SCALES OF INTERANNUAL VARIABILITY IN THE CALIFORNIA CURRENT SYSTEM: ASSOCIATED PHYSICAL MECHANISMS AND LIKELY ECOLOGICAL IMPACTS

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ABSTRACT

We examined interannual change in several physical environmental indexes to isolate the main scales of variation previously reported—the high (~5–7 years), decadal-bidecadal (~20–30 years), and very low frequency (~50–75 years)—in the California Current system. We employed smoothing filters for the purpose of isolating the scales, using their spectral frequencies to analyze their adequacy. In the case of the decadal-bidecadal scale, we tested the coherence between the series against that of random number series. Later, we extracted the first principal component from all series at each scale of variation and compared this to published information, to the physical mechanisms, and to their effects on biological indexes associated with each. We suggest that all the examined frequencies of interannual variation are related to two opposing states of the system, one state associated with relaxed flow of the California Current; intensification of the Aleutian Low, the Alaska Current, and the California countercurrent; increased coastal sea-surface temperature and sea level; frequent mesoscale eddies formation and persistence; and northward advection of southern fauna; the other state associated with the contrary.

INTRODUCTION

Scales of interannual change in the California Current system (CCS) have been the subject of a considerable number of studies in recent years (e.g., Roemmich and McGowan 1995; Brodeur et al. 1996; McGowan et al. 1996). As part of a retrospective experiment of the Living Marine Resources Panel of the Global Ocean Observing System (GOOS) we have been integrating a number of studies dealing with the scales of interannual change and the possibilities of forecasting them, one of which has already been published (Lluch-Belda et al. 2001).

Interannual variability has been reported on a considerable array of frequencies, some of them often mixed; however, Ware (1995) analyzed the interannual variability in the eastern North Pacific Ocean and found four dominant scales: the quasi-biennial oscillation (2–3 years), the El Niño-Southern Oscillation (ENSO) scale (5–7 years), the bidecadal oscillation (20–25 years), and a very low frequency scale (50–75 years). We will be dealing with the last three.

Perception of interannual change in the northeast Pacific has been dominated by ENSO. This recurrent, often intense phenomenon has very obvious physical and biological consequences every few years, so most analysts have been able to follow several of them. Its mechanism is for the most part well understood, and short- to mid-term forecasts are in the process of being developed. Detailed descriptions of recent events include those by Lynn and Bograd (2002) and Schwing et al. (2002b), and Miller et al. (2000) have presented modeling advances.

At the other extreme of the shorter-than-centennial time scale, very low frequency or regime variation has become evident through the quasi-cyclic fluctuations in the abundance of some species, particularly the small pelagic fishes. Their explosive population growth and even more rapid collapse, together with the very high biomass that their populations can attain, result in major changes in their availability to fisheries and are therefore very noticeable. Their characteristic of leaving scales in the laminated sediments allows us to know that such enormous variations are not an exclusive consequence of harvesting but rather are naturally induced fluctuations. Finally, the synchronic behavior of their population abundance in widely separated ocean areas strongly suggests that global environmental variations may be in the root of such changes. Benson and Trites (2002) reviewed many of the published studies on the subject; Chavez et al. (2003) updated and amplified the information on regime changes.

Between those two scales of variation, a number of researchers have reported decadal to bidecadal periods of variation in the eastern North Pacific Ocean (Wooster

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and Hollowed 1995; Ware 1995). Schwing et al. (2002a) found alternating decadal-scale periods on a roughly 14-year cycle. Minobe (2000) pointed out that the pentadecadal (very low frequency) and bidecadal signals arise from different physical mechanisms and likely have different origins. In essence, alternating multi-year warm/cool periods have been identified in temperature (both sea and air, instrumental and reconstructed), location, and intensity of atmospheric pressure cells (particularly the Aleutian Low) and associated wind fields, sea level, upwelling intensity, mixed layer depth, and some biological indexes mostly associated with recruitment level in some populations. Schwing et al. (2002a) updated the description of the cool/warm periods described by Wooster and Hollowed (1995) after the early 1980s.

A number of physical variables have been associated with each of these scales, often with reference to an environmental index. These include, among others, the intensity and east-west position of the Aleutian Low (Emery and Hamilton 1985; Miller and Schneider 2000), intensification/relaxation of the Alaska and California Currents (Wooster and Hollowed 1995; Brodeur et al. 1996), tropic to extratropic teleconnections (Schwing et al. 2002a), winds (Parrish et al. 2000), sea-level height and mixed-layer depth anomalies (Bernal 1979; 1981; Bernal and Chelton 1984; Chelton et al. 1982; Polovina et al. 1995; Parrish et al. 2000), intensified northward advection of the California countercurrent (McLain and Thomas 1983), mesoscale eddies formation and persistence (Longhurst 1966; MacCall 2002), and upwelling intensity (Wooster and Hollowed 1995; Polovina et al. 1995; Schwing and Mendelssohn 1997; Bograd et al. 2001). Some of them may reveal mechanisms of change, based on their correspondence with other variables.

Detected ecological effects of interannual variability include changes in primary and secondary productivity (Polovina et al. 1995; Rebstock 2002), distribution of fauna (Hubbs and Schultz 1929; Hubbs 1948; Radovich 1961; Schoener and Fluharty 1985; Smith 1985; Karinen et al. 1985; Ainley et al. 1995; Dorn 1995; Hamman et al. 1995; Lenarz et al. 1995; Smith 1995; etc.), and recruitment in several fish stocks (Lluch-Belda et al. 1989; Hollowed and Wooster 1992; Bakun 1996; Mantua et al. 1997; Klyashtorin 1998; Norton 1999; Hare and Mantua 2000; Botsford 2001; Botsford and Lawrence 2002; Chavez et al. 2003).

In this study we use several century-long physical/environmental series, attempt to isolate and characterize the reported scales of variation, and seek to relate the variations to reported ecological fluctuations.

DATA AND METHODOLOGY

Monthly average sea-surface temperature (SST) series were extracted from the Comprehensive Ocean-Atmosphere Data Set (COADS) (Mendelssohn and Roy 1996) for 76 quadrants (2° × 2°) (fig. 1), in an effort to cover most of the CCS. The climatology for each quadrant was estimated as the average SST for each month for all the existing data between 1900 and 1990. Monthly anomalies were computed (monthly value minus monthly climatology) and then averaged for the year. Finally, a global index reflecting the SST anomalies of the CCS (hereinafter referred to as CST) was obtained by annually averaging the individual yearly anomalies at all 76 quadrants. The representativeness of these data was analyzed in a previous paper (Lluch-Belda et al. 2001), including averaging procedures, amount, and completeness of the original data and their similarity to other large-scale indexes, particularly given the reservations that have been expressed regarding their validity prior to the 1950s (for instance, MacCall 1996). Similarly, an index of the yearly coastal SST anomalies (COT) was derived from data at coastal stations obtained from the PACLIM database (Cayan et al. 1991), including those at Point Hueneme, Crescent City, Pacific Grove, Los Angeles, San Francisco, and San Diego.

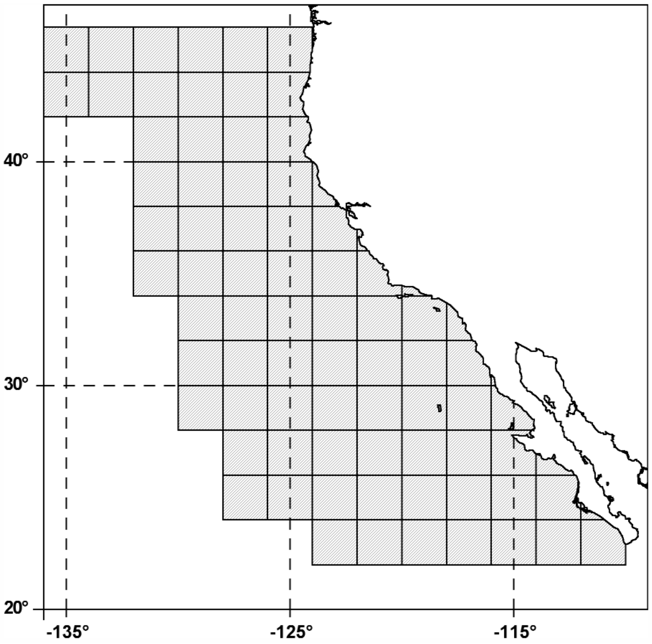

Figure 1. The COADS quadrants used to obtain the annually averaged sea-surface temperature anomalies for the California Current system.

The same procedure was applied to build an index of sea-level height yearly anomalies (SLH), using monthly values obtained from the University of Hawaii Sea Level Center (Kilonski 1998) for San Francisco and San Diego, California. The series were detrended and yearly averaged, further standardized (standard score = [raw score − mean] / standard deviation) and averaged between the two.

TABLE 1
Sources of Data Series Considered in the Analyses

Series	Brief description	Source
Aleutian Low Pressure index (ALP)	Relative intensity of the Aleutian Low pressure system of the North Pacific	Beamish et al.(1997)
Pacific Decadal Oscillation index (PDO)	Leading principal component of monthly SST anomalies in the North Pacific Ocean, poleward of 20°N	Mantua et al.(1997)
Atmospheric Forcing index (AFI)	First principal component from an analysis of the ALP, PDO, and the northwesterly atmospheric circulation anomalies for the North Pacific	McFarlane et al.(2000)
OSCURS index (OSC)	Annually averaged latitudes at each trajectory end point	AFSC-NMFS Web site, http://www.afsc.noaa.gov

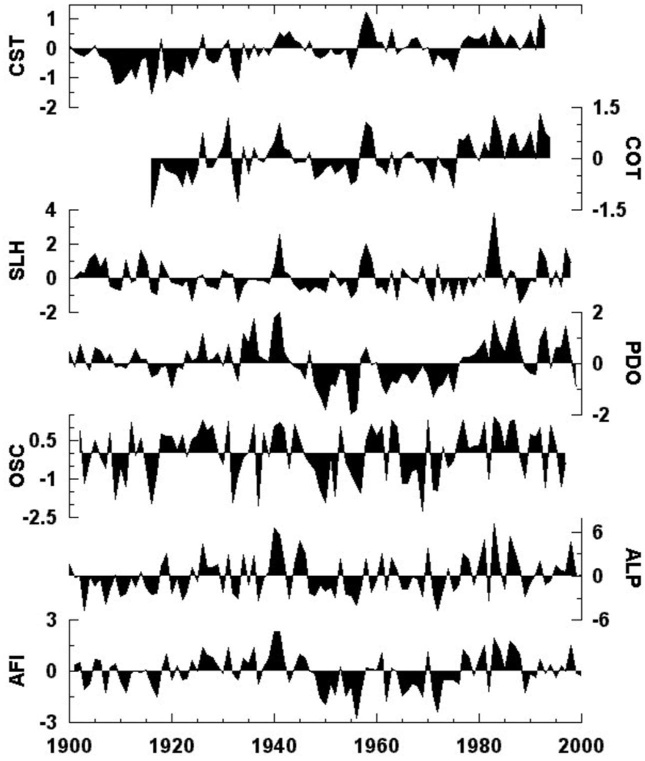

Figure 2. The raw data series. Global index of the California Current system SST anomalies (CST), index of yearly coastal SST anomalies (COT), index of yearly sea-level height anomalies (SLH), Pacific Decadal Oscillation index (PDO), OSCURS index (OSC), Aleutian Low Pressure index (ALP), and Atmospheric Forcing index (AFI).

We used the Aleutian Low Pressure index (ALP), the Pacific Decadal Oscillation index (PDO), the Atmospheric Forcing index (AFI) and the Ocean Surface Current Simulations (OSCURS) index (hereinafter OSC) as large-scale indexes of the environmental condition of the northeastern Pacific Ocean. (For information on the indexes used, see tab. 1.)

All series (shown in fig. 2) were standardized (standard score = [raw score − mean] / standard deviation) prior to computing their correlation coefficients. Each series was then filtered by means of Hamming windows of 10 and 30 years. This is a weighted moving average transformation computed as

$$w_j = 0.54 + 0.46 * \text{cosine}(\pi * j/p) \text{ (for } j = 0 \text{ to } p)$$

$$w_{-j} = w_j \text{ (for } j \neq 0)$$

$$\text{where } p = (m - 1)/2$$

This weight function will assign the greatest weight to the observation being smoothed in the center of the window and increasingly smaller weights to values that are further away from the center, standardizing the weights so that they sum to 1 (Blackman and Tukey 1958).

The two filtered series that resulted from each (untransformed) series were used to decompose its variability into three main time-scales as follows:

1. The difference between the raw series minus the 10-year Hamming filtered series, assumed to represent the high-frequency (<10 years) component; referred to as the HF series.
2. The difference between the 10-year Hamming filtered series minus the 30-year Hamming filtered series, as containing the decadal-bidecadal (10–30 years) component; referred to as the DB series.
3. The 30-year Hamming filtered series, representing the very low frequency (>30 years) component; referred to as the LF series.

Summarizing, the procedure resulted in three series (HF, DB, and LF) for each of the series shown in Figure 2.

While the HF and LF series result from a single filtering procedure, the same does not occur with the DB series, which results from a double-filtering process. Since filtering itself may induce a certain pattern, ten series of random numbers were processed by the same procedure, and simple linear correlation was performed between the resulting series. The DB series were also correlated among them for comparison. This process was only used for testing the effect of double-filtering at artificially increasing the correlation coefficient, thus the random number series were not utilized further. Later, spectrum analysis (Fourier transform), with 15% tapering and padding the series to a power of 2, was performed for each unfiltered series and the corresponding HF, DB, and LF series. Finally, we obtained the first

TABLE 2
Correlation Coefficients between Raw Data Series (*Below* and *Left*) and *N* Pairs of Values (*Above* and *Right*)

	CST	COT	SLH	PDO	OSC	AFI	ALP
CST		78	93	94	92	93	94
COT	**0.84**		79	79	79	79	79
SLH	**0.58**	**0.67**		98	96	98	98
PDO	**0.47**	**0.66**	**0.52**		96	99	100
OSC	**0.35**	**0.42**	0.18	**0.48**		96	96
AFI	**0.31**	**0.48**	**0.25**	**0.73**	**0.78**		100
ALP	**0.40**	**0.50**	**0.31**	**0.60**	**0.72**	**0.86**	

Note: Boldfacing indicates $p < 0.05$.

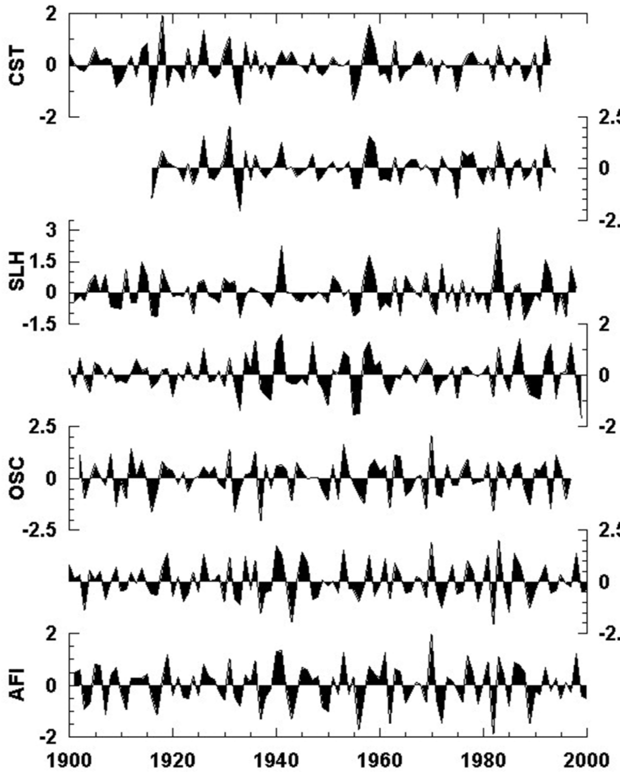

Figure 3. The high-frequency filtered series (residuals of raw data minus 10-year Hamming filter).

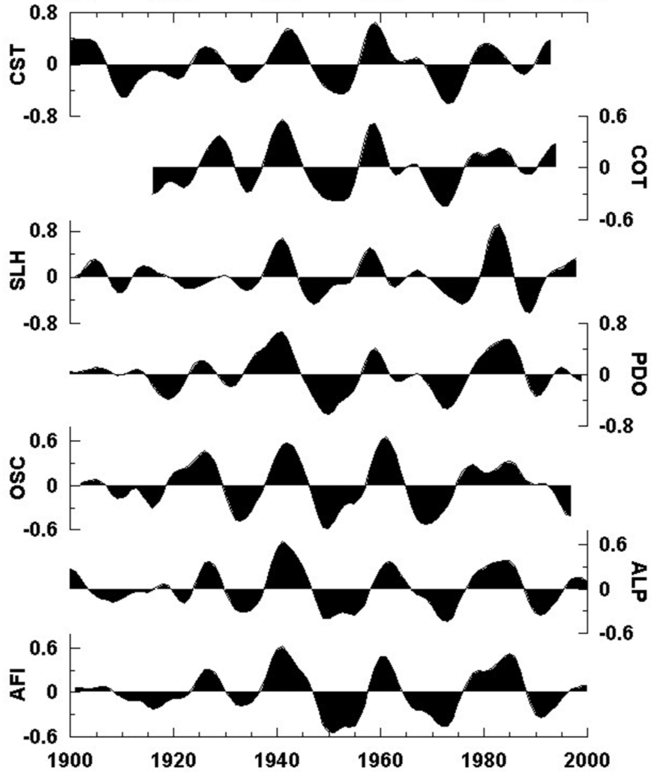

Figure 4. Decadal-bidecadal series (residuals of 10-year Hamming filter minus 30-year Hamming filtered series).

principal component (PC) of the HF, DB, and LF series (i.e., one analysis per time scale) substituting the lacking data by means, to obtain a series representing the main variation pattern for each temporal scale. We compared these principal components with those in published sources. We searched for published reports of latitudinal displacement of fauna, trying to discriminate between large-scale movements and single-species extensions of range.

RESULTS

The correlation coefficients between the raw data series are shown in Table 2. Except for the OSC-SLH case, all are significant at the 5% level.

The HF series that resulted from the filtering of the seven environmental indexes are shown in Figure 3. In spite of the noisy variation, with the lower frequencies removed El Niño events become more evident (e.g., 1940, late 1950s, 1982).

Regarding the DB series (fig. 4), the results show strikingly coherent signals in all of the series, with clear peaks during the late 1920s, early 1940s, late 1950s, and early 1980s. The analysis of random number series indicates that DB filtering will not produce the correlated cycles observed in this figure. This is due to the fact that, although the bidecadal filtering procedure does generate oscillating patterns of about 20 terms in the random number series, the shape of the double filtered series is

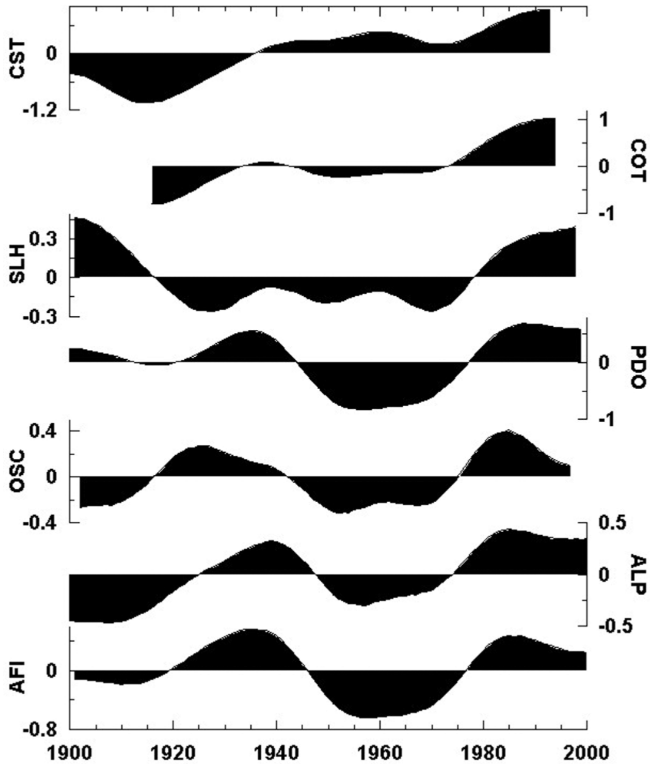

Figure 5. Low-frequency filtered series (Hamming filter of 30 terms).

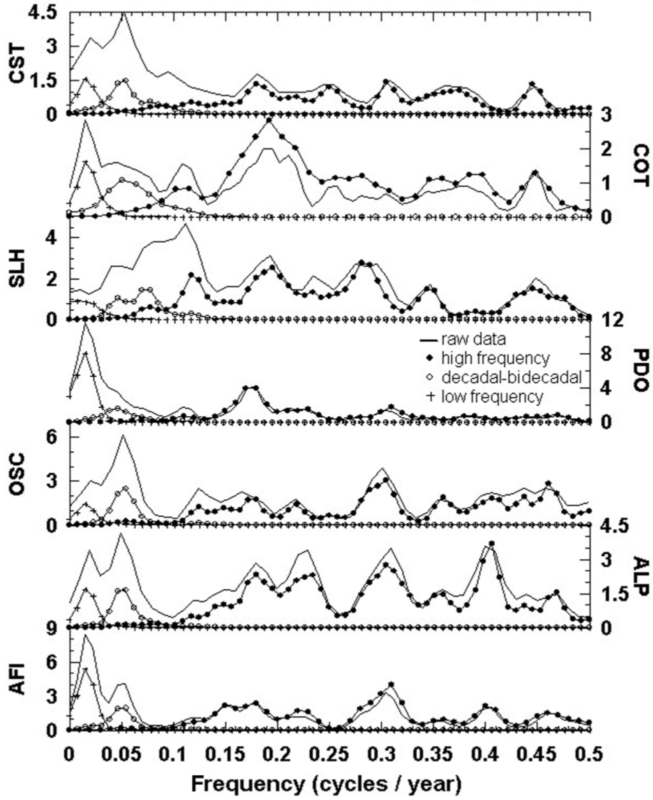

Figure 6. Spectral densities of CST, COT, SLH, PDO, OSC, ALP, and AFI (see fig. 2 for definitions).

different in each case—that is, peaks and troughs occur randomly in time.

As for the LF component (fig. 5), the series of basin scale indexes (ALP, AFI, PDO, and OSC) are quite similar, whereas the others (CST, COT, and SLH, all of them CC-scale indexes) show some differences. This may well indicate, as one of the anonymous reviewers noted, that the basin has a much stronger LF signal than the CC region does. Peaks are more or less evident right before 1940 and after 1980.

Spectral densities for the unfiltered, HF, DB, and LF series are shown in Figure 6. For each case, the solid line shows the spectral density of the unfiltered series; the spectral densities of the HF, DB, and LF series are also shown. In general, the filter works adequately, isolating each spectral window such that the shape of the HF, DB, and LF spectra is always very similar to the spectra of the unfiltered series at the corresponding frequency region.

The HF spectra are noisy, but three main peaks are evident in most of them, one at 0.45 (about a 2-year period), and two ENSO-related (0.3, about 3, and 0.19, about 5-year periods). These frequencies correspond to the tropospheric quasi-biennial (about 18–35 months) and lower frequencies (about 32–88 months) shown by the spectra of most ENSO-related variables (Barnett et al. 1995). The DB and LF spectra each show a characteristic peak (DB 0.05, about 20 years; LF 0.02, about 50 years) in all but the SLH.

The extraction of the first principal component seems to result in reasonable representation of the main variation patterns in each group of the frequency-isolated series. The extraction-utilizing means to substitute missing values is based on the significant correlation coefficients between the raw series (tab. 2) and the convenience of having full-century series for comparison.

The first principal component series for each scale of variation (HF, DB, and LF) are shown in Figure 7. The factor loadings are shown in Table 3. The table also shows that the percentage of variance each PC1 accounts for is greater than 50% for all three scales.

In Figure 7 the high-frequency principal component (HF-PC) is compared to El Niño events as described by Quinn (1992) and to northward displacement of southern fauna reports as shown in Table 4. This is the noisiest frequency, as would be expected. However, the main peaks do correspond to El Niño events and to northward faunal dispersal. In fact, two major events per decade (or two very closely related minor events instead of a major one in some cases) result in a frequency of about 5 years per event, as noticed by Lluch-Cota et al. (2001) for the northeast Pacific north of the mouth of the Gulf of California.

For the DB signal, its PC1 is compared to warm and cool periods described by Wooster and Hollowed (1995)

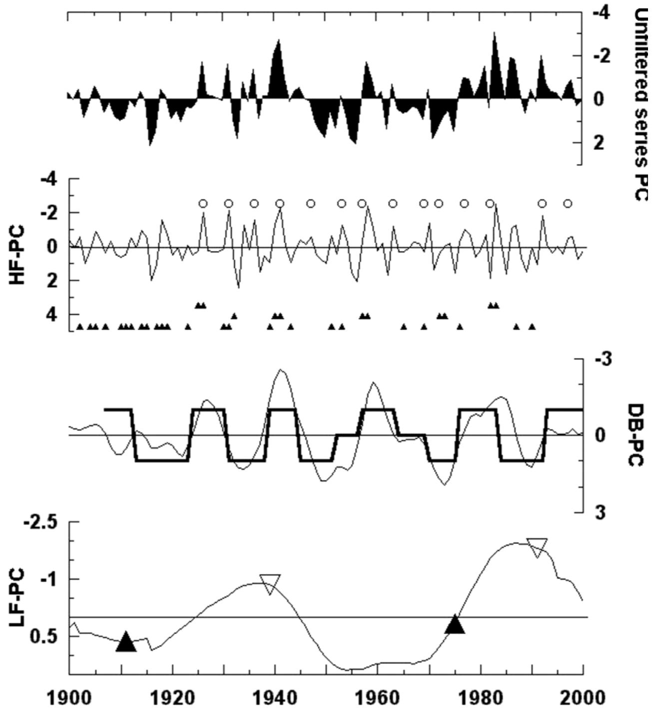

Figure 7. The first principal component (PC1) of the series at each analyzed scale, compared to other indexes. High-frequency (HF-PC): ▲ represents El Niño events (after Quinn 1992), with relative vertical position indicating event strength; ○, northward dispersal of fauna (tab. 4). Decadal-bidecadal (DB-PC): thick line represents cool and warm periods, after Wooster and Hollowed (1995) and Schwing et al. (2002). Low-frequency (LF-PC): ▲ represents cool-to-warm regime shifts; and ▼, warm-to-cool regime shifts.

and updated based on Schwing et al. (2002a). The DB series result in the largest explained variation by the extraction of the first principal component, as would be expected from their remarkable coherence.

Finally, the LF signal is compared to described regime shifts; the main trends are coherent with the cooling and warming periods as described by Lluch-Belda et al. (2001).

DISCUSSION

Coherency between the original series is obscured by the noisy variation, decadal changes, and short-term events, even though some particularly strong signals (as the strongest ENSO events and the mid-1970s regime shift) are suggested in most (fig. 2). Filtering proved useful for substantiating the specific variation at the three scales considered, particularly the DB and LF (figs. 3–5). The coherency is further shown by spectral analysis at all scales, with particularly coherent peaks for DB and LF in most series but SLH (fig. 6).

PC1 extraction from the series proved appropriate for the purpose of obtaining one single series for each scale containing most of the common variability. Each of the principal components agrees with the main features of previously published information: ENSO events, northward faunal movements, cool/warm periods, and regime shifts (fig. 7).

TABLE 3
Factor Loadings of the First Principal Component Extracted for the Series

	Raw data	High frequency	Decadal-bidecadal	Low frequency
CST	−0.68	**−0.78**	**−0.84**	−0.34
COT	**−0.81**	**−0.81**	**−0.88**	**−0.73**
SLH	−0.57	−0.60	−0.67	−0.45
PDO	**−0.80**	**−0.78**	**−0.88**	**−0.90**
OSC	**−0.72**	−0.68	**−0.81**	**−0.85**
AFI	**−0.83**	**−0.75**	**−0.93**	**−0.90**
ALP	**−0.81**	**−0.77**	**−0.90**	**−0.86**
Variance	3.94	3.85	5.01	3.94
Explained variance, %	56	55	72	56

Note: Boldfacing indicates $p > 0.7$.

TABLE 4
Short Period Reports of Southern Fauna Intruding Northward

Year	Fauna	Author(s)
1859	Pelagic red crab stranding in Monterey Bay, California	Hubbs and Schultz (1929)
1880	Considerable number of southern species	Jordan and Gilbert (1881)
1926	*Vellela* and several fish species	Hubbs (1948)
1931	Southern fish strays off California	Hubbs (1948)
1936	Intrusion of southern forms in British Columbia	Hubbs (1948)
1941	Pelagic red crabs off California	Hubbs (1948)
1947	Southern species of fish in Oregon, Washington, and British Columbia	Hubbs (1948)
1953	Northward shift of sardine population center	Radovich (1959)
1957	Intrusion of many southern species	Radovich (1961)
	Doliolum denticulatum off California	McLain and Thomas (1983)
1958	Pelagic red crabs off California	Longhurst (1966)
1959	Pelagic red crabs in Monterey	Longhurst (1966)
1963	Salps of likely southern origin off Oregon	Hubbard and Pearcy (1971)
1969	Pelagic red crabs in Monterey Bay	Hardwick and Spratt (1979)
	Several species of invertebrates	McLain and Thomas (1983)
1972	Pelagic red crab off California	Alvariño (1976)
	Pelagic red crab	Hardwick and Spratt (1979)
1977	Southern fauna	Karinen et al. (1985)
	Subtropical zooplankton	McLain and Thomas (1983)
1978	Salps off British Columbia and southeastern Alaska	McLain and Thomas (1983)
	Pelagic red crab off Ensenada, Baja California	McLain and Thomas (1983)
1982	Pelagic red crab off California	P. Smith, pers. comm.
1983	Southern fauna off Washington	Schoener and Fluharty (1985)
	Southern fauna off Canada	Mysak (1986)
1992	Southern fauna off Canada	Hargreaves et al. (1994)
1997	Pelagic red crab off California	P. Smith, pers. comm.
2002	Pelagic red crab off California	R. Schwartzlose, pers. comm.

The principal component extraction also provides insight on the relation between local and basin-wide index series at each time scale: in all cases relationships are direct and mostly strong as indicated by the factor scores showing the same sign and relatively high absolute values (tab. 3). This indicates that local conditions of the California Current are fluctuating in agreement with the basin-scale indexes and, thus, are likely affected by the same mechanisms that have been related to each of the basin-scale indexes at all analyzed time scales. Therefore, we suggest that the variability at all analyzed scales may conform to two alternative states of the system.

From the local analyzed series (CST, COT, and SLH) the first state would correspond to periods during which the CCS warms up and coastal SST and sea level height tend to be anomalously high. The direct relationship of these local indexes to OSC indicates that these periods would correspond to intensified flow of the Alaska Current and a relaxation of the California Current (Ingraham et al. 1998). Such changes are likely driven by an anomalously strong Aleutian Low, as revealed by their relationship to ALP (Beamish et al. 1997). Further, directly variating values of AFI represent above-average frequency of westerly and southwesterly winds (McFarlane et al. 2000). Finally, cooling of SSTs in the central North Pacific is suggested by the covariance of the CCS indexes with PDO (Mantua and Hare 2002).

The alternative state would be essentially the reverse: cooling of the California Current and anomalously low coastal SST and sea-level height corresponding to an intensified California Current, a relaxed Alaska Current, and a weakened Aleutian Low. Westerly and southwesterly winds would be relatively infrequent, and possibly a warming of SSTs in the central North Pacific would take place during those periods.

These and other related changes have been well-described by many others, though usually in reference to a particular time scale. At the higher frequency, usually associated with ENSO events, various authors have described the relaxation of the California Current (Alvariño 1976; Bernal 1979, 1981; Chelton et al. 1982), intensified northward advection of the California countercurrent (McLain and Thomas 1983), and the Alaska Current (Emery and Hamilton 1985; Brodeur et al. 1996) and mesoscale eddies formation (Longhurst 1966). La Niña corresponds to the second state at this time scale.

At the decadal scale, Hollowed and Wooster (1992) described two environmental states related to weak/strong circulation of the Alaska Gyre and to cool/warm coastal SST, while later Wooster and Hollowed (1995) estimated the average duration of such eras as about 17 years. The Alaska Gyre was shown to be related to the relative position and intensity of the Aleutian Low by Emery and Hamilton (1985), who found that an intensified/weak and eastward/westward-displaced Aleutian Low is associated to strong/weak circulation pattern. During periods of strong circulation, the Alaska Gyre is stronger while the California Current relaxes, concomitant with increased northward flow of the west wind drift bifurcation (Wooster and Hollowed 1995; Brodeur et al. 1996), similar to Chelton and Davis's (1982) description that the Alaska and California Currents fluctuate out of phase. Strong circulation also corresponds to high temperature at 100 m, high coastal sea level, high atmospheric pressure, and low upwelling during January–February; offshore (beyond ~140°W), opposite conditions to those of the coastal area occur (Hollowed and Wooster 1992).

The low-frequency scale has often been regarded as equivalent to the regime variation; it also likely corresponds to the pentadecadal variation described by Minobe (2000). Regarding this scale, Parrish et al. (2000) made a review of previous information together with an analysis of wind data and suggested that surface water entering the California Current was of more subtropical origin after 1976. After this year, the surface of the central North Pacific cooled by 1°C or more, whereas along the North American coast and in the Gulf of Alaska it warmed by a similar amount. Furthermore, there was ~20 m shoaling of the mixed layer depth in the subarctic gyre after 1976 and deepening by a similar amount in the subtropical gyre. Dynamic heights and SST increased at the Gulf of Alaska after 1976, and transport into it increased while weaker transport occurred in the California Current.

Brodeur et al. (1996) and more recently Ingraham et al. (1998) report on a surface-drift simulation model (OSCURS, included in this study) that showed that winter trajectories begun at Ocean Station P drifted more toward the California Current before 1976 and more into the Alaska Current after 1976. Polovina et al. (1995) found that from 1976 to 1988 there was a period of intensified Aleutian Low, with deepening of the mixed layer at the eastern subtropical Pacific and shoaling at the Gulf of Alaska, as compared to the 1960–1976 period.

In summary, among the analyzed time scales many of the physical signals of variability seem qualitatively similar, thus suggesting similar large-scale changes in ocean current patterns and associated atmospheric states. If so, it would be difficult to discriminate among short- and long-term variability (e.g., a strong El Niño and the onset of a regime shift) solely from the examination of physical information. However, biological indexes may reflect changes at each scale in a different manner.

For example, the warming phase of short-term events (essentially those connected to ENSOs) are often associated with reports of some tropical species at locations poleward of their usual distribution limit. This is the case with the northward advection of pelagic red crabs (*Pleuroncodes planipes*), usually restricted to the Sebastián Vizcaíno Bay and south of it. Longhurst (1966) discussed the likely mechanisms responsible for their northward advection during the 1957–59 El Niño, including the intensification of the California countercurrent and the Davidson Current, the development of semi-permanent eddies, and the offshore displacement of the main current. Other passive fauna advected northward during these events include *Vellela* and *Doliolum lenticulatum*. Northward advection of passive fauna mostly results in a part of the population lost to nonsuitable areas where reproduction does not occur.

However, not only passively transported fauna move northward during warming events. Many pelagic, nectonic, and benthic strong-swimming fishes, particularly tunas, would hardly be passively transported. If they move north, it must be because the general conditions of the otherwise unsuitable area are appropriate at the time. Johnson (1962) related sea temperatures and albacore availability off Oregon and Washington, and Clark et al. (1975) showed interannual variations in the percentage of albacore tuna fished north or south of San Francisco related to climatic fluctuations. As one of the anonymous reviewers noticed, ENSO events are quite different among them (Schwing et al. 2002b), thus some species such as albacore may become more vulnerable when they access the California Current from the west as warm water expands to the east (Pearcy 2002). In any event, biological responses of other local populations, such as increased recruitment of the southeastern Alaska herring (Mysak 1986) or survival index of Pacific mackerel (Sinclair et al. 1985), do point toward large-scale conditioning of the area during ENSO years.

Biological effects of decadal-scale warm periods in the northeast Pacific include an increase of primary and secondary productivity (Polovina et al. 1995), together with strong recruitment in several groundfish stocks (Hollowed and Wooster 1992). Salmon stocks in Alaska show enhanced productivity, contrary to those in the U.S. Pacific Northwest (Mantua et al. 1997). Parker et al. (1995) discussed climate's forcing biological changes in Pacific halibut recruitment and affecting the productivity of a number of salmon species. Wooster and Hollowed (1995) suggest that changes in the intensity and direction of flow are required to account for the large time and space scales of the variations observed.

The regime variation has been linked to sardine and anchovy population abundance in several areas of the world's oceans (Lluch-Belda et al. 1989; Schwartzlose et al. 1999). In the Pacific, there have been reports of a number of other species' being affected, including albacore and several groundfishes, such as pollock (Bakun 1996), salmon, and jack mackerel (Klyashtorin 2001). In general terms, the warming regimes (~1910–40 and ~1975–90) have coincided with growth of the sardine, jack mackerel, salmon, and Alaska pollock populations; whereas increased abundance of herring and anchovies has occurred during the cooling regime (~1940–75). These changes in the abundance of fisheries populations seem to be synchronic, but not a consequence, of temperature; rather, they seem to be caused by large-scale modifications of ocean currents and associated atmospheric states (Lluch-Belda et al. 2001).

Finally, a relevant question brought up by one of the reviewers is the characterization of climate variability. Two extreme shapes would consist of a saw-tooth warming/cooling pattern, on the one hand, and a boxcar pattern of warm and cool periods with rapid transitions, on the other. At least at the low-frequency scale of variation, the pattern appears to be the former. For example, consider that the growth of sardine populations begins while the area is still cool (at the end of the cooling trend), and the onset of collapse occurs while it is warm, at the peak of the warming period; it is the change itself that makes the difference (Lluch-Belda et al. 2001). This would seem to be the case as well with the decadal-bidecadal variation (fig. 7); high-frequency ENSO events are too short to permit characterizing the type of change occurring and they might be different, particularly since they are not equal among themselves. A boxcar shape should be expected, however, when measuring certain variables. For instance, if we measured the direction of change around a long-term average, then we would have a negative period along a cooling trend, a rapid reversal, and a positive interval afterward during a warming trend. The change would occur during the regime shift, when the direction of change is reversed.

CONCLUSIONS

Climate variability in the CCS shows qualitatively similar physical signals at the three analyzed time scales: increased sea level and coastal temperatures, relaxation of the California Current, and intensification of the Alaska Current occur during warm episodes, while the contrary takes place during cool ones.

These alternative states appear to be consequences of similar large-scale changes in ocean current patterns and associated atmospheric states, thus making it difficult to discriminate between short- and long-term physical variability. Some biological indexes, however, respond differently to each scale of variability and thus may be useful for discriminating among their signals. Interannual variation in the CCS is better described as alternating periods of continuous change at the time scales considered, rather than as sustained warm and cold periods.

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