

LONG-TERM TRENDS OF INTERANNUAL VARIABILITY IN THE CALIFORNIA CURRENT SYSTEM

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ABSTRACT

Several series of physical and biological parameters from the California Current region were analyzed for coherent long-term (>20 years) trends of change. Three different scales of change, related to the availability of data and different degrees of precision, were obtained: one for the period of most extensive and intensive CalCOFI sampling, roughly 1951–98; the second for the full century; and the third for the last 2,000 years.

Only one regime shift—that of the mid-1970s—was found in the shorter series. The shift consists of a long-term trend reversal, including both physical and biological data; no sudden step was found. The century-long series reveals two other shifts, both consisting of long-term trend reversals, the first in the early 1910s and the second during the early 1940s. Three other less certain shifts seem to have occurred about 1860, 1880, and 1900. If these indications are true, the ~60-year cycle of sardine abundance may have been much more variable than previously believed.

Sardine abundance appears to be enhanced during warm periods and diminished during cool ones; outbursts are very dynamic, lasting only a few decades. Regimes should be related to the change itself (either warming or cooling), rather than to warm or cool periods. Thus, the main factor for change might not be temperature, but possibly large-scale ocean current changes and associated alterations in wind systems. We found monitoring biological indices to be the most feasible tool for nowcasting regime shifts. There is not yet enough information for long-term forecasting.

INTRODUCTION

At their first meeting, held in 1998, the Living Marine Resources Panel of the Global Ocean Observing System (LMR-GOOS) decided to conduct a series of retrospective analyses at well-known ocean areas in order to examine whether ocean changes could have been forecasted on the basis of present knowledge. The authors conducted such an experiment for the California Current system (CCS), one of the best known regions, particu-

larly following the intensive, extensive, and persistent work conducted by the California Cooperative Oceanic Fisheries Investigations (CalCOFI) program.

The analysis was rather limited and particularly focused to find readily available environmental and biological variables that could prove practical for monitoring and eventually forecasting change. We selected some of the most commonly accessible variables, such as sea-surface temperature, sea-level height, and upwelling as indices of physical change; we used macrozooplankton volumes, larval fish species abundance, and sardine and anchovy relative abundance as biological indices. Although these variables are not exhaustive reflections of change, they are somehow related to it and easily obtained.

In this paper we discuss trends of such variables at longer than 20-year periods; this scale corresponds to the very low frequency described by Ware (1995). A number of authors use the term *regimes* to denote multidecadal periods separated by shifts. The duration of these regimes and the timing of their onset and end have been examined by several authors (fig. 1). Hubbs (1948) described both annual and long-term persistent changes based on the presence of southern- and northern-affinity fauna; in particular, he described the warm period during the 1860s.

Lluch-Belda et al. (1989), looking at sardine and anchovy population abundance, pointed out high sardine abundance during the 1930s–40s and low abundance during the 1960s–70s. Michaelsen (1989) extracted an El Niño–Southern Oscillation (ENSO) index from tree rings of northern Mexico and the southwestern United States and found that both the amplitude and frequency of the signal were modulated over an 80–100-year time scale.

Baumgartner et al. (1992) analyzed sardine deposition rates at varved sediments and found a predominant signal of about 60 years in both sardines and anchovies and about 100 years for anchovies, but not for sardines.

A different approach to the problem was taken by Ebbesmeyer et al. (1991), who examined the 1976–77 climate shift (Kerr 1992) and demonstrated how a wide array of both biological and environmental variables changed during the period.

Francis and Hare (1994) described regime shifts dur-

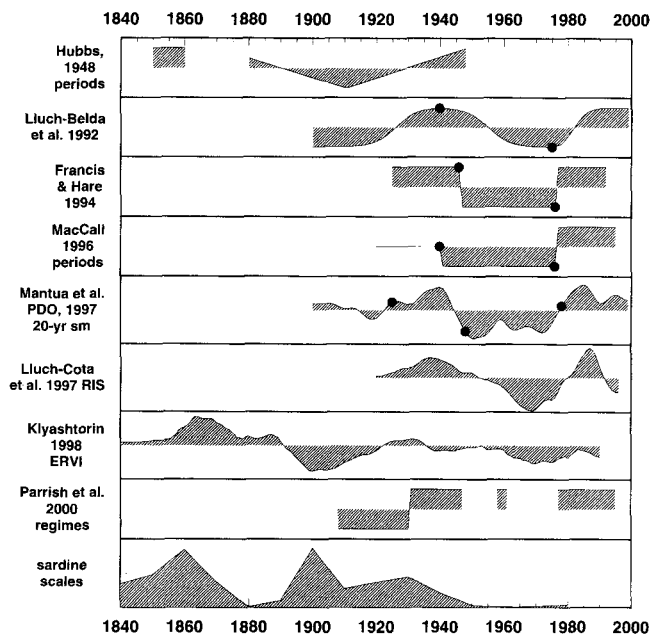


Figure 1. Schematic representation of warm and cool periods and timing of regime shifts, after several authors.

ing the late 1940s and the late 1970s in the northeast Pacific, based on several environmental variables and two biological indices (zooplankton and salmon production). Ware (1995) analyzed changes in the marine climate of the NE Pacific, particularly British Columbia, and found five principal periodic signals: the QBO (quasi-biennial oscillation, ~2–3 years); two ENSO-related (~5–6 and ~11–14 years); the BDO (bidecadal oscillation, ~20 years); and the VLF (very low frequency, ~50–90 years).

Polovina et al. (1995) found that from 1976 to 1988, a period of intensified Aleutian Low, there was a deepening of the mixed layer in the eastern subtropical Pacific and shoaling in the Gulf of Alaska, as compared to the 1960–76 period. Hsieh et al. (1995) found intensified winter downwelling along Alaska and British Columbia and intensified winter upwelling off Baja California since 1940.

MacCall (1996) reviewed low-frequency variability of fishes in the CCS and referred to biological variability in 50–70-year scales; he further noted that the conditions after 1976 were similar to those of 1850–70. He described the regime shifts of 1940 and 1976 and discussed the evidence of a brief cold period around 1890.

Brodeur et al. (1996) and more recently Ingraham et al. (1998) report on a surface drift simulation model (OS-CURS) which showed that winter trajectories beginning at Ocean Station P drifted more toward the CCS before 1976 and more into the Alaska Current after 1976.

Mantua et al. (1997) calculated the Pacific decadal oscillation index (PDO) and found it to be predominantly positive during 1925–46, negative in 1947–76, and again

positive since 1977. They further proposed 1925, 1947, and 1977 as dates of climate shift.

Lluch-Cota et al. (1997) analyzed environmental variability together with sardine and anchovy population abundance in a global perspective and concluded that climate regime trends and periods lasted for several decades (more than two, less than four) in the twentieth century; they also found that from 1870 to 1915 the periods were shorter. Sardines were abundant from 1925 to 1950 (peaking during the mid-1930s), and anchovies from the early 1950s to the late 1970s (peaking around the late 1960s); sardine abundance increased again from the late 1970s and in most of the 1980s, perhaps declining in the early 1990s.

Looking at mesoscale disturbances in the American southwest, Swetnam and Betancourt (1998) showed that the first part of the century (1905–30) had wet winters, followed by a dry period from 1942 to 1964; after 1976, winters have been wet and warm, with erratic summers.

One of the few papers that deal with long-term trends of change in this temporal scale is that of Klyashtorin (1998), who reports the similarity of trends between the abundance of several fish stocks and large-scale environmental variables, mostly related to the atmospheric circulation index, the length of day index, and the earth rotation velocity index (ERVI). This last index shows some interesting similarities to the rest, although the peaks and troughs are somewhat dephased.

Parrish et al. (2000) reviewed previous information together with an analysis of wind data and arrived at a number of relevant conclusions, including that surface water entering the CCS was of more subtropical origin after 1976. Parrish et al. considered the best example of decadal climatic change to be the 1976 shift. After 1976, the surface of the central North Pacific cooled by 1°C or more, while the North American coast and Gulf of Alaska warmed by a similar amount. Further, there was ~20 m shoaling of the mixed layer depth in the Subarctic Gyre after 1976, and a similar deepening in the Subtropical Gyre. Dynamic heights and SST increased in the Gulf of Alaska after 1976; transport into it increased, while transport decreased into the California Current.

Parrish et al. (2000) further noted that the principal source of the biological bonanza in the CCS during the late 1970s lay in processes associated with the shift from one climate state to the other, not in the new state itself. With regard to multidecadal periods, they found an extensive cold period from 1908 to 1930 and warm intervals during 1931–47, 1958–61, and 1977–95.

Minobe (2000) examined the interaction between the bidecadal and pentadecadal variation in the North Pacific and suggested that major regime shifts are caused by the phasing of both cycles, as occurred during the 1920s, 1940s, and 1970s shifts, while minor regime shifts (such

as that of 1988–89) could be caused by the bidecadal variation alone. Minobe and Mantua (1999) found that interannual variance in the strength of the Aleutian Low was large during the mid-1920s to the mid-1940s and during the 1980s, but low from 1899 to the mid-1920s and from the mid-1940s to the mid-1970s. Hare and Mantua (2000) studied the proposed 1989 regime shift by analyzing a large number of biological and physical series, and concluded that although the biological series offer strong support for the case, the physical series are less convincing.

The published information discussed above leads to a number of possible conclusions:

1. There have been multidecadal, irregular, alternating climatic periods in the 50–100-year range.
2. The most documented regime shift occurred around 1976.
3. Other likely shifts have occurred in the 1940s and between 1910 and 1927, with lessening certainty.
4. The best-documented prolonged period is the cool one extending from about 1940 to the late 1970s; the warm stretch after it is possibly coming to an end (Ware 1995; MacCall 1996; Lluch-Cota et al. 1997) or has already ended (Hare and Mantua 2000).
5. An additional cool period seems to have occurred about the 1910s; another might have been present about 1890.
6. Other earlier warm periods have likely happened during the 1930s–40s and about 1850–60. If there was a cold period about 1890, then a short warming might have been present at about 1890–1900.
7. During warming periods, the mixed layer at the eastern subtropical Pacific deepens while it shoals at the Gulf of Alaska. Also, the flow of the Alaska Current intensifies while that of the CCS relaxes. Links to atmospheric changes are suggested both by the relative interannual variability in the strength of the Aleutian Low and by the parallel alternation of dry and wet winters in the southwestern United States.

In this paper, we examine several biological and environmental data series in the framework of these long-term changes.

Three temporal windows result from data availability: (1) 1950–present, roughly half a century: for upwelling and most biological indices (zooplankton volumes, larval fish species abundance, and sardine and anchovy relative abundance); (2) century-long: mostly for sea-surface temperature, sea-level height, and sardine fishery data; (3) millennial proxies: basically global temperature, sea-surface temperature, and sardine and anchovy scale numbers in varved sediments as indices of their relative abundance.

DATA AND METHODOLOGY

We extracted monthly average SST series from the COADS database (Mendelssohn and Roy 1996) for the 76 $2^\circ \times 2^\circ$ quadrants shown in figure 2, assuming that it covered most of the CCS. The annual cycle of each quadrant was estimated as the average SST for each month for all the existing data between 1900 and 1990. Anomalies were then calculated as the yearly average of the monthly departures from the mean. The global index (AST) was obtained by annually averaging the individual yearly anomalies at all 76 quadrants. Principal component analysis (see Storch and Zwiers 1999) was used to estimate the first principal component of the averaged yearly anomalies for each quadrant (from now on, PST).

Yearly averaged SST anomalies were also estimated from data at coastal stations and were obtained from the PACLIM database (updated after Cayan et al. 1991), including Point Hueneme, Crescent City, Pacific Grove, Los Angeles, San Francisco, and San Diego (CST = coastal SST anomalies). Yearly anomalies were estimated as the averaged departures from the monthly means of the full series. Average yearly air temperature anomalies for the conterminous United States were obtained by digitizing figure 2 in Karl et al. 1995. Global air surface temperature anomalies and global SST anomalies were obtained from the Web site of the British Meteorological Office (<http://www.metu.gov.uk/>).

Monthly sea-level height was obtained from the University of Hawaii Sea Level Center Web site (<http://uhslc.seest.hawaii.edu>) for San Francisco and San Diego. We

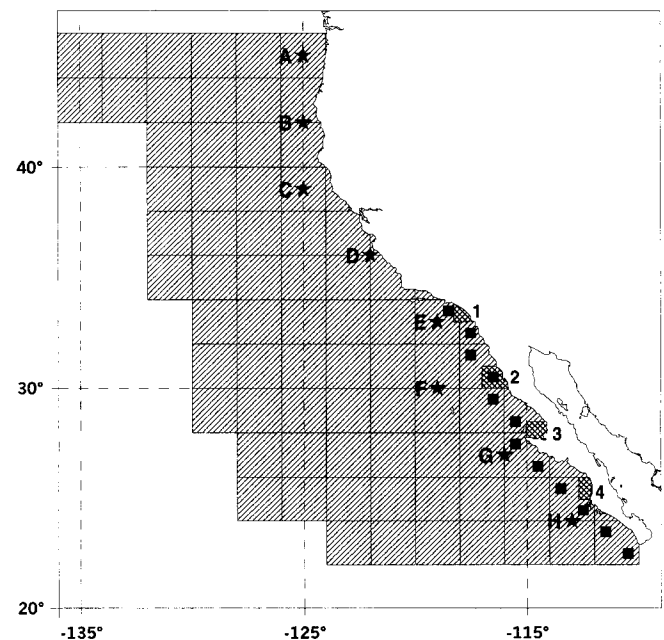


Figure 2. General map of the U.S. West Coast and Baja California area, showing the location of the 76 COADS quadrants (hatched) and their latitudinal transects; the four coastal areas for biological indices (crosshatched); SST anomalies sites (■) and upwelling indices (★), reconstructed for this paper.

detrended and standardized both series before calculating the annual means for each and averaging them into one index (SLH). Upwelling indices (Bakun 1973) were obtained from NOAA/PFEL (<http://www.pfel.noaa.gov/>) as monthly values for the points shown in figure 2 (UW a , where a stands for the point).

Four coastal areas, enumerated in figure 2, were used to estimate relative abundance of zooplankton, fish larvae species, and sardine and anchovy eggs and larvae. The data are from the CalCOFI database, and were kindly provided by Paul Smith. In the case of zooplankton (ZP n , where n stands for the area number shown in fig. 2), the index is the yearly averaged macrozooplankton displacement volume at all occupied stations in each area; the total number of different fish larvae species per year for each area is the second index (SP n). The annually averaged number of individuals per occupied station was used as an index for sardine egg abundance (SE n), sardine larvae abundance (SL n), anchovy egg abundance (AE n), and anchovy larvae abundance (AL n), after transforming each of these series by $\ln(x+1)$ to account for their log-normal distribution.

Longer series were obtained from Douglas (1976), who reports SST reconstructed time series for six coastal points based on tree-ring data (also shown in fig. 2). The series consist of quarterly anomalies; they were averaged for the year for each estimation point. Principal component (PC) analysis of the yearly averaged series readily separates two PCs: the first one captures 64.5% of the total variance, and is related to points north of Magdalena Bay, the coastal area of the CCS; the second (14.3% of the total variance) is linked to the subtropical variations at the southern tip of the peninsula. The PC1 of these series was used as an index.

All the half-century (1950 to present) indices were standardized and grouped by Ward's method (Ward 1963) with $(1 - \text{Pearson's } R)$ as a measure of distance; three groups were obtained. Averaged values were then calculated for each year, and smoothed by a 20-year Hamming window.

We were unable to find a single corresponding temperature time series for the last 2,000 years for comparison to sardine scale abundance, so we used four different temporal scales, associated with unequal scales of precision. First, we digitized figure 2 in Crowley 1998 to obtain a proxy of global temperature anomalies for the last two millennia, and used reconstructed global temperatures from Mann et al. (1999) for the last 1,000 years. We used the PC1 of coastal SST anomalies in Douglas 1976 as a proxy for the 1800–1900 period, and the average SST anomalies in the CCS for the 1900–2000 period.

The number of sardine scales in varved sediments of the Santa Barbara Basin is from Baumgartner et al. 1992, kindly provided by Paul Smith.

RESULTS

Half-Century Trends

Tree clustering separates three major groups (fig. 3):

- group 1 includes sardine egg and larval abundance at areas 2 (Punta Baja) and 3 (Sebastián Vizcaíno), macrozooplankton abundance at all areas, and upwelling at the southern areas (south of the Southern California Bight);
- group 2 incorporates all anchovy egg and larval abundance series at all areas, the number of fish larvae species at all areas, and sardine egg and larval abundance at the southernmost area (Golfo de Ulloa);

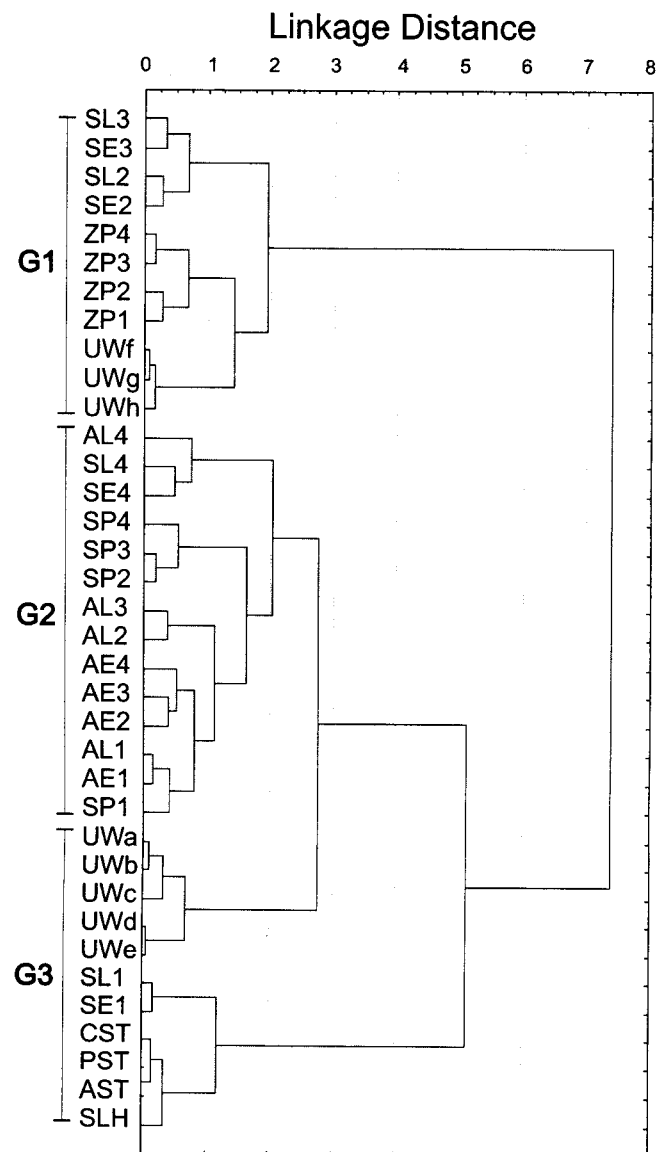


Figure 3. Tree diagram (Ward's method) of the 36 variables in the 50-year series. (See text for explanation of variables.)

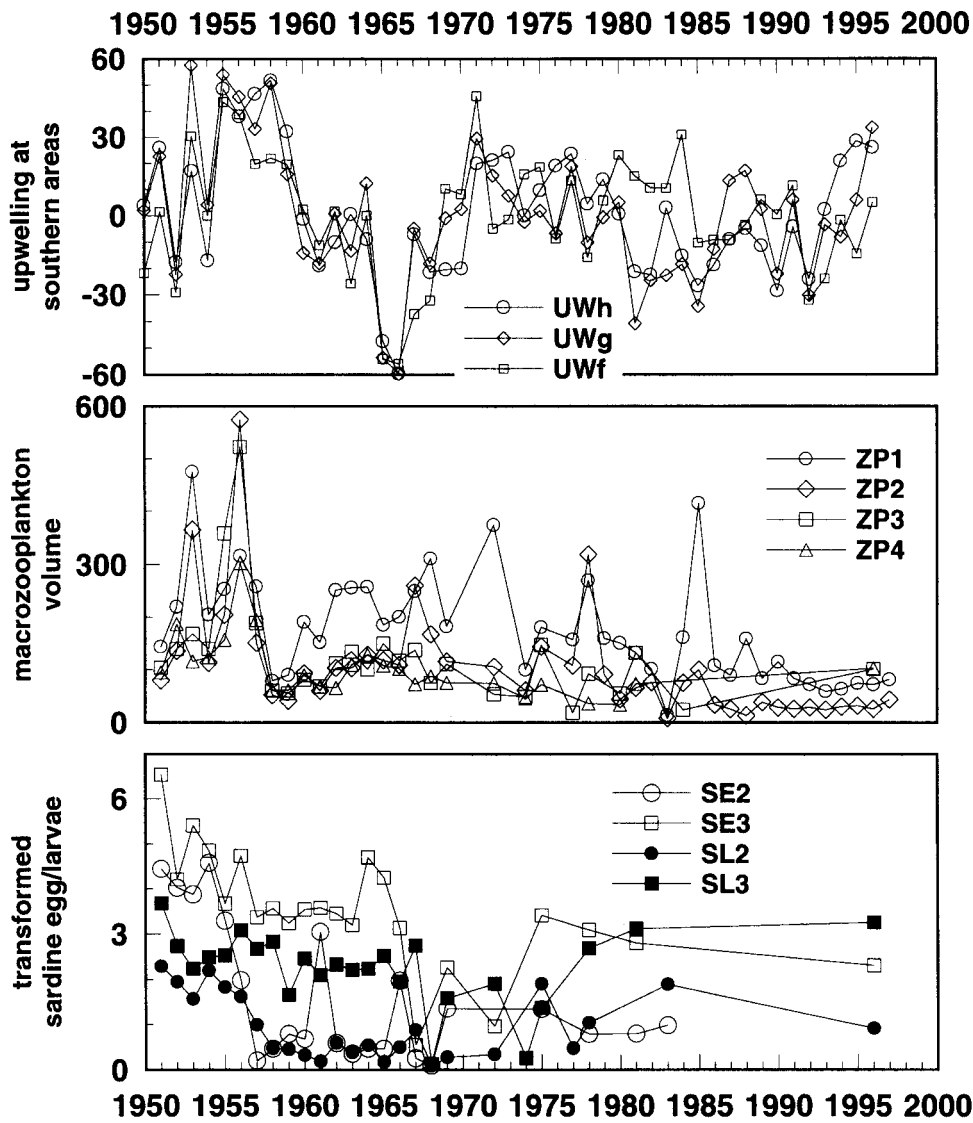


Figure 4. Half-century series group 1: yearly values of upwelling indices at the southern areas; macrozooplankton volumes and transformed number of sardine eggs and larvae at areas 2 and 3.

- group 3 encompasses all the AST, PST, and SLH series, plus sardine egg and larval abundance at area 1 (Santa Barbara).

The annual data for each group are shown in figures 4 (group 1), 5 (group 2), and 6 (group 3). The annual means for each group are shown in figure 7, together with their 20-year smoothed series. Although a large interannual and interdecadal variability exists, long-term trends are apparent: groups 1 and 3 are mainly opposed, G1 decreasing in the long term, while G3 increases; also, their interdecadal variations are contrary. Group 2 also shows large interannual and interdecadal variability. As for the long term, an increasing trend from 1950 to the mid-1970s changes to a decreasing trend since then.

Century-Long Variation

Figure 8 shows the mean yearly SST anomalies for the COADS quadrants shown in figure 2. There is considerable high-frequency interannual variation; the average year-to-year change is about 0.4°C, with a positive maximum of 1.3° and a largest negative value of -1.5°. The series shows nearly average values at the onset of the century, a cool period after 1906 lasting until roughly 1940, leveled fluctuating anomalies until the mid-1970s, and a sustained warm period since then. There are some clearly consistent multiyear warming and cooling episodes.

Reservations have been expressed about using COADS data before the 1950s; MacCall (1996) has de-

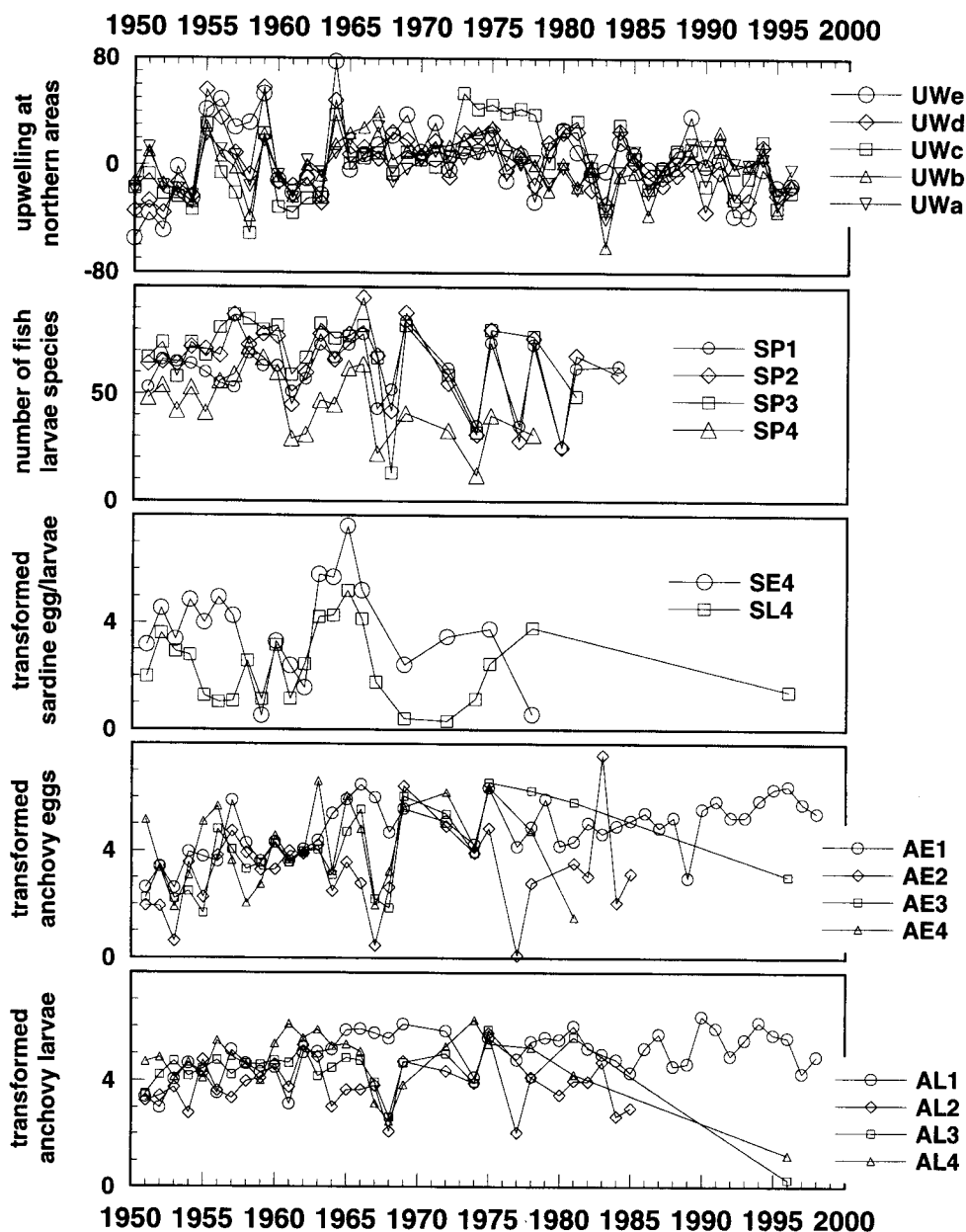


Figure 5. Half-century series group 2: yearly values of upwelling indices at the northern areas; number of fish larvae species at all areas, transformed sardine egg and larvae number at area 4, transformed anchovy eggs at all areas, and transformed anchovy larvae at all areas.

scribed some of them. In essence, the concern is based on gaps in the individual quadrant series due to incomplete sampling, which might bias averaging procedures. Figure 9 shows the number of quadrants with a nonzero value per year throughout the century; it is evident that the cool period coincides with poor coverage. The question is whether—if sampling were systematically biased due to, for instance, the colder, temperate portion being more intensively sampled than the warmer subtropical region—this difference would bias the average. Since the

point is not a trivial one, we used a number of criteria to increase the confidence in the series.

First, the lower average temperatures from the mid-1910s to late 1940s do not seem to be a consequence of incomplete sampling at warmer areas, since the procedure to estimate SST anomalies precludes geographic bias, being calculated for each individual quadrant and then averaged. The only possible drawback would be that each region had different trends.

However, all of the series are significantly ($p < 0.05$)

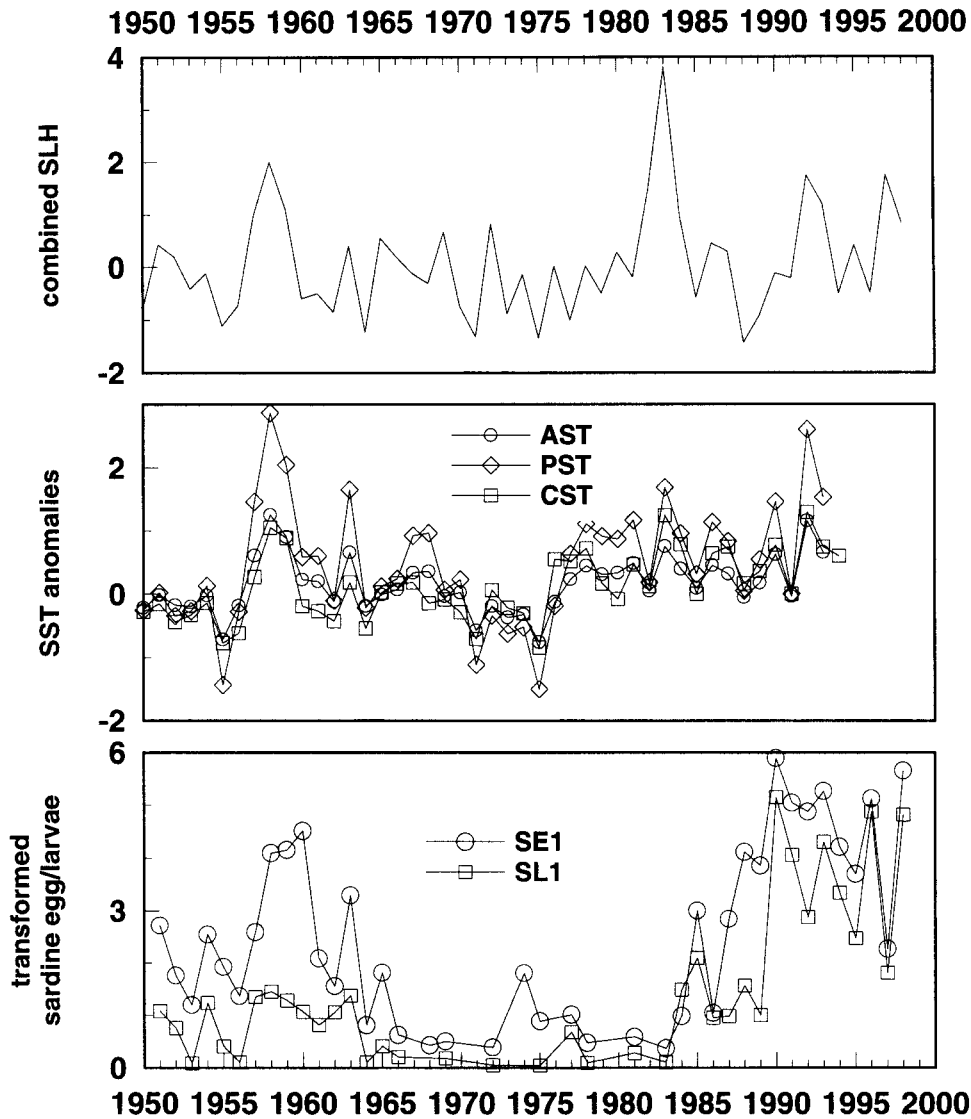


Figure 6. Half-century series group 3: combined sea-level height, sea-surface temperature series, and transformed number of sardine eggs and larvae at area 1.

correlated with each other, except for only two quadrants (22° – 24° N, 120° – 122° W, in 22% of the cases, and 26° – 28° N, 118° – 120° W, in 9% of the cases), and these are among the least represented in time, so no major bias should be expected from this factor.

Completeness per quadrant (the actual number of observations divided by the maximum possible number) for the full century and for the 1914–28 period (the one with poorest representation; fig. 9), is shown in figure 10. Transects conform to the horizontal divisions of the COADS area shown in figure 2. There is always rather good latitudinal coverage, particularly in the coastal areas, so no related bias from this source should be expected either.

Factor loadings for PC1 of the SST anomalies for

each of the 76 COADS quadrants are shown in figure 11. The California Current limits, digitized from Lynn and Simpson (1987) are indicated by dashed lines for comparison. There is geographic coherence in the fact that higher PC1 factor loadings coincide rather well with the current itself.

Comparison to a number of similar interval and related time series, all shown smoothed in figure 12, shows similar trends. The 10-yr Hamming window smoothed series are all significantly correlated ($p < 0.05$). The PC1 of all the series, excluding the SST anomalies estimated from the COADS quadrants, is displayed in figure 13, together with the global SST anomaly ($r = 0.7627^{**}$, $n = 94$).

Hubbs (1948) described a warm period during the

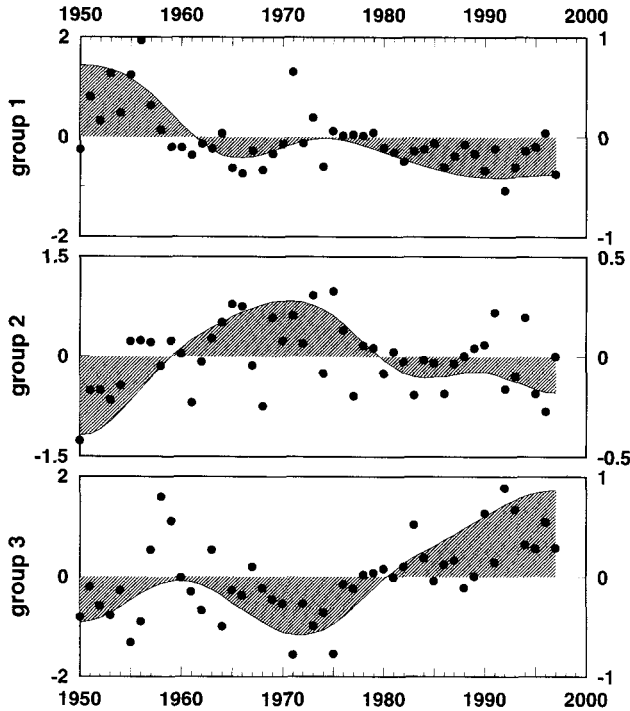


Figure 7. Means of the three groups in figure 3; annual values shown by circles, 20-yr. Hamming smoothed series as the hatched background line. Note the different scales.

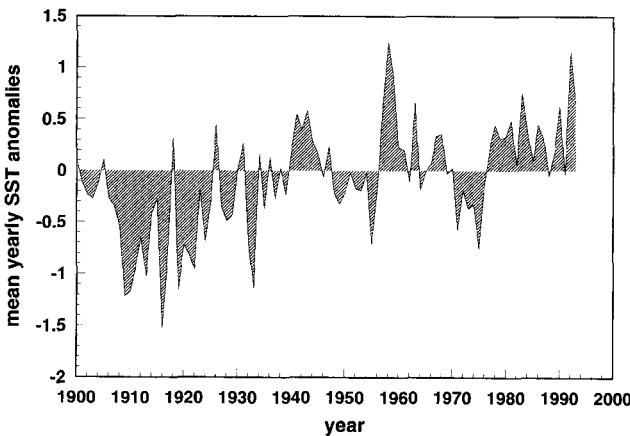


Figure 8. Yearly averaged SST anomalies for the COADS quadrants shown in figure 2.

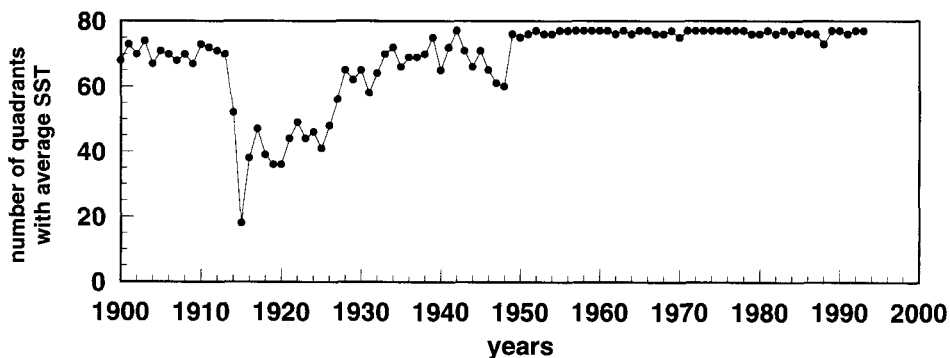


Figure 9. Number of COADS quadrants with nonzero value per year.

1850s–60s and a subsequent cooling until about 1910, after which there was a moderate reversion toward warmer conditions. Radovich (1961) stated that ocean temperatures were high during 1926, 1931, and 1941, and very low from 1948 through 1956. MacCall (1996) described a moderate and highly variable period from the beginning of the series (1920) to about 1940, a cold interval until 1976, and a warm period since then. Parrish et al. (2000) found an extensive cold period from 1908 to 1930 and warm intervals during 1931–47, 1958–61, and 1977–95. All four accounts agree well with the annual SST average anomalies series from the COADS database.

The low-frequency pattern shows cooling since the onset of the century until the first or second decade, then warming until the 1930s–40s, slight cooling until the mid-1970s (with a warming event during the late 1950s), and warming from then to the present.

Interannual Variation at Longer Time Scales

Series for the most recent two centuries appear in figure 14. The upper panel shows the 10-year Hamming smoothing of the PC1 (related to areas north of Magdalena Bay) of the coastal SST series from Douglas (1976) and number of sardine scales at the varved sediments of the Santa Barbara Basin described by Baumgartner et al. (1992) as a proxy for species abundance in 10-year intervals for an almost 1,000-year period. Starting at about 1830, a warming period is closely followed by increased sardine abundance, peaking during 1850–60, the time for which Hubbs (1948) described a warm period in the CCS. Rapid cooling afterwards also parallels a decline in sardine abundance, with a minimum in about 1880. An outburst of sardine abundance in 1890 corresponds to a very intense and sudden temperature increase at about the same time. The anecdotal accounts are not clear as to what happened between the recognized warm 1850s period and about 1910, the coolest year in the century-long series (see also MacCall 1996).

In the twentieth century, a low sardine abundance

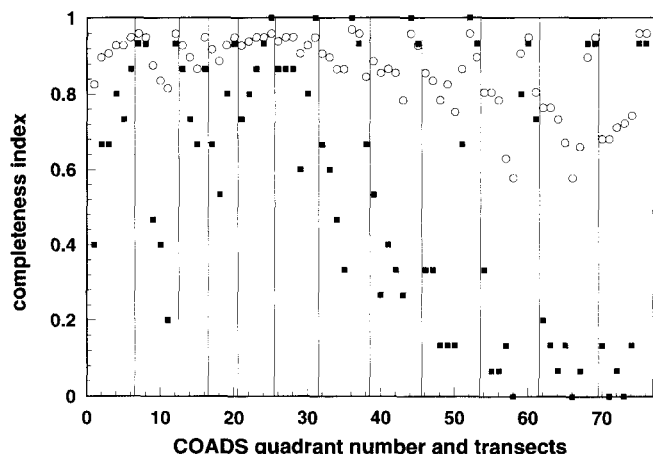


Figure 10. Completeness index: actual number of nonzero values divided by the maximum number: squares, the 1914–28 period; circles, remainder of the series. Vertical lines indicate the latitudinal transects shown in figure 2.

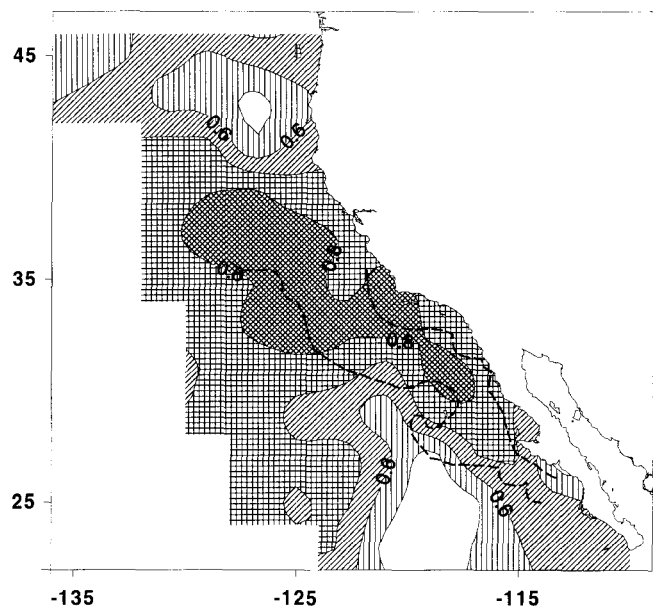


Figure 11. Spatial PC1 of SST anomalies in the 76 COADS quadrants. Approximate limits of the California Current, digitized from Lynn and Simpson 1987, shown as broken lines.

value about 1910 coincides with the lowest recorded temperature. The following population growth of sardine basically parallels the development and growth of the fishery, whose landings peaked about 1940, when sardine scales were already diminishing. The low abundance trend persists until the 1970s–80s, when a reversal seems to occur.

The full series of sardine scales at sediments is shown in the lower panel of figure 15; temperature proxies for the global temperature and the Northern Hemisphere are displayed in the upper panel.

Keeping in mind the uncertainty of the temperature

proxies, we suggest a number of gross characteristics of both series. First of all, there seems to be a correspondence between temperature and sardine abundance, as previously proposed (Lluch-Belda et al. 1989). It appears, however, that high sardine population abundance is related not so much to sustained warm temperatures as to periods of warming.

A long period of low abundance of sardine extended through the Little Ice Age (~1400–1900), but a particularly interesting event occurred during the mid-1400s: rapid cooling followed by intense warming. The warming phase was soon followed by an explosive increase in sardine abundance. This is an isolated event, immersed in a cool period.

DISCUSSION

Interannual change occurs at all time scales in the California Current system; even if high frequency is eliminated by smoothing, the remaining trends still change irregularly. The different length, coverage, and precision of the available data series make the search for patterns of change difficult and uncertain. Within the evident limitations of the present exercise, however, some blurred relations may yield interesting grounds for building a number of hypotheses about trends.

For the most recent 50 years, the CalCOFI database adds invaluable information about a great number of variables, of which we have only used a few. Nonetheless, their mode of change makes it possible to group them into three main patterns, as shown in figure 3.

It should be kept in mind that the trend, obtained by means of a 20-year smoothing window, makes the extreme years in the series depend on fewer points as they approach the beginning and end of the series; also, the smoothed filled line (trend) is exaggerated in the vertical scale, as can be seen in the right axis of figure 7. In general terms, only one of the groups (G1) shows a consistent long-term declining trend; the other two display fluctuating trends. Although these fluctuations in the last two groups seem basically to change on a decadal to bidecadal frequency, that of G2 begins low, increases to a maximum during the 1970s, and declines again; from this perspective, G2 is the only one that shows a trend reversal. Group 3 appears almost as inverse to G2, but also begins low. If not for the considerable effect of the 1957–59 ENSO, G3 would show a basically increasing trend.

In G1, upwelling in the southern areas, zooplankton volume in all areas, and sardine spawning in the central area fundamentally tended to decline from 1950 to 2000; the series is dominated by the very high values of the early 1950s, subsequent plummeting in the late 1950s, followed by a steady decrease. Upwelling would seem to be the dominant physical feature determining pro-

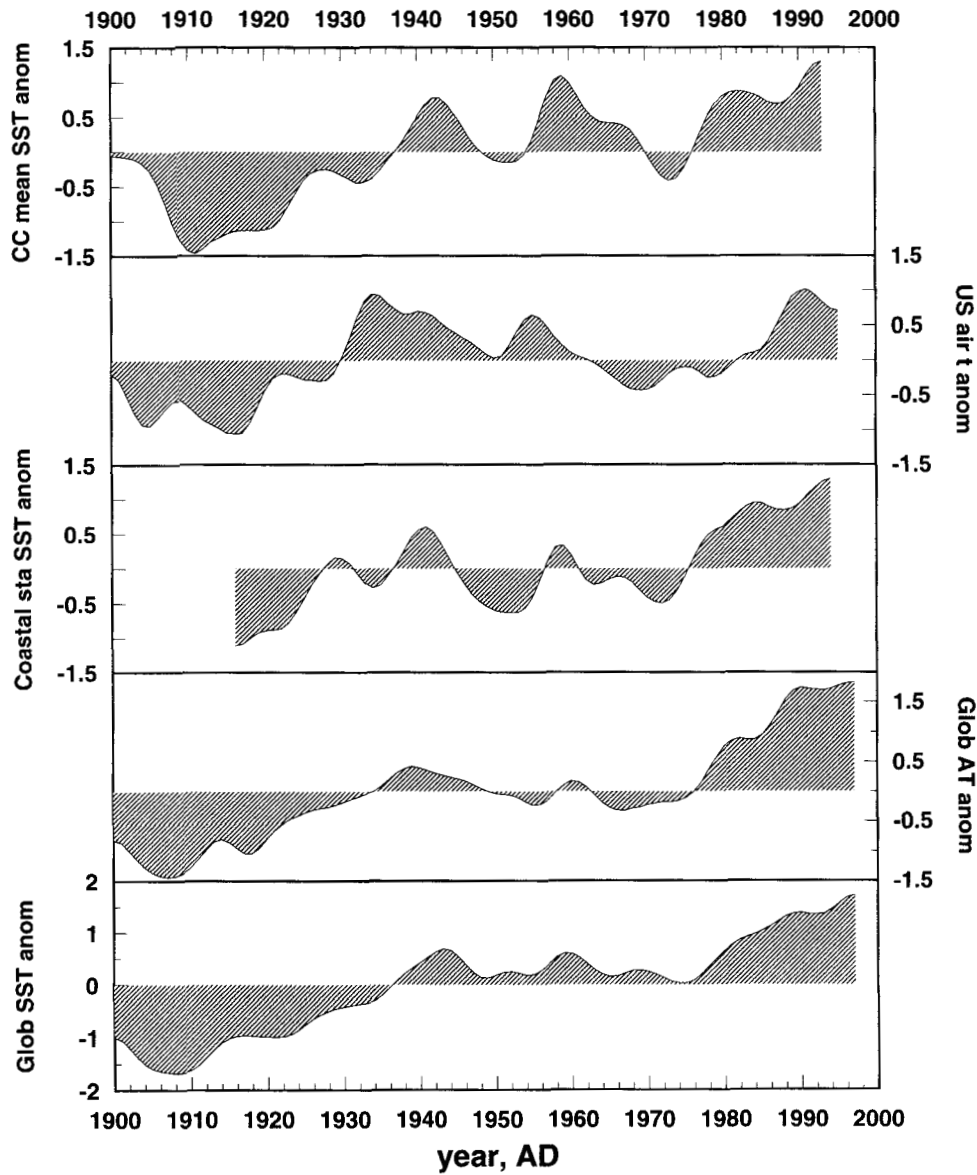


Figure 12. Yearly averaged SST anomalies in the 76 COADS quadrants; conterminous U.S. yearly air temperature anomalies; yearly averaged SST anomalies at coastal stations; global air surface temperature anomalies; and global SST anomalies; all series smoothed by a Hamming window of 10 terms.

ductivity; however, Bernal (1981) summarized earlier work that shows that zooplankton volume in the CCS is more related to southward advection than to upwelling. One possibility is that in these southern CCS areas the effect of advection gradually diminishes and upwelling becomes more determinant. While zooplankton volumes and upwelling decreased through the full 1950–97 period, sardine egg and larval data are interrupted in these areas after the mid-1970s. Nonetheless, they also diminished in the existing data period.

Conversely, AST, CST, PST, SLH, and sardine spawning in the northern area have been increasing, as shown

in G3 (fig. 6). The series show the signal of the 1958–60 warming event. Sardine spawning increase fits with previously proposed mechanisms (Lluch-Belda et al. 1991). Both warming (G3) and zooplankton decline (G1) match the findings of Roemmich and McGowan (1995).

On the other hand, in G2, upwelling north of Santa Barbara, anchovy spawning at all areas, and sardine spawning at the southernmost area (although the series is interrupted during the mid-1970s) tend to increase until the 1970s and decline afterwards. Unfortunately, upwelling is the only parameter recorded for all areas throughout the full period. Sardine spawning increase

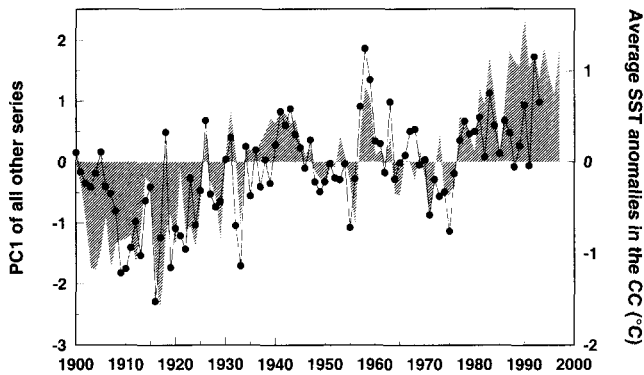


Figure 13. Yearly averaged SST anomalies at the COADS quadrants (shaded) and PC1 of all other series shown in figure 6.

matches previously proposed mechanisms for concentrating population at the equatorward limits during cool periods, but the series is too short to determine whether spawning declined afterwards.

Upwelling seems to show the regime shift signal. Hsieh et al. (1995) found upwelling trend reversals during the 1940s shift on a differential latitudinal basis, similar to what we have described here for the 1970s shift. Schwing and Mendelsohn (1997) showed a minimum in spring-summer SST off southern California about 1970 due to a temporal maximum in coastal upwelling, while similar SSTs off Baja California have risen steadily.

Anchovy spawning also shows the change in trend at all areas, but sardine spawning differentiates latitudinally.

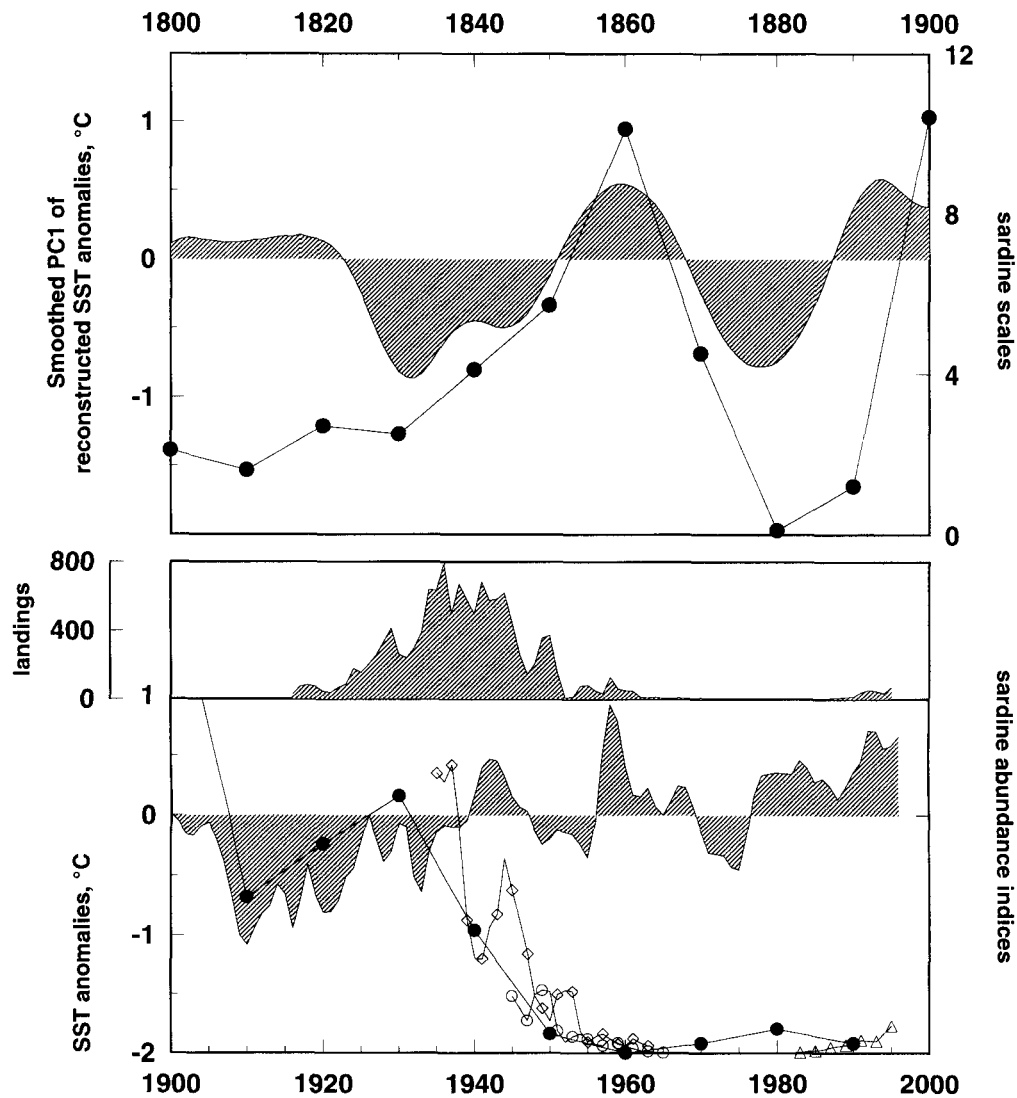


Figure 14. Upper panel: smoothed coastal reconstructed SST anomalies (shaded) and sardine scale number, 1800–1900; lower panel: yearly averaged SST anomalies at the COADS quadrants and various indices of sardine abundance: ● sardine scales at varved sediments (Baumgartner et al. 1992), ○ 2+ adult biomass (MacCall 1979), △ 1+ biomass (Deriso 1996), and ◇ spawning biomass (Jacobson 1995).

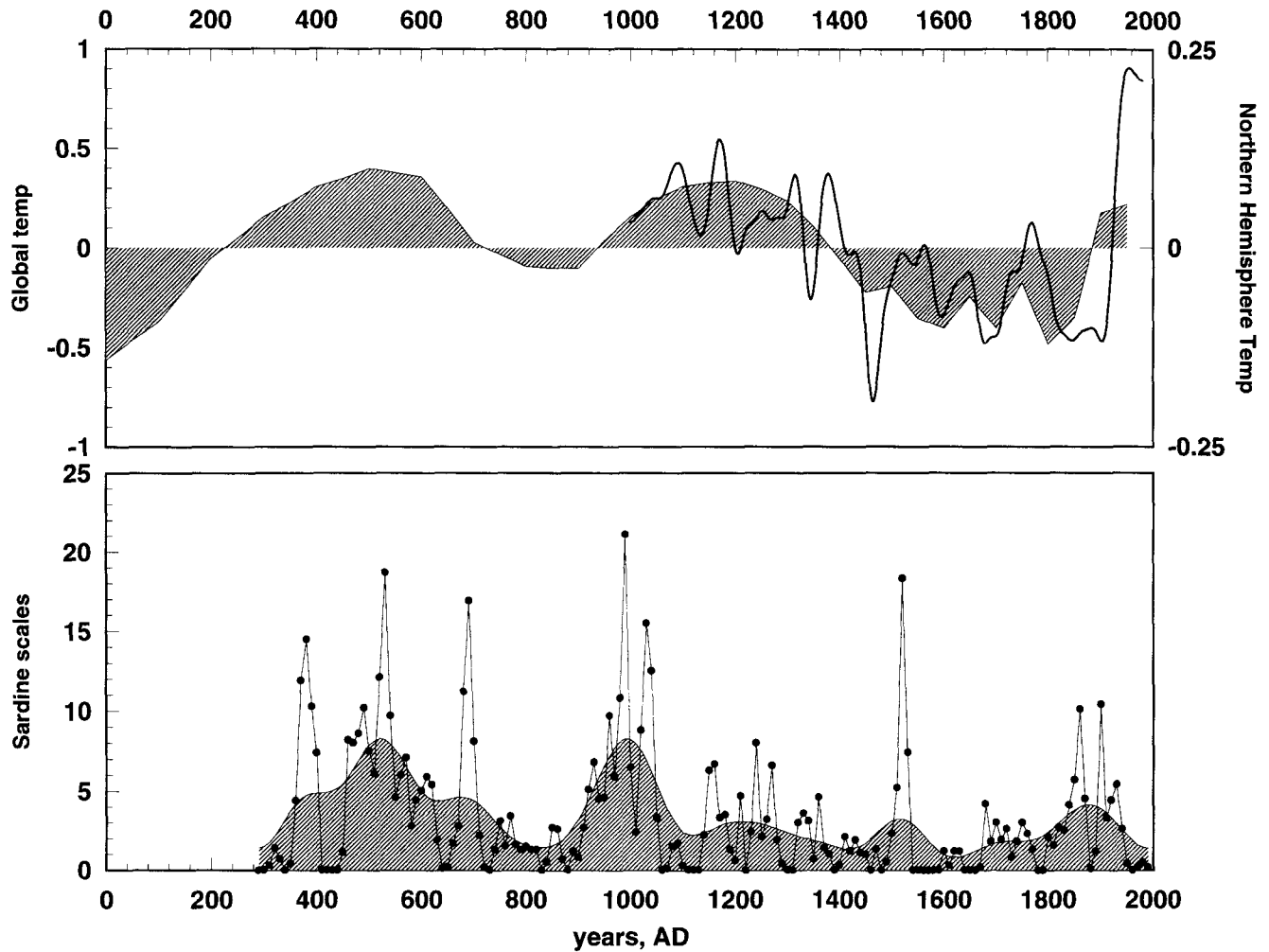


Figure 15. *Upper panel:* temperature proxies: global temperature anomalies in 50-year intervals (Crowley 1998, hatched line); Northern Hemisphere temperature anomalies (from Mann et al. 1999, line). *Lower panel:* sardine scale abundance at the Santa Barbara Basin at 10-year intervals, together with a 10-term smoothing.

This might support the idea that anchovies are more related to the California Current itself, while sardines have more of a coastal nature (Hernández-Vázquez 1994). A promising index, taking into account the coherence between different latitudes, is that of the number of larval fish species; unfortunately, the series extends only to the mid-1970s.

The shift in the mid-1970s looks like a trend reversal approximately coincident with the reported regime shift of 1976. Kerr (1992) showed an abrupt jump in several environmental variables between 1976 and 1977; we find a reversal of trend in the original nonsmoothed series, not a step, but this would depend on what kind of variable is being analyzed.

Turning to the century-long series, we suggest that figure 8 reasonably represents the basic shape of the SST anomalies during this period, as confirmed by a number of other series and anecdotal references. The series shows average temperatures at the beginning of the cen-

tury, a fast cooling period to the 1910s, and a warming trend peaking during the 1940s.

Afterwards, there was a cooling trend until the mid-1970s; the intense but brief warming resulting from the 1958–59 El Niño is evident in this series but did not change the trends, as described above for the 50-year period. The trend reversal occurred during the mid-1970s, and has persisted to the end of this series.

We thus suggest that there have been three trend reversals or regime shifts: about 1910+ \uparrow , 1940+ \downarrow , and mid-1970s \uparrow . The last two agree well with those proposed by MacCall (1996), Lluch-Cota et al. (1997), Mantua et al. (1997), Minobe and Mantua (1999), and Parrish et al. (2000). The first is dephased from that proposed by Mantua et al. (1997) around 1925, but agrees with the description of Hubbs (1948). Parrish et al. (2000) considered 1958–61 as a warm period.

If the above description is true, then we have been able to observe only one full cycle during the century,

extending between minima at 1910+ and the mid-1970s, or roughly 60 years. This period matches that described by Baumgartner et al. (1992) as the dominant signal in sardine scale abundance, and with periods discussed by MacCall (1996), Ware (1995), and Lluch-Cota et al. (1997). It also fits with the period suggested by Francis and Hare (1994), since their interval between shifts extends for about 30 years.

During the twentieth century (lower panel of fig. 14) sardine abundance increased until 1930, and then fell off. We suggest that this breakdown was facilitated by an intense fishery (landings data shown in fig. 14); if population abundance had followed previous patterns, it would have increased to the 1940s at least, as MacCall (1996) earlier proposed. The population began growing again after the mid-1970s, and this increase became apparent during the early 1980s.

Before 1900, however, the 60-year cycle seems to be one of several (figs. 14 and 15). A warm peak during 1860 coincides with the account of Hubbs (1948) and a maximum abundance of sardine scales; between then and 1910 anecdotal references seem contradictory as to the existence of an intense brief period (MacCall 1996), but both sardine scale abundance and reconstructed SST show a minimum during 1880 and a fast increase to about 1900. If this is correct, then the resulting cycle would be only about 40 years.

Even within the limited resolution (10 years) of the sardine scale abundance series, a sardine population buildup appears to be an explosive process, usually taking less than 40 years, but population collapses seem to be even more abrupt, mostly between 20 and 30 years. Baumgartner et al. (1992) showed that recoveries range from 20 to 70 years, 36 on average, while collapses average 30 years (20 to 50 years). Such outbursts are much more frequent and reach higher values during warm periods, but are also present during cool ones (e.g., about 1450). In the long perspective, sardines were at least two times as abundant before the onset of the Little Ice Age than afterwards, although there was some recovery during the 1800s.

Within this longer perspective, it becomes clear that the fundamental sardine abundance regimes are not those of warm or cool periods, but those of warming or cooling intervals. As Richard Schwartzlose (Scripps Institution of Oceanography, pers. comm.) suggested at the Scientific Committee on Ocean Research Working Group 98, it is the change itself that makes the difference: sardine populations begin growing explosively while it is cool, and start collapsing when the environment is still warm. In figure 15, the growing trend of the sardine population between A.D. 200 and 500, and the lapse from 900 to 1100 follows the warming trend, while declines occur during the cooling periods. Parrish et al. (2000) sug-

gested that the principal source of the biological bonanza in the CCS during the late 1970s lies in processes associated with the shift from one climate state to the other, not in the new state itself.

Changes in both population abundance and environmental temperature must result from some underlying process variations; we suggest that oceanic current patterns might be associated with such changes, as earlier proposed by several authors (Wooster and Hollowed 1995; Bakun 1996; Lluch-Cota et al. 1997), such as intensification/relaxation of the ocean gyres (Bakun 1996), diversion of flow (Trenberth 1990; Latif and Barnett 1994), etc.

The scales of variation discussed above, in spite of their very different precision, show some common features; warming and cooling periods seem to be the norm. Instead of prolonged cool or warm intervals, change seems to be continuous at every scale shown here, from millennia to years. Although we have often referred to sustained conditions as those that extend between crossings of the average, no single level is supported for a long time, whatever the scale. However, cooling or warming trends extend for decades and more. The CCS seems to be a huge subarctic/subtropical mixing area, permanently under the changing predominance of one environment or the other.

There is coherence between the analyzed scales and formerly described processes, particularly when dealing with biological indices. Even though the most detailed and potentially useful ones span only a few decades, those that may be related between time scales and to other series (such as sardine abundance and temperature proxies) show coherence in time and between parameters.

Temperature at the CCS is closely related to U.S. and global air temperature and other indices at the century-long scale; thus it seems reasonable to use global and Northern Hemisphere temperature proxies. At all analyzed time scales, sardine abundance and temperature maintain a direct but not causal relationship, which is consistent with previous results.

On the other hand, sardine abundance also appears to vary simultaneously with other biological and physical parameters, as becomes apparent in the short but detailed series. Thus it is not unlikely that sardine abundance variations in the long term are related to, at least, similar changes in the same parameters, suggesting that change is not exclusive to small pelagic fishes, but likely affects the whole ecosystem.

Regimes were first detected through their biological consequences (Hubbs 1948), as were their basic theoretical concepts (Isaacs 1976), global nature (Kawasaki 1983; Lluch-Belda et al. 1989), and persistence (Soutar and Isaacs 1969; Baumgartner et al. 1992). The most detailed report of a regime shift incorporated a consid-

erable number of biological indices (Kerr 1992). What has been difficult is finding the original sources of variation and the physical mechanisms through which they operate to produce biological change.

Looking at physical variability itself, Zhang et al. (1997) pointed out the inadequacy of characterizing periods solely on the basis of interdecadal regime shifts that become apparent only with the benefits of hindsight. They further stated that changes during the 1957–58 period were no less dramatic than those around 1976–77, the only difference being that the resulting warming persisted for only a few years.

Certainly, the AST series shows a more intense event during the late 1950s and early 1960s than during the early 1940s. The cooling phase of both looks similar and lasted about the same time. The 1957–60 event is considered a warm period by authors looking at physical parameters (Ware 1995; Wooster and Hollowed 1995).

In spite of all these similarities, authors working with the regime scale of change and basically using biological indices identify ~1940 as a regime shift, but not ~1957 (fig. 1). The latter change did not result in a sustained increase in sardine population, even though spawning intensified in the Southern California Bight during this lapse (Lluch-Belda et al. 1991).

The origin of regime variation is still obscure. Solar radiation, operating through phytoplankton production (Kawasaki 1983); changes in the spawning habitat due to temperature variations (Lluch-Belda et al. 1991) or current shifts (Kondo 1980; Watanabe et al. 1996; Wada and Jacobson 1998; Nakata et al. 2000); wind regimes and offshore advection (Parrish et al. 2000); upwelling and primary production (Kifani 1998; Yasuda et al. 1999); and intensification of ocean gyres (Bakun 1996; Lluch-Cota et al. 1997), among other changes, have all been proposed as the forcing mechanism. While most authors agree that sardines undergo large fluctuations on the decadal scale related to global climate, the question remains as to how individual stocks respond to common physical forcing in remote marine ecosystems (Matsuura 1999; Schwartzlose et al. 1999).

Ware (1995) discussed some global cycles related to thermohaline circulation and to solar cycle length, and concluded that there is no consensus about the origin of the VLF signal.

If regimes are global, their origin has to be either a very strong and persistent internal change to affect most oceans, or external. If external, then solar variations or planetary motion or both seem to be the obvious sources to look at. Even if a likely original source is found, there has to be a reasonable physical link between it and the biological indices described before it can be convincing. At this point, it appears to us that large-scale ocean current changes and associated atmospheric modifications

could be that link (Wooster and Hollowed 1995; Bakun 1996; Lluch-Cota et al. 1997; Parrish et al. 2000).

Regarding the possibility of forecasting, many uncertainties remain. Relatively short-term prediction (as derived from the long-term scales dealt with here) has been proposed by some authors. Lluch-Belda et al. (1992) suggested that a new shift occurred during the 1980s, when sardine abundance decreased in Japan and in the Humboldt Current and increased in the Benguela Current. Ware (1995) predicted that the transition to the next cool climate state could occur around 2001, but it should be noted that he was basically referring to decadal-bidecadal fluctuations and not to a long-term regime shift. MacCall (1996) cautiously speculated about the possibility that a transition to a cooler regime is likely in the next decade or so, based on biological indicators. Lluch-Cota et al. (1997), on the basis of their regime indicator series (RIS), suggested that a new global cooling trend could begin during the 1990s. Hare and Mantua (2000) found evidence for a regime shift about 1989.

Monitoring some biological indices still seems to be the most promising clue to regime shifts, looking for early warnings such as trend reversals in abundance, synchrony, species substitution, etc. Biological indices seem to more entirely integrate the full array of environmental changes associated with regime shifts than do physical parameters taken one or a few at a time. Even hindcasts seem uncertain when relatively few variables are taken into account (Zhang et al. 2000); however, some indices such as the PDO (Mantua et al. 1997) are proving very appropriate for nowcasting. Hare and Mantua (2000) suggested that closely monitoring ecosystem variations could make it possible to identify regime changes sooner than monitoring climate alone.

Although the potential value of being able to predict regime shifts is beyond question, it should be noted that long-term forecasting is still unreliable; regime cycles have been variable in the past and are likely to be so in the future. Global indices such as the ERVI (Klyashtorin 1998) are still based on previous behavior during relatively short periods and thus uncertain. Forecasting regime shifts and periods on a long-term basis still requires much work. Minobe (2000) states that the usefulness of an empirical forecast is significantly limited by the small number of events observed, and that nowcasts of regime shifts should be based on an understanding of their physical mechanisms. Hare and Mantua (2000) show that, even with retrospective analysis of ecosystem data, contemporary detection of regime changes is not yet possible.

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the Living Marine Resources Panel of the Global Ocean Observing System. This is also a much delayed aftermath of Scientific Committee on Ocean Research Working Group 98, which dealt with large fluctuations in sardine and anchovy populations; Alec MacCall has led the way in publishing derivatives of its results. Paul Smith provided many of the data used, and the orientation. Raymond S. Bradley kindly oriented us to paleoecological data. This paper had support from the Instituto Politécnico Nacional DEPI 988004 project and the Centro de Investigaciones Biológicas del Noroeste, S.C. (CIBNOR). DBLC is doctoral student at CIBNOR on scholarship (CONACYT 95344).

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