence in physical processes were developed from available published data sets by accumulating anomalies from 1930 to 2000 or longer means.

Anomalies from means, X , were accumulated or integrated through time,

$$A - X(y) = \sum_{i=b}^y X(i) \quad (6)$$

where $A - X(y)$ is the accumulation of the anomaly time series X , b is the first year of the accumulation, and y is a year between b and 2001. This operation adds persistence (autocorrelation) to the physical series (Klyashtorin 2001; Hanley et al. 2002; Norton and Mason 2003).

The accumulated series may be interpreted in terms of processes that together cause negative or positive anomalies (Norton and Mason 2003). If a series trends or slopes in a positive (negative) direction, processes that led to positive (negative) anomalies dominate the interval. Seasonal and many interannual events are attenuated in the records, making accumulated series valuable for illustrating climate-scale (5–30 year) changes. These methods were used to derive the seven accumulated climate-index series described below.

Southward wind stress (SWS) was computed for an area off central California with consistently large numbers of observations through the sampling interval in the Comprehensive Ocean-Atmosphere Data Set (COADS). This area is bounded by the California coast and 39°N, 124°W; 37°N, 124°W; 37°N, 123°W; and 36°N, 123°N (Parrish et al. 2000; Norton and Mason 2003). By convention, greater SWS is indicated by larger negative values. A-SWS is the accumulated index.

Monthly mean sea-surface temperatures (SST) taken at the Scripps Institution of Oceanography Pier in La Jolla, California (32.9°N, 117.3°W), were developed into the La Jolla A-SST climate index. The monthly mean SST taken during August–October at Hopkins Marine Station in Pacific Grove, California (36.6°N, 121.9°W), was developed into the PG A-SST index. SST data are available at <ftp://ccsweb1.ucsd.edu/pub/shore>.

Sea-level atmospheric pressure (SLP) at Darwin, Australia (12.4°S, 130.9°E), is related to El Niño ex-

pression (Bjerknes 1969; Norton et al. 1985; Norton and McLain 1994). Darwin SLP is available from Kousky (2003) at <http://www.cpc.ncep.noaa.gov>. A-DSLP is the accumulated index.

Average equatorial SST (EqSST) from an area defined by 4°N to 4°S, 150°W to 90°W is also known as the JMA ENSO index (Hanley et al. 2002). EqSST is available at http://www.coaps.fsu.edu/~legler/jma_index1.shtml, and A-EqSST is the derived index.

August–October San Francisco, California (37.8°N, 122.4°W), mean sea level (SFSL) is available from NOAA/National Ocean Service Center for Operational Oceanographic Products and Services (CO-OPS), <http://co-ops.nos.noaa/data-res.html>. The only correction to SFSL was for a 1.2 mm per year increase (Roemmich 1992). The climate index is A-SFSL.

The Pacific circulation index (PCI), available at http://www.pac.dfo-mpo.gc.ca/sci/sa-mfpd/climate/clm_indx.htm, is a temporal accumulation (eq. 6) of atmospheric flow anomalies over the North Pacific Ocean (King et al. 1998). Positive PCI-values suggest increased northward atmospheric flow along the coasts of the northern United States, Canada, and Alaska. (Note that the signs of La Jolla A-SST, PG A-SST, A-SFSL, and the PCI are reversed in fig. 5).

Significance levels for all correlations were adjusted for effective degrees of freedom, which were determined by the long-lag (20–30%) correlation method (Chelton 1983). In general, correlation coefficient magnitudes larger than 0.8 ($|r| > 0.8$) are likely to occur by chance at a rate of less than 1 in 20 trials ($p < 0.05$).

RESULTS

Norton and Mason (2003) showed that there is considerable agreement in the time-varying coefficients representing landings variation in species composition, C1 and C2, when they are computed from either 43 market-group or 29 single-species market-group matrixes, $[D_{43}]'$ or $[D_{29}]'$. In the following section we explore the dependence of C1 and C2 on dominant species in $[D]'$ and illustrate how species associations develop in the landings through time. The linkages of C1 to remote equatorial and C2 to local North Pacific physical forcing regions are also examined.

Stability in EOF Calculations

Four input data matrixes, $[D]'$, were compared to examine the effects of removing dominant species and species groups from the EOF computations. Time-varying coefficients, C1 and C2, were computed from $[D_{29}]'$ and $[D_{43}]'$ and from $[D_{29}]'$ with either the sardine or squid landings series deleted. C1 patterns are more similar ($r \geq 0.93$, $p < 0.01$) than the C2 patterns ($r \geq 0.74$, $p < 0.10$) among the four alternatives (figs. 1

and 2). The largest differences in the computed C1 and C2 curves are in the last half of the record (figs. 1 and 2). We selected $[D_{29}]$ to develop further because this matrix excludes noise introduced by combined-species market groups. The individual species of combined-species market groups may react differently to ocean climate changes.

Sardine made up 80–90% of total landings from 1930 to 1944 and 15–30% of landings from 1995 to 2000. Squid catch grew from 10% to 20% of the total landings in the mid-1970s to about 50% of landings from 1999 through 2000. When either squid or sardine are omitted from $[D_{29}]$, the C1-values are generally similar ($r \geq 0.93$, $p < 0.01$), with the largest differences in C1 in the 1990–2000 interval (fig. 1). Sardine landing patterns through 1930–2000 appear, in Figure 1, to be similar to $C1_{29}$ ($r = 0.91$, $p < 0.01$). Even though sardine is a dominant species in terms of percentage of landings before 1950 and after 1995, it does not greatly influence the results of the C1 computation when it is deleted from the input matrix (fig. 1). C2-values were nearly identical ($r = 0.99$, $p < 0.01$) when either sardine or squid were omitted from the calculations (fig. 2). The C1 and C2 temporal patterns are apparently important in the life histories of many of the 29 species and are not solely characteristics of the species contributing the highest percentages to total landings.

Temporal Change in Species Groups

Each of the 29 species in $[D_{29}]$ has had five-year or longer periods when its recorded landings were near maximum. The temporal distribution of these species-maxima show species characteristic intervals within the 1930–2000 period. The progression of species maxima through the 71 years is presented in Figure 3, where EOF1₂₉ loading values for each species are plotted on a horizontal axis and EOF2₂₉ loading values are plotted on the vertical axis. In the 1930s and 1940s (fig. 3, center right) sardines, scorpionfish, barracuda, and yellowtail were at or near their individual maximum landings. In the 1950s and 1960s (fig. 3, upper left) jack mackerel and albacore were near their maximum landings. During the 1970s (fig. 3, center left), anchovy and sablefish were near their maximum abundance in the landings. Skipjack, yellowfin tuna, swordfish, hake, and herring were common in the landings during the 1980s and 1990s (fig. 3, lower left and center). A cycle appears to be completing in the 1990s (fig. 3, lower right), with Pacific mackerel and sardine increasing in the landings. The progression of species-maxima may indicate integrated changes in the flow of productivity (renewable food energy) through California Current ecosystems.

Some species, such as butterfish, have always contributed less than 1% to the total landings, while in-

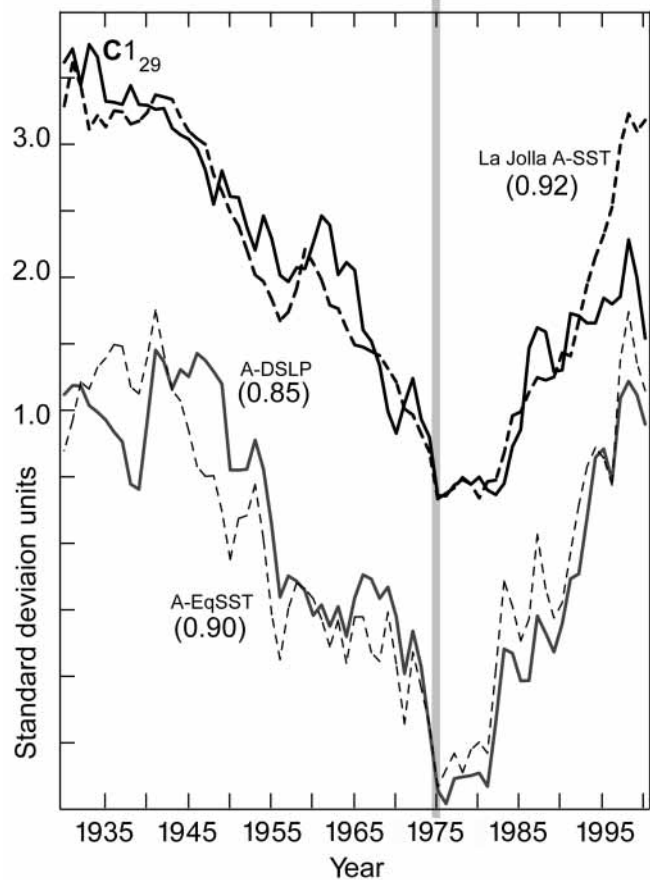


Figure 4. Comparison of C1 computed from 29 single-species market groups, $C1_{29}$ (upper solid line), to environmental indexes formed by accumulation of anomalies. All series are standardized and offset in standard deviation increments for comparison. The index derived from sea-surface temperature (SST) at La Jolla, California (La Jolla A-SST), is the upper dashed line. The lower solid line is the Darwin SLP index (A-DSLP), and the lower dashed line is the equatorial SST index (A-EqSST). Correlation of $C1_{29}$ with the physical indexes is in parentheses. Correlation of La Jolla A-SST to A-DSLP is $r = 0.93$ and to A-EqSST is $r = 0.95$ ($p < 0.015$).

creases or declines of other species, such as the mackerels and anchovy, cause large changes in the fishery, as described by MacCall (1996) and Chavez et al. (2003). The general implications of Figure 3 are consistent with these previous studies (MacCall 1996; Chavez et al. 2003) and they extend the conclusions of these previous studies to include a larger number of commercial fish and invertebrates.

Large-scale Environmental Forcing

Changes in landings composition shown by $C1_{29}$ over the 1930–2000 period are closely related to persisting anomalous conditions in the CFHE as indicated by anomalies in SST measured at La Jolla, California (Norton and Mason 2003). The integrated anomaly index for southern California, La Jolla A-SST, and $C1_{29}$, are also closely related to equatorial atmosphere-ocean processes indexed by A-DSLP and A-EqSST (fig. 4). All series shown in Figure 4 are well correlated ($r \geq 0.85$, $p > 0.05$).

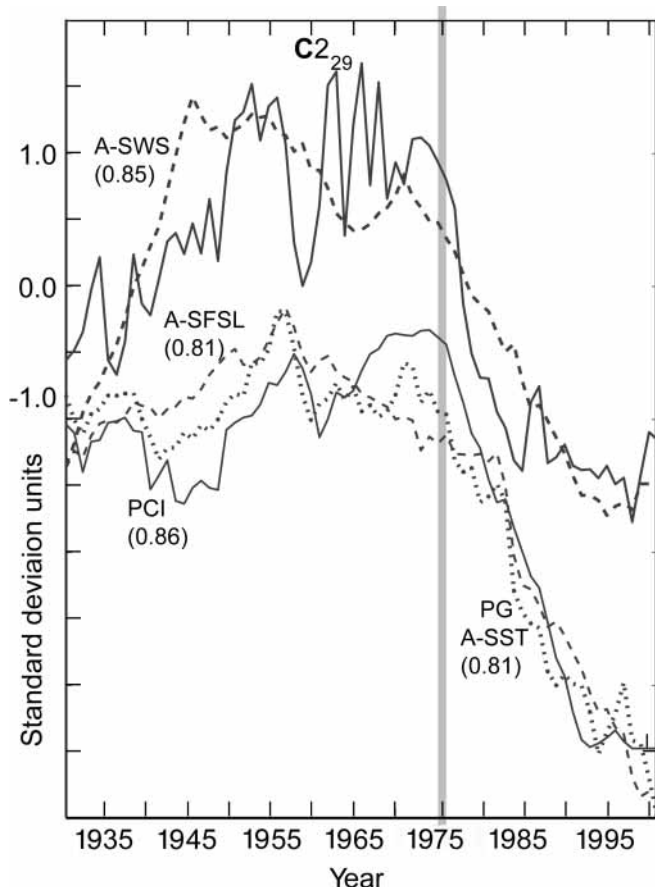


Figure 5. Comparison of $C2_{29}$ computed from 29 single-species market groups, $C2_{29}$ (upper solid line), to environmental indexes formed by accumulation of anomalies. All series are standardized and offset in standard deviation increments for comparison. The index of central California southward windstress (A-SWS) is the upper dashed line. The lower dashed line is the sign-reversed August–October San Francisco sea-level index (A-SFSL). The lower dotted line is the sign-reversed August–October Pacific Grove sea-surface temperature index (PG A-SST). The lower solid line is the sign-reversed Pacific circulation index (PCI). Correlation of $C2_{29}$ with the physical indexes is in parentheses.

These physical indexes are more similar to each other than any of them are to $C1_{29}$, because of the lower slope in $C1_{29}$ after 1990. The implication of causal connection among variables is supported by the progression of multiyear events that occur earlier in the equatorial indexes than in La Jolla A-SST and $C1_{29}$ (fig. 4).

Of several events that show progression from equatorial to California Current indexes, the best example may be the well known 1955–1960 warming event (Sette and Isaacs 1960; Parrish et al. 2000). After three to four years of negative anomaly, this event is shown by positive excursions that first appear during 1955–1956 in the equatorial regions. It continues in 1956–1958 in the La Jolla A-SST and was evident during 1958–1960 in the California fish landings, $C1_{29}$ (fig. 4).

Landings changes indicated by $C2_{29}$ are closely related to changes in southward wind stress (SWS), August–October A-SFSL and PG A-SST, and the Pacific circu-

lation index (PCI) (fig. 5). The relationship to the PCI suggests that forcing of $C2_{29}$ is related to large-scale atmospheric processes occurring over the northeastern Pacific Ocean (King et al. 1998; Chelton et al. 1982; Parrish et al. 2000) rather than to unique California Current processes. The $C2_{29}$ temporal pattern also corresponds to variation in the concentration of fish larvae and other zooplankton over the 1954–1998 period (McGowan et al. 1998; Norton and Mason 2003).

The PCI is a large-scale atmospheric indicator for the North Pacific (King et al. 1998), but the large-scale North Pacific Ocean indicator that covers the 1930–2000 period has not yet been identified. Instead, we present the A-SWS, A-SFSL, and PG A-SST indexes because these are derived from the only available published data that is continuous for 1930–2000.

Association of Species and Environmental Indexes

Observations that species-groups at their maximum landings abundance change through time may be quantified and modeled in terms of physical indexes (figs. 3–5). The horizontal axis (EOF1) in Figure 3 corresponds to La Jolla A-SST. Positive trend in La Jolla A-SST (fig. 4) corresponds to species groups on the right side of Figure 3 and shows persistence of remote warming influence. Similar scales might be developed for the remote climate influence of A-DSLP and A-EqSST. EOF2 is associated with southward wind stress (SWS). By convention, increased SWS has anomalously high-magnitude negative values. Therefore, persisting anomalously strong SWS, indicated by negative slope in A-SWS, will be associated with species in the lower two quadrants of Figure 3. A-SFSL, PG A-SST, and PCI indexes are negatively correlated to EOF2; a quantitative scale for indexes would be the reverse sign to the ordinate shown in Figure 3. The potential availability of any species might be modeled as functions of species association and environmental indexes. This modeling approach will be pursued as additional landings data become available.

DISCUSSION

The California commercial finfish and invertebrate landings data (CACom) are not a rigorously select scientific sample, but our results are reasonably clear and indicate low noise levels. Several conditions contribute to this result. First, thousands of fishers and scores of fish dealers have been in compliance, or at least proportional compliance, with state regulations requiring recording of the weight of commercial landings by market category (tab. 1). Minimum estimated recording has been 5,000–35,000 landings records per year (assuming five commercial landings per boat each year; Norton and Mason 2003). Second, California Department of Fish

and Game statisticians have been precise and consistent in keeping landings records over the 1930–2000 period. Third, intensive utilization of California fisheries resources contributes to close correlation between species composition of the landings, as indexed by C1 and C2, and physical environmental indexes.

Intensive utilization of CFHE fish and invertebrate resources occurred as the result of increasing consumption of fish and fish products and exploitation of world markets by California fish dealers (Dietz et al. 2003). From 1930 to 2000 the human population of California increased sixfold, but the overall weight of fish landed in California ports in the 1990s was half that of the 1930s and 1940s. From 1930 to 2000, per capita annual consumption of edible fish in the United States grew from 4.5 kg in 1930 to 7.1 kg in 2000. In addition, the U.S. population has more than doubled from 1930 to 2000, leading to a 340% increase in U.S. fish consumption.

The fact that almost half of the total fish and invertebrate products consumed in the United States is imported (O'Bannon 2001) suggests that demand exceeds supply for most U.S. fisheries. Products receiving labor-intensive preparation and species not available to U.S. fishers are obtained from foreign sources at a lower cost and therefore do not increase demand on CFHE resources. These exceptions, however, do not hinder the tentative conclusion that many California fisheries have become fully utilized during the 1930–2000 period.

During 1930–2000, the three-fold increase in the world's human population and the extension of foreign markets have created continuing utilization incentives for California commercial fishers (Dietz et al. 2003). For example, there is a major market in Japan for urchins and another in China for squid. The sea urchin (*Strongylocentrotus* sp.) fishery is the only major California fishery not included in the present analyses, because there was no commercial fishery for urchins before 1970. Much of the recent sardine catch has been exported to Australia (Leet et al. 2001). Because these species constitute large percentages of total California landings (Mason 2004), their sales destinations illustrate the influence of foreign markets on CFHE resources. The statistics reviewed above and the reasonably clear results of this report lead to the proposition that because of full and intensive resource utilization, the CACom landings records yield reasonable indications of relative changes in CFHE commercial fish stocks.

Sardine Availability and Physical Processes

Total catch of sardines over the 1930–2000 period exceeded 8 million metric tons (t), with most of the landings occurring between 1930 and 1950. Total landings of sardine were five times greater than landings of either Pacific mackerel or anchovy, which were second

and third, respectively, in total landings (fig. 3). The largest catch of sardines was in 1941, when 572,550 t were reported. Landings declined to fewer than 100 t in the 1970s (fig. 1). The population rebounded in the 1980s and 1990s when average annual landings totaled 13,400 t and 30,400 t, respectively (Wolf et al. 2001). Since the total catch of sardines has been nearly equivalent to the total catch of all other species during 1930–2000, it might be expected that the sardine landing pattern would dominate C1 and C2 calculations but this is not the case. C1 and C2 patterns remain when the sardine landings series is excluded from the calculations (fig. 1).

Sardine management regulations followed catch declines from 1940 to 1973 and preceded increases in landings after 1985. Before 1967 the state did not limit total sardine landings, but in 1967 incidental catch was set at 15%, and landings for bait were limited to 250 t. In 1974 a moratorium was placed on all directed sardine fisheries, but 15% bycatch was allowed. Following initial rebound of sardine stocks, directed fisheries resumed in 1986 with a quota of 1,000 t. After 1991, quotas were increased until 1999, when 51,476 t were landed (Wolf et al. 2001; Mason 2004). Market demand and responsive regulation have allowed landings to follow sardine availability (fig. 1).

The sardine time series is closely correlated to the same physical indexes that are closely related to C1₂₉: La Jolla A-SST, $r = 0.90$; A-DSLP, $r = 0.87$; and A-EqSST, $r = 0.86$ ($p \leq 0.05$), suggesting a strong relationship between sardine availability and climate processes forced from the equatorial ocean. Figure 1 shows that the sardine series and C1₂₉ without sardine are closely related ($r = 0.86$, $p < 0.05$), indicating that many of the other 28 species used in calculating the C1₂₉-pattern are affected by the same environmental factors that affect sardine abundance. Many other species throughout California Current ecosystems probably follow similar patterns of abundance in response to the environmental effects of remote climate forcing.

Climate Forcing

It is not within the scope of this report to attempt a detailed account of California Current processes that have changed on climate scales during the 1983–2000 rebound of the sardine fishery or during other changes in landings composition (figs. 1–3), but there are some generalities worth noting. Local North Pacific forcing affects large areas of the North Pacific Ocean, including the California Current, on a continuing basis. The remote signal comes partially along the eastern ocean margin and spreads westward to become a dominant environmental influence in the CFHE (Fu and Qui 2002). Atmospheric components of remote forcing are

also important, particularly during the northern winter (Alexander 1992).

The PCI index represents large-scale aspects of local North Pacific forcing. Southward wind stress off central California (A-SWS) and San Francisco sea-level variation indexed by A-SFSL show the large-scale local signal in the California Current system and within the CFHE. The Darwin sea-level pressure indexed by A-DSLPL and the equatorial SST indexed by A-EqSST are unambiguous representations of equatorial climate signals. The remote climate signal is clearly represented within the CFHE by the La Jolla A-SST.

CONCLUSIONS

The species composition of the California finfish and invertebrate commercial fishery has followed two dominant patterns of climate-scale variation that are related to remote equatorial Pacific and local North Pacific large-scale oceanic and atmospheric processes. In addition, there are five related results. First, the empirical orthogonal functions (EOFs) explain more than 45% of the variance in landings data constituting more than 85% of the total landings. The low noise levels in the data, summarized landings indicated by the large percentage of variance explained by EOF1 and EOF2, suggest that consistent landings of more than 25 species during the 71-year study period and the demand-responsive fishery contribute to the utility of the CACOM data. Second, the progression of species maxima in the landings is tied to environmental conditions that appear to be completing a cycle and returning in the 1990s to physical and biological conditions similar to those of the 1930s and 1940s. Third, landings patterns (EOFs) are robust to changes in species groups and to the removal of dominant species from the input data matrixes. This indicates that the characteristics of the EOFs and their temporal variability (C1 and C2) are shared by many of the commercially landed species and possibly by other major components of California Current ecosystems. Fourth, remote and local modes of atmosphere-ocean forcing correspond to time variation in EOF1 and EOF2, respectively. This association, together with the grouping of species, presents predictive possibilities that will provide opportunities for proactive ecosystem management. Fifth, the history of sardine landings is similar to the time variation in EOF1 (C1). Sardine landings appear to be closely related to climate events occurring first in the equatorial atmosphere-ocean system and propagating into the California Current from the south. This relationship implies that fluctuations in sardine abundance within the 1930-2000 interval were environmentally dependent and not caused primarily by the directed fishery or its management.

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