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ANOMALOUS WARM EVENTS IN EASTERN BOUNDARY CURRENT SYSTEMS

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ABSTRACT

Monthly means of sea-surface temperature are computed for 3° blocks of latitude and longitude along the eastern coasts of the Pacific and Atlantic oceans from March 1971 to June 1984. Long-term mean, between-year standard deviation, and monthly anomaly values are computed and used to describe major anomalous warm events in the California, Peru, Canary, and Benguela eastern boundary current systems. Possible causes of warm events include anomalous local onshore transport, propagation of coastally trapped waves, and anomalous solar radiation.

RESUMEN

Se computan las medias mensuales de temperatura superficial del agua para sectores de 3° de latitud y longitud a lo largo de las costas orientales de los oceanos Pacífico y Atlántico desde marzo de 1971 hasta junio de 1984. Los cálculos de la media de este período, la desviación estándar interanual y las anomalías mensuales se utilizan para describir los principales eventos anómalos de calentamiento en los sistemas de corrientes de margen oriental de California, Perú, Canarias, y Benguela. Las causas posibles de los fenómenos de calentamiento incluyen transporte local anómalo hacia la costa, propagación de ondas retenidas por las costas, y anomalías en la radiación solar.

INTRODUCTION

The four major eastern boundary current systems—California, Peru, Canary, and Benguela—are characterized by equatorward surface flow; persistent coastal upwelling of cold, nutrient-rich waters; high biological productivity; and similar marine populations (Parrish et al. 1983). In certain years, anomalous warming events occur to disrupt the normal upwelling of nutrients and to reduce the surface water's productivity. Severe impacts on local fish populations may occur. In the California Current, warm events have occurred many times in the past, but major recent events have been in 1931-32, 1940-41, 1957-58, 1972-73, 1976-77, and 1982-83. Warm events have been studied intensely in the California Current (e.g., Sette and Isaacs 1960). This paper will describe anomalous events in the California Current and extend the analysis to the other eastern boundary current systems.

During warm events in the California Current, the surface layer warms and deepens and may remain warmer and deeper than normal for a year or more (Table 1). The greatest interannual variability of oceanic conditions off California occurs in winter. Thus, to compare conditions in different years, we computed winter quarterly means (December to February) using the years 1971 to 1984 as a normal. We chose these years because later we will present sea-surface temperature (SST) data for these years. During the winters of 1957-58 and 1982-83, the SST at Scripps Pier was 1.2° to 1.7°C above normal, and positive anomalies persisted into the following winter. Deepening of the surface layer can be represented by the depth of the 14°C isotherm, which is near the top of the thermocline off San Diego (Barilotti et al. 1984). During winter 1957-58, the 14°C isotherm was about 20 m deeper than normal off San Diego, and positive depth anomalies persisted into the following winter. During the 1982-83 winter, the 14°C isotherm was over 40 m deeper than normal and remained deeper than normal the following winter. Deepening of the thermal structure also causes sea level, as

TABLE 1
Winter Quarterly Mean Ocean Conditions During Warm Winters and Comparison with 1971-84

	December-February Quarterly Means				
	Mean winter 1971-84	1957-58	1958-59	1982-83	1983-84
SST at Scripps Pier (°C)	14.5	16.2 (1.7)	15.9 (1.4)	15.7 (1.2)	15.3 (0.8)
Depth of 14°C isotherm off San Diego (m)	48	69 (21)	65 (17)	91 (43)	58 (10)
Sea level at San Diego (cm)	201	204 (3)	203 (2)	215 (14)	202 (1)

Quarterly means were computed as means of monthly mean values for the months December to February. Quarterly anomalies from the mean winter 1971-84 are shown in parentheses. SST data from Scripps Pier, Scripps Institution of Oceanography, La Jolla, California. Depth of 14°C isotherm off San Diego computed from data of Fleet Numerical Oceanography Center (Barilotti et al. 1984). Sea-level data from National Ocean Service, NOAA, Rockville, Maryland.

observed at tide gages, to stand higher. Monthly mean sea level at San Diego was about 6 cm higher than normal in 1957-58 and up to 16 cm higher than normal in 1982-83.

Two biologically significant processes occur during warm events (McLain and Thomas 1983). One is an intensification of the normal seasonal poleward flow of undercurrents over and along the edge of the continental shelf. Current-meter observations in five winters off the central Oregon coast (Table 2) suggest that during winter 1982-83, the speed of poleward flow over the continental shelf (13.0 cm/sec) was almost twice the mean speed observed in the other four winters (7.5 cm/sec). This increased poleward flow advected warm southern water poleward, further increasing coastal temperatures. The strong poleward flows and warm coastal waters allowed warm-water fish species to extend their ranges poleward along the coast or inshore from warmer waters offshore. Occurrences of warm-water species in the California Current during warm years have been described by many authors (e.g., Radovich 1961). Bonito, barracuda, white sea bass, and others have been caught far north of their normal ranges during warm years. Whereas the larger animals may swim northward in the warm waters, many warm-water planktonic organisms also have been observed far north of their normal ranges, suggesting that poleward transport is a contributing factor in range extension.

A second major effect observed during warm events has been decreased biological productivity of the surface waters. The thickened and warmed surface layer reduces the ability of upwelling-favorable winds to cause upwelling of nutrients into lighted surface waters. Chelton et al. (1982) showed that zooplankton volumes observed on CalCOFI surveys during 1957-59 were much lower than on later surveys during the 1960s and 1970s. Although fewer observations of this type have been made in recent years, available data do suggest similar low zooplankton volumes and decreased productivity in the California Current in 1983 (McGowan 1984). Biological observations of poor reproduction of many species of fish and sea birds (Ainley 1983) and the extremely low harvest of kelp off southern California (Barilotti et al. 1984), for example, all suggest a sharp drop in biological productivity following the winter of 1982-83.

TABLE 2
Mean Poleward Speed of California Undercurrent Observed with Current Meters at Midshelf off Central Oregon

Winter	Poleward speed (cm/sec)
1973-74	7.5
1977-78	10.2
1981-82	5.8
1982-83	13.0
1983-84	7.0
Mean of four winters 1973-74, 1977-78, 1981-82, and 1983-84	7.5

Mean speeds are for the 93-day period October 30 to January 30. Current meters were about 25 m off the bottom in water depths of 90 to 120 m. Data from Dr. Robert Smith, Oregon State University, Corvallis, Oregon.

CAUSES OF ANOMALOUS WARM EVENTS

Two major hypotheses have been suggested to explain anomalous warm events in the California Current system: (1) propagating coastal waves in the ocean, and (2) atmospheric circulation changes. The ocean hypothesis suggests that during periods of strong trade winds over the tropical Pacific, warm surface water piles up in the western tropical Pacific, causing a rise in sea level there (Wyrtki 1975). When the trade winds relax or reverse, sea level falls and a pulse of warm surface water flows eastward toward South America, propagating as an equatorially trapped Kelvin wave. El Niño occurs as the warm water intrudes against the South American coast, causing a rise in sea level, and depressing the thermocline along the coast. The depression of the thermocline may be as large as 150 m (at 0°N, 85°W in October 1982, Toole 1984).

Wave theory (Gill 1982) suggests that the depression can propagate in two ways: (1) westward along the equator as equatorially trapped Rossby waves, and (2) poleward along the coast as both coastally trapped waves and coastal Kelvin waves. Since the trapping distance of coastal Kelvin waves is limited to the Rossby radius of deformation, they narrow as they proceed poleward and eventually become coastally trapped waves. Therefore, we will refer to the two types of poleward-propagating waves as coastally trapped waves. As they propagate poleward the coastally trapped waves lose energy by numerous processes, including generation of very slow, westward-propagating planetary Rossby waves. As the depression of the thermocline propagates poleward along the coast, it geostrophically forces an intensification of normal poleward coastal countercurrents. After the depression passes a point on the coast, the countercurrent may reverse to equatorward. The poleward flows commonly occur in winter, and the reversals, called spring transitions, are most intense following warm winters (Breaker 1983).

One shortcoming with the ocean hypothesis is that it does not explain the very wide expanse of anomalously warm water observed off the West Coast in early 1983 and the simultaneous formation of a pool of colder than normal water in the central North Pacific. Published SST anomaly charts for winter 1982-83 (U.S. Dept. Commer. 1983) show that SSTs were above normal for over 800 km seaward of the California coast. A coastally trapped wave would be restricted to within about 50 km of the coast and thus could cause positive anomalies only near the coast, leaving the offshore cold pool unexplained. Simpson[1] suggests that the westward-propagating Rossby waves generated by the poleward-propagating coastally trapped waves cannot explain the offshore cold anomalies observed in winter 1982-83.

Coastally trapped waves of higher than annual frequency are generated by tropical storms and have been observed off Central America in hourly sea level records (Christensen et al. 1983). As these waves propagate poleward, they become trapped in the Gulf of California and do not propagate poleward past the tip of Baja California. Evidently, coastally trapped waves must be of very large spatial scale and of several months' or longer duration to propagate past the Gulf of California.

Subsurface temperature data provide empirical evidence for the existence of poleward-propagating thermal depressions. Brainard and McLain (in press) computed anomalies of temperature at 100 m for areas along the west coast of North and South America. They analyzed over 115,000 temperature profiles from the files of Fleet Numerical Oceanography Center for a series of 3° blocks of latitude along the coast from 30°S to 50°N from 1951 to 1984. Anomalies of monthly mean temperature at 100 m computed from these profiles show that regions of anomalously warm water at 100 m occurred along the coast during 1957-58, 1972-73, 1976-77, and 1982-83. The regions appeared to expand poleward from near the equator, with their leading edges occurring progressively later in time with distance away from the equator. Although this could be evidence of a poleward-propagating coastally trapped wave, the leading edges of the anomalies traveled at speeds of 6 to 44 km/day, much less than the theoretical speeds of coastally trapped waves. Likewise, other authors (e.g., Enfield and Allen 1980; Chelton and Davis 1982) have found relatively low speeds of coastally propagating disturbances. The low propagation speed of the anomalies suggests that changes in advection may also occur (Chavez et al. 1984). Brainard and McLain (in press) also showed a general warming trend along the whole coast at 100 m beginning in 1976 and culminating in the extremely strong warm event in 1982-83. This warming trend was described by McLain (1983) and is similar to that described by Huang (1972) for the years 1958-69 relative to the years 1948-57.

Sea-surface temperature observations are more abundant than subsurface profiles and show the same general pattern of anomalies. Figure 1 shows the locations of 39 3° blocks of latitude and longitude in the Pacific, and 37 3° blocks in the Atlantic where monthly mean SST was computed. The SST reports used were received in real time by Fleet Numerical Oceanography Center from March 1971 to June 1984. The monthly means of SST were made for the 3° blocks by first averaging the reports by 1° blocks each month and then making 3° means of the 1° submeans. The number of observations in each 1° block varied widely from 0 to over 50 reports per month. Thus, making the 3° means from the 1° submeans reduced the spatial bias of sampling. A 3° mean was made if there was at least one 1° submean available. Because of the inhomogeneous distribution of the reports, this may have caused spurious 3° means in areas of sparse data. The number of reports used in each 3° block (shown in Table 3) varies from over 40,000 in the California and Canary currents to fewer than 100 in the Peru Current. Anomalies of SST were computed relative to the long-term mean for the period March 1971 to June 1984.

The long-term mean annual cycle of SST in the California Current region (Figure 2, left) is dominated by seasonal migration of a region of closely packed SST isotherms along the coast of Mexico between 18° to 28°N (Blocks 27 to 31 in Figure 1). This region represents a frontal zone between the colder water to the north (where the seasonal cycle of heating and cooling is strong) and the warmer water to the south (where seasonal fluctuations are small). A similar frontal region migrates seasonally in the Peru Current region from 0° to 10°S off Ecuador. The two frontal regions lie at the equatorward end of the California and Peru eastern boundary currents where the currents leave the coast and turn to the west.

Interannual variability of SST is described by between-year standard deviations of the individual monthly mean SST values (Figure 2, right). The greatest interannual variability of SST along the coast is in the Southern Hemisphere, with between-year standard deviations of over 1.0°C from the equator to at least 40°S. Peak variability (over 2.0°C standard deviation) occurs in a region from 15°S to 25°S from November to February, representing El Niño fluctuation. This

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[1] Simpson, J.J. MS. The Aleutian Low teleconnection between equatorial and midlatitude "El Niño-type" events. Submitted to J. Geophys. Res.

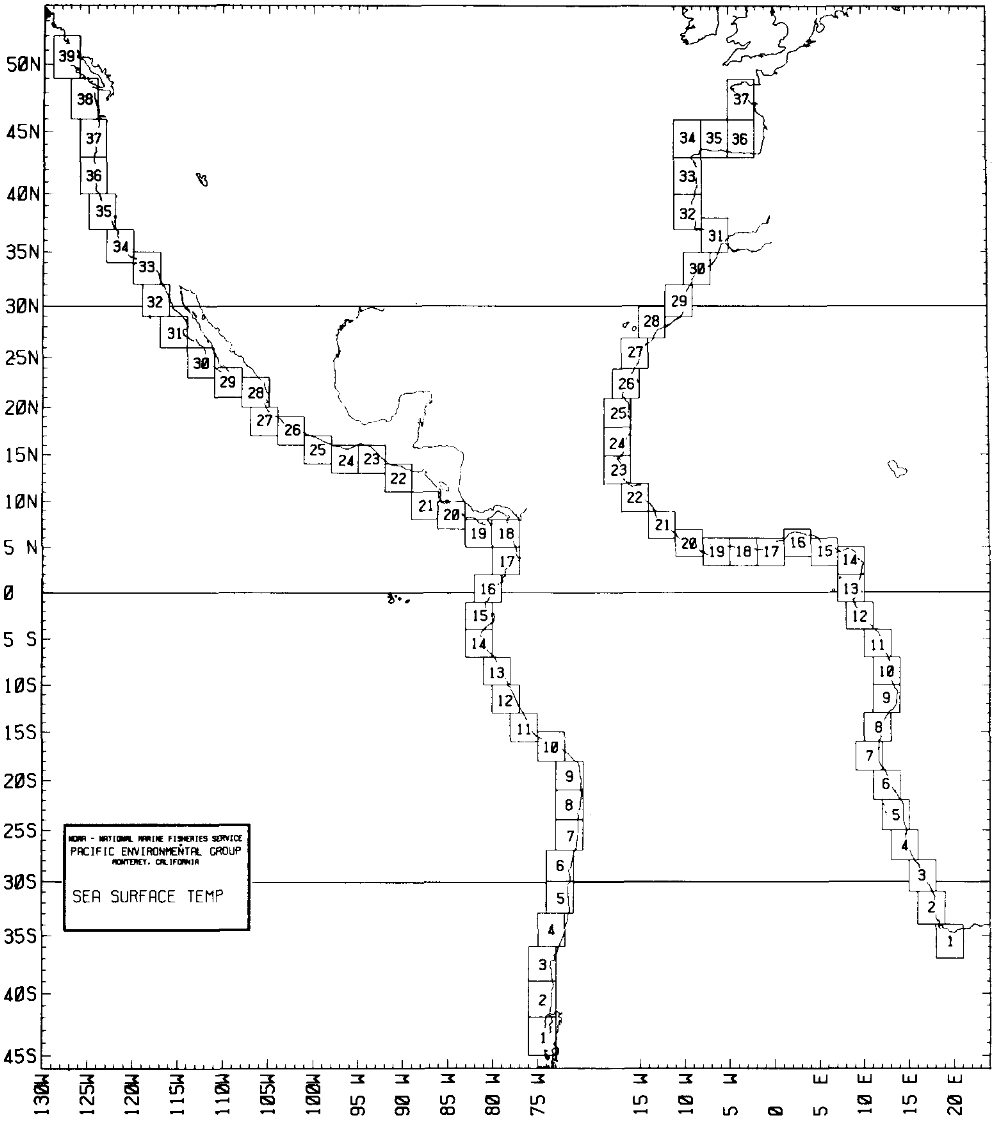

Figure 1. Locations of 3° blocks of longitude and latitude along eastern boundaries of Pacific and Atlantic oceans where monthly mean sea-surface temperature was computed for the period March 1971 to June 1984.

region is somewhat south of the region off Ecuador and Peru where El Niño is normally thought to be strongest. Perhaps the extreme scarcity of reports off Peru and Chile caused the apparent center of greatest interannual variability to be shifted southwards. Interannual variability in the California Current is lower than in the Peru Current and has between-year standard deviations of 0.5° to 0.8°C. The standard deviation is locally highest near the frontal zone off Mexico, representing interannual changes in the seasonal migration of the zone.

The computed anomalies of SST along the eastern Pacific were very noisy, with many small regions of positive and negative anomaly. Anomalies in the Peru Current were particularly noisy, perhaps because of the extreme scarcity of reports there. To smooth the array of SST anomalies, we applied two filters to the array in succession. First, we eliminated spikes with a 3 × 3 nonlinear or median filter in which the central value of each 3 × 3 subarray was replaced by the median of the 9 values in the subarray. Second we passed a 3 × 3 linear smoother with an arbitrarily chosen smoothing factor of 0.5 over the array. After this filtering, only the major anomalies remain.

Regions of positive anomaly of great coastwise extent occurred in the eastern Pacific in 1972-73 and 1982-83 (Figure 3), with peak values of about +4.0°C in December 1982 and January 1983 off Ecuador and Peru, and smoothed values of greater than +2.5°C. A positive coastwise anomaly of lesser magnitude and extent occurred in 1976-77. Because these coastwise anomalies are contemporaneous with major tropical El Niño events, they are probably of tropical origin. Negative coastwise anomalies occurred from 1973 to

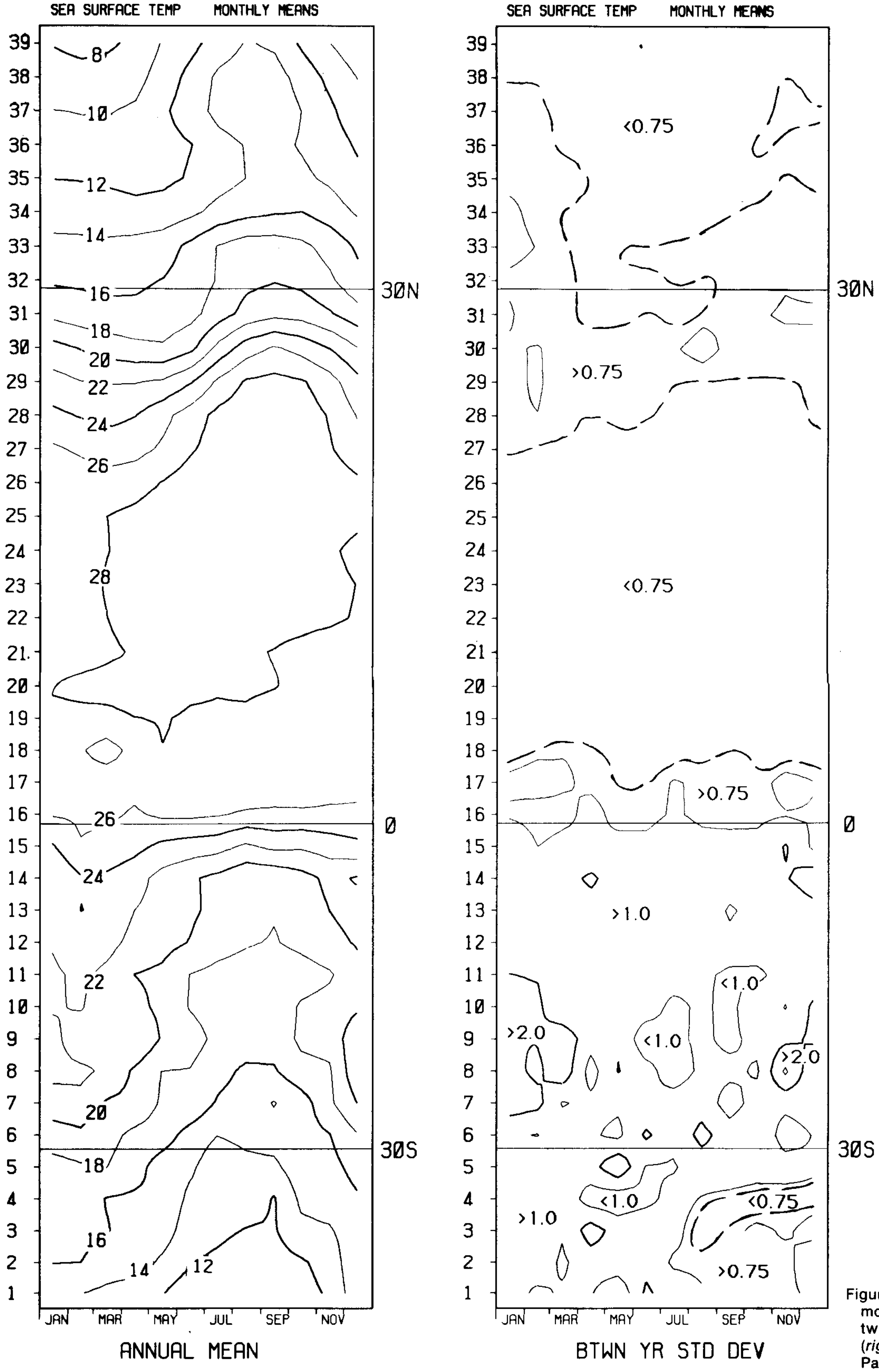

Figure 2. Annual cycle of long-term monthly mean SST (*left*) and between-year standard deviation (*right*) along eastern boundary of Pacific Ocean. Contour intervals are 2°C for the annual means and 1°C for the standard deviations (dashed line is 0.75°C).

TABLE 3
Total Number of SST Observations in 3° Blocks in the Eastern Atlantic and Pacific Oceans from March 1971 to June 1984

Block number	Pacific	Atlantic
39	5,710	—
38	47,092	—
37	20,581	15,980
36	30,149	5,415
35	82,058	14,797
34	42,885	46,279
33	35,568	46,759
32	8,107	30,665
31	8,956	21,035
30	10,559	10,817
29	10,020	6,510
28	5,427	11,503
27	8,886	19,488
26	9,763	59,190
25	9,103	32,198
24	8,600	24,063
23	5,592	22,255
22	7,126	9,426
21	8,016	15,075
20	8,067	5,466
19	7,122	5,030
18	1,475	3,825
17	332	2,201
16	985	1,121
15	673	930
14	879	553
13	636	456
12	477	452
11	305	1,453
10	120	5,946
9	62	4,659
8	70	1,661
7	73	12,238
6	150	15,424
5	115	6,113
4	81	3,269
3	115	7,258
2	110	10,693
1	198	8,440
Total	386,243	488,643

1975. Because of the large coastwise extent of these anomalies, the California and Peru current systems may have had similar anomalies simultaneously.

Large positive anomalies occur in regions such as off Baja and Alta California, where SST normally decreases rapidly with distance poleward along the coast. Stronger than normal poleward coastal flow during anomalous warm events would tend to cause positive SST anomalies in these regions. In contrast, off Central America, reduced positive or even negative SST anomalies occur as gaps in the coastwise positive anomalies. Negative SST anomalies also appear in maps of SST anomaly off Central America during February 1983 (U.S. Dept. Commer. 1983). A possible explanation for negative SST anomalies off Central America at a time when one might expect positive anomalies is that the mean coastwise SST gradient is small or negative in this region. A stronger than normal poleward flow along this coast would have little tendency to cause positive SST anomalies. Other possible reasons for gaps in positive coastwise SST anomaly might be: (1) wind mixing by Tehuantepec and Papagallo winds, which occur in this region and cause local cooling, and (2) upwelling of cold waters off Costa Rica. Douglas and Englehart (1983) found that cold anomalies off Mexico and Central America were correlated with alterations in the paths of tropical hurricanes.

In contrast to the coastwise warm events of 1972-73, 1976-77, and 1982-83 and the cold events of 1973-75, other anomalous periods occurred locally in the California Current and were not associated with tropical warm events. These included positive anomalies in the winters 1977-78, 1979-80, and 1980-81, and the negative anomalies in the winters of 1970-71, 1971-72, and 1978-79. Near-zero anomalies occurred in winter 1981-82. Similarly, many local SST anomalies occurred in the Peru Current that were not related to the major El Niño tropical warm events.

The second major ocean warm-event hypothesis—atmospheric circulation changes—suggests that the local anomalies in the California Current are caused by variations in wind-induced, onshore transport in midlatitudes. Recent work of Simpson (1983, 1984a, 1984b) and others emphasizes the importance of onshore transport of warm surface waters during local warming events. Horel and Wallace (1981) showed that a particular pattern of midlatitude upper atmospheric circulation, the "Pacific/North America" pattern, is associated with, or "teleconnected" to El Niño warming events in the Pacific. When there is anomalous warming in the tropical Pacific, there often is an associated shift in the upper atmospheric circulation, which causes a trough over the central North Pacific, a ridge over western Canada, and a trough over the eastern United States. This pattern of upper-atmospheric circulation is associated on the surface with an intensification of the Aleutian Low. Emery and Hamilton (in press) present maps of the winter mean surface atmospheric pressure over the North Pacific and show that years with a strengthened Aleutian Low are often associated with anomalous warmings in the tropics. During winter 1982-83, the Aleutian Low was several standard deviations deeper than normal and was shifted 10° to 20° of longitude east of its normal position over the central Aleutians, causing

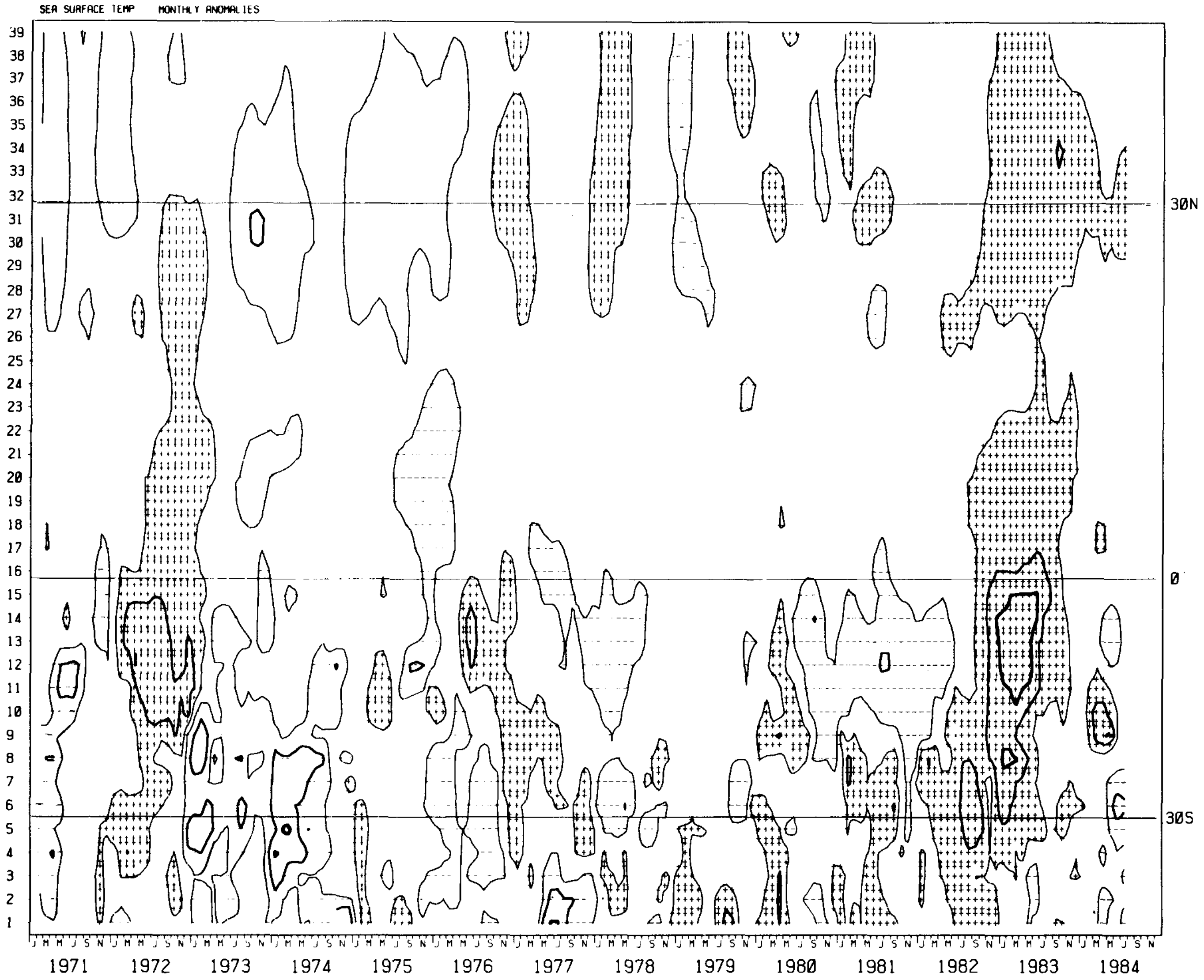

Figure 3. Anomaly of monthly mean SST along eastern boundary of Pacific Ocean. Small plus and minus signs represent anomalies before smoothing of greater than +0.5°C and less than −0.5°C, respectively. Contouring was performed after median and linear filtering. Light contour lines represent +0.5° and −0.5°C; dark contour lines represent −2.5°, −1.5°, +1.5°, and +2.5°C.

a very strong negative pressure anomaly over the Gulf of Alaska. The strong Aleutian Low combined with a weakened North Pacific High to cause a change in surface winds that resulted in very strong onshore transport of surface waters against the California coast.

Evidence of the importance of onshore transport in causing anomalous warm events off California can be seen in indices of upwelling intensity computed for 15 points along the west coast of North America (Figure 4) using methods of Bakun (1973). The strong upwelling off central California in summer has peak upwelling index values of greater than +200 m^3/sec/100 m coastline (Figure 5). During winter, tongues of negative upwelling index, representing onshore transport or downwelling, intrude southward along the coast from the Gulf of Alaska, where onshore transport occurs during much of the year. The tongues of onshore transport did not generally extend south of about 36°N in the early 1970s except in winter 1972-73. From 1976 to 1980, however, onshore transport extended south to about 33°N each winter. Increased frequency of onshore transport of warm surface water off central California in winter may thus have been a cause of the general warming along the coast during 1976-80.

During winter 1982-83, there was an extremely strong pulse of onshore transport with upwelling index

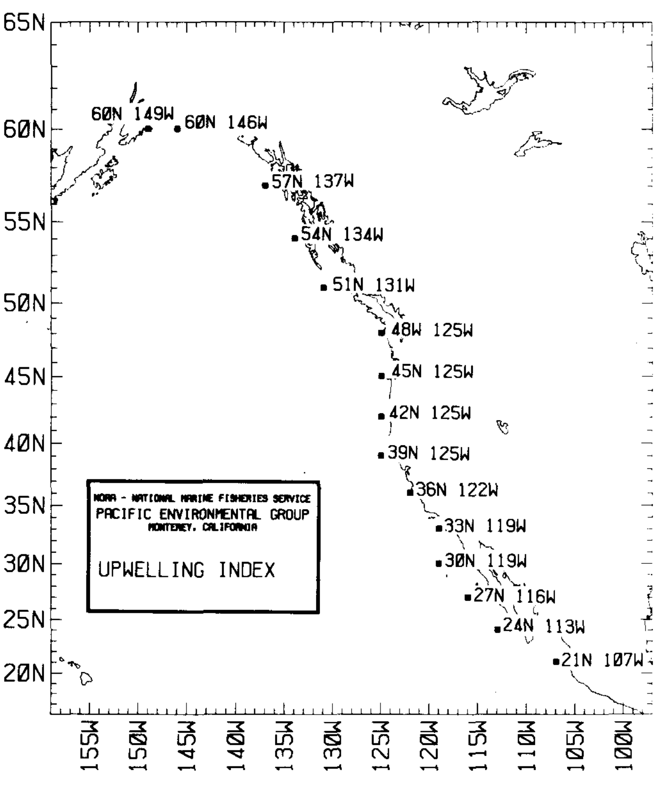

Figure 4. Locations of 15 points along west coast of North America where upwelling indices were computed by methods of Bakun (1973).

values of less than −200 units for two consecutive months. Onshore transport in the California Current region is not normally less than −150 index units in any one month. The largest total onshore transport (sums of negative index values at 42°N) of any winter in the period of record, 1946-84, occurred in 1982-83 (Norton et al. in press). There were −765 total units of negative upwelling index that winter, three times the normal of −251 index units. During the warm winter of 1957-58, there was also strong onshore transport, with a total of −544 index units. During the warm winter of 1972-73, however, strong onshore transport did not occur (−219 index units), suggesting that warming in 1972-73 was primarily a tropically related phenomenon. Lack of local reinforcement of the tropical warming in 1972-73 prevented positive SST anomalies from extending as far north as in 1982-83 and from persisting as long. During the more normal winter of 1981-82, the total onshore transport was −215 index units, and SST anomalies were near zero. Only very weak onshore transport occurred off California in winter 1978-79 (−99 index units), and negative anomalies (Figure 3) resulted.

The mechanism of onshore transport can explain a number of other features of anomalous coastal events. For example, it can explain the large offshore extent of the warm water along the coast in 1982-83 and the

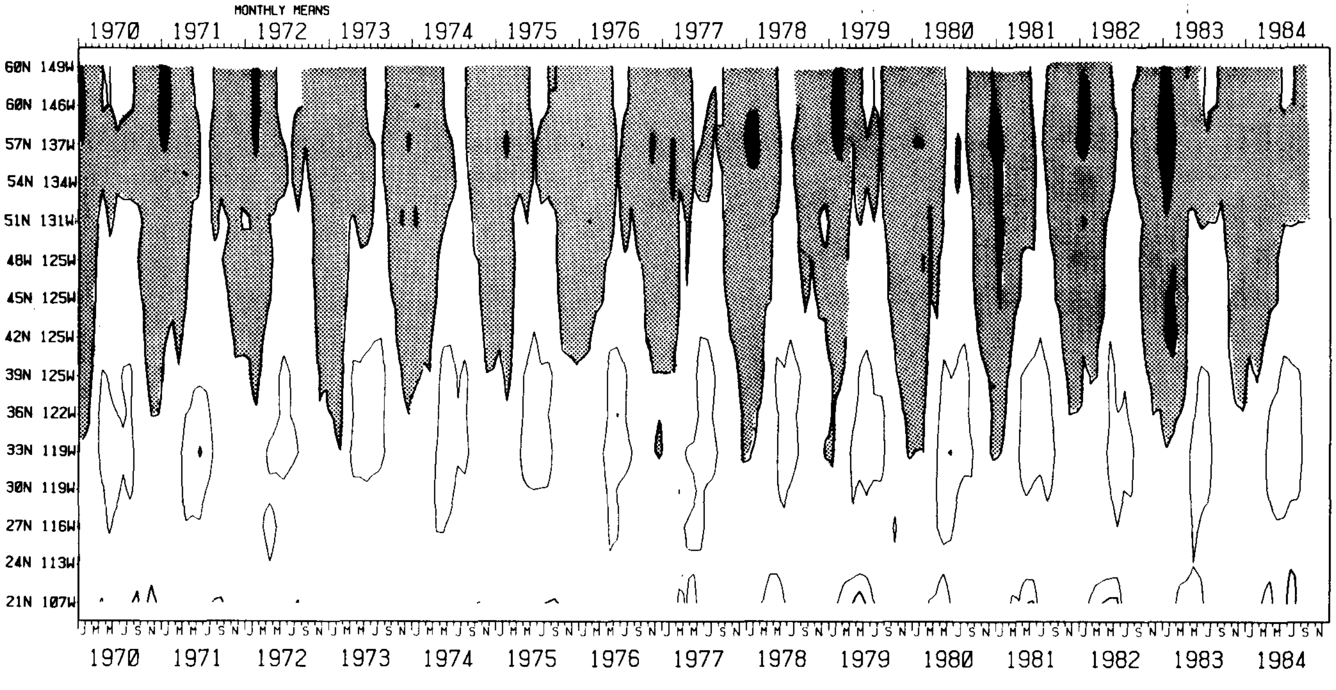

Figure 5. Monthly mean indices of upwelling intensity computed for 15 points along the west coast of North America. Units are m³/sec/100 m of coastline. Heavy contour lines are zero index and enclose tongues of onshore transport or negative upwelling index. Black areas are less than −200 index units. Fine contour lines are +200 index units and enclose areas of strong upwelling off central California in summer.

simultaneous formation of a pool of anomalously cold water in the central North Pacific. The onshore transport mechanism can also explain the low-salinity, high-dissolved-oxygen water observed in early 1983 on CalCOFI line 90 off San Diego (Simpson 1984a). Low-salinity waters have also been observed at frequently occupied coastal monitoring stations after periods of onshore transport (McLain and Thomas 1983).

In some years, local heating may contribute to anomalous warming events. In 1976-77, a blocking high-pressure system persisted over much of the western United States, causing record drought. The many warm, calm days associated with this high-pressure system probably caused increased solar radiation and warming of the surface waters. Solar heating cannot, however, explain the 1982-83 subsurface temperature anomalies, which were larger than those at the surface.

Thus it appears that anomalous warming events in Pacific eastern boundary current systems may be either—or both—tropical or locally forced events. El Niño events in the tropics can cause poleward-propagating coastally trapped waves, but because they narrow and lose energy, these waves do not seem to explain the large coastwise SST anomalies. Both processes may occur in the same year, and when they occur together, local onshore transport can reinforce the effects of coastally trapped waves to create the observed large anomalies in midlatitudes. Interannual variations in local onshore transport can cause local warm and cold events in the California Current. Onshore transport itself could generate coastally trapped waves, which would propagate the effects of the onshore transport poleward. To an observer at a point along the coast, both tropical and local processes would cause apparent depression of the thermal structure and intensified poleward coastal currents. When local reinforcement occurs, these effects may be additive. During 1982-83, for example, both processes were unusually intense, and combined to cause an extremely strong warm event in the California Current: warming in the tropics was the greatest in many decades, and local onshore transport was the strongest of any winter during the period of record 1946-83 (Norton et al. in press). The resulting depression of the thermal structure and poleward currents along the coast were very large (Tables 1 and 2). In contrast, during the tropical warm event of 1972-73, when local reinforcement was not strong, SST anomalies in the California Current were of short duration and did not extend far up the coast. Local reinforcement by onshore transport in the Peru Current has not been demonstrated (Fonseca 1984).

SST FLUCTUATIONS IN THE EASTERN ATLANTIC

The long-term mean annual cycle of SST fluctuations in the eastern Atlantic (Figure 6, left) is dominated by seasonal migration of frontal zones between 10°N and 20°N between Cape Vert and Cape Blanc in the Canary Current (Wooster et al. 1976) and between 10°S and 20°S near Cape Fria in the Benguela Current (Wooster, in Picaut 1983). As in the Pacific, the frontal zones represent regions where the eastern boundary current turns offshore. Seasonal heating and cooling is strong poleward of the frontal zones, and seasonal variations are weak equatorward of the zones.

Interannual variability of SST in the eastern Atlantic (Figure 6, right) is similar to that of the Pacific, with low values of between-year standard deviation in the Northern Hemisphere and large values in the Southern Hemisphere. Local, weak maxima of variability occur in the Canary Current near the frontal zone. Interannual variability in the Benguela Current is high, and between-year standard deviations range up to 2.2°C near 10°S, reflecting large interannual variations in the front. A band of high interannual variability occurs from 25° to 30°S as a result of multiyear anomalous periods.

The anomalies of SST in the eastern Atlantic (Figure 7) appear somewhat similar to those of the Pacific, except that no large coastwise anomalies occur. Anomalies in the Canary Current are weak and of local nature. There was a general warming trend evident during 1971-84 in the Canary Current; it was cool in 1972 and 1974 and then warming in 1976 and remaining generally warm thereafter, with positive anomalies occurring in 1978, 1979-80, 1981-82, and 1983-84.

SST values in the Benguela Current were above normal from 1971 to early 1979 and below normal from 1979 to 1983. Greatest negative anomalies (less than − 1.0°C) occurred off Namibia from November 1981 to May 1982, in rough agreement with the cold period observed there during February to September 1982 by Boyd and Agenbag (1984). The persistence of these anomalous periods is unusual. Whereas in the other eastern boundary current systems, SST anomalies are more coherent with distance along the coast than in time (causing the generally vertical features in Figures 3 and 7), in the Benguela Current, anomalies were very persistent in time (causing the more horizontal features at the bottom of Figure 7). This suggests that the upwelling-related winds over the Benguela Current must be very persistent, but Picaut (1983) mentions that south of about 20°S in the Benguela Current the correlation between winds and SST anomalies is low. Perhaps the large persistence of the

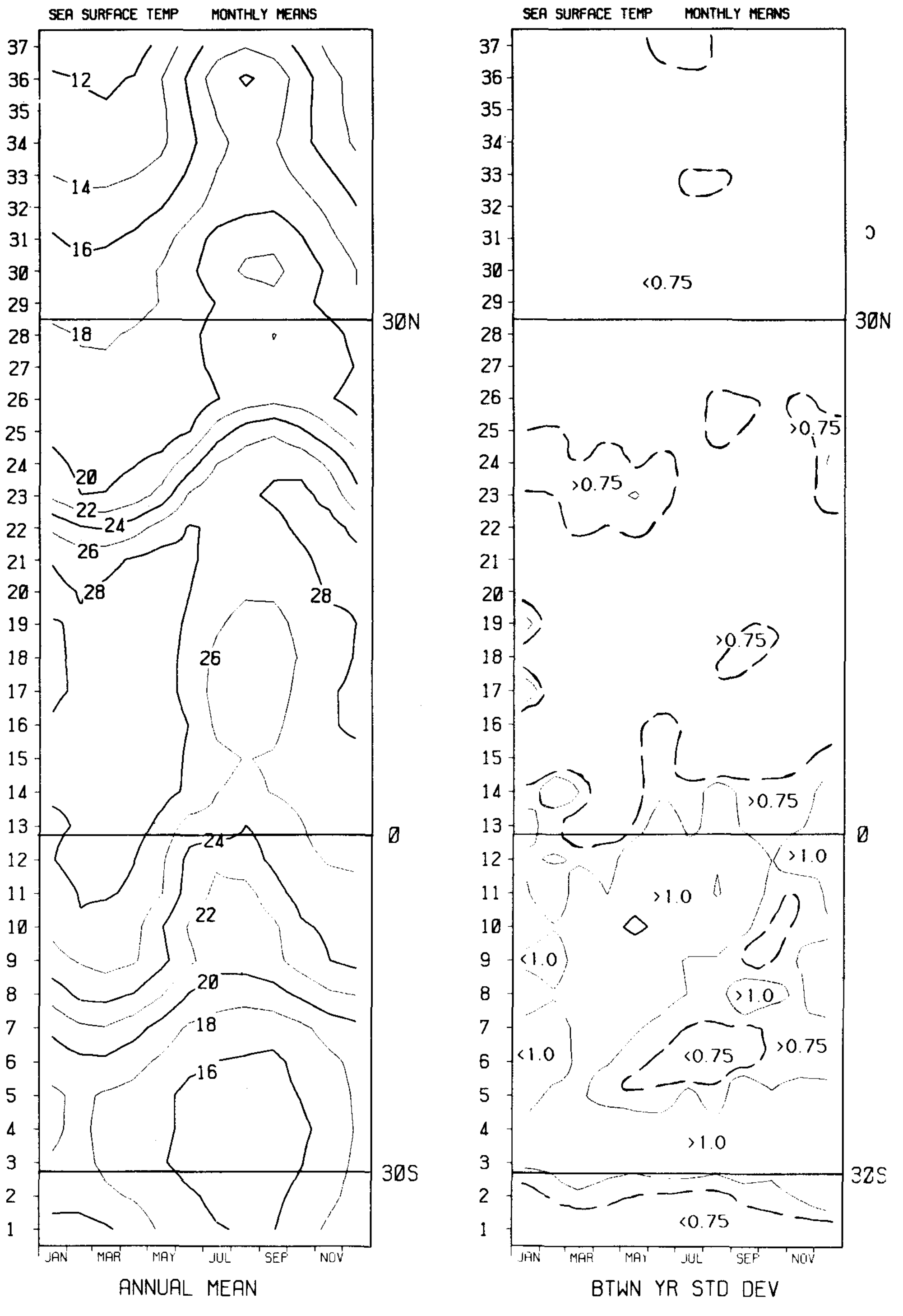

Figure 6. Annual cycle of long-term monthly mean SST (*left*) and between-year standard deviation (*right*) along eastern boundary of Atlantic Ocean. Contour intervals are 2°C for the annual means and 1°C for the standard deviations (dashed line is 0.75°C).

anomalies in this region is related to very slow changes in advection in the South Atlantic gyre.

An intense local warming occurred in the Benguela Current from March to at least May 1984. SSTs greater than 29°C intruded as far south as latitude 15°S. The warm event started along the coast near Cape Fria (12° to 19°S) and expanded equatorward, becoming most intense near Point Noire, Congo (5° to 10°S), in June 1984, with anomalies of up to 3.5°C. In contrast, Boyd and Thomas (1984) examined hydrographic data taken within 1° of the coast from 18° to 26°S and found water up to 6°C warmer than normal, particular-

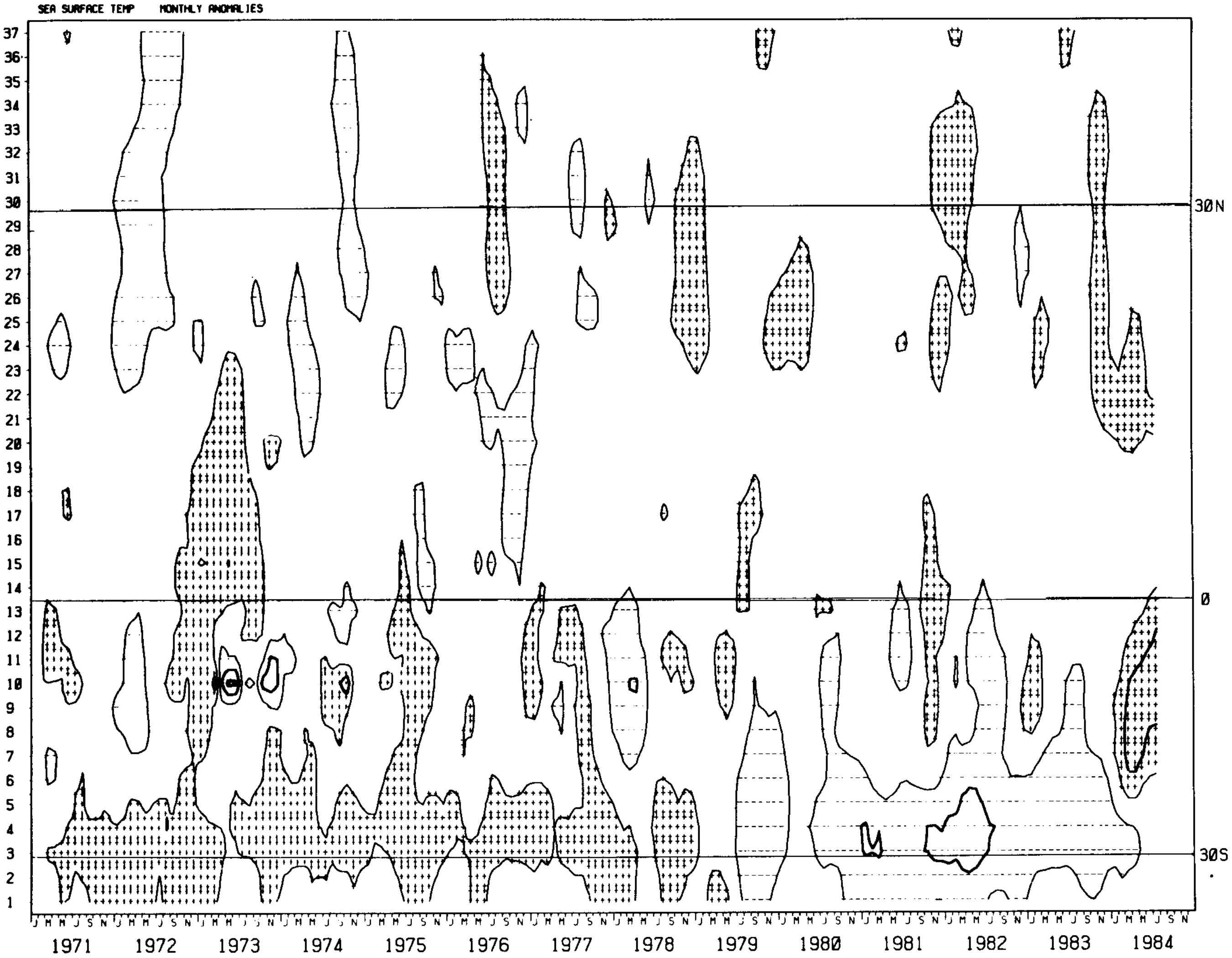

Figure 7. Anomaly of monthly mean SST along eastern boundary of Atlantic Ocean during the period March 1971 to June 1984. Small plus and minus signs represent anomalies before smoothing of greater than +0.5°C and less than −0.5°C, respectively. Contouring was performed after median and linear filtering. Light contour lines represent +0.5° and −0.5°C; dark contour lines represent −2.5°, −1.5°, +1.5°, and +2.5°C.

ly near the coast. They suggest that the warm event was caused by a southward intrusion of equatorial water. If so, the intrusion may have come from offshore, reaching the coast near Cape Fria, and then expanding generally northward, as seen in the 3°-block SST data. It may also have expanded southward and been seen in the hydrographic data, very close to the coast.

In contrast to the large coastwise extent of SST anomalies in the Pacific, anomalies in the eastern Atlantic are more local and do not have the large coastwise extent. The Atlantic anomalies generally were restricted to one of the three regions: Benguela Current, Gulf of Guinea, and Canary Current. Only the warm events in 1972-73 and mid-1981 in the Benguela and Gulf of Guinea regions spanned more than one region. This suggests that different oceanic or atmospheric processes affect the three regions. Also, SST anomalies in the Pacific tended to occur in northern winters, but Atlantic anomalies occurred throughout the year.

RELATION OF TROPICAL ATLANTIC AND PACIFIC ANOMALIES

Because there was an anomalous warm event in the tropical Atlantic in early 1984, one year after the major warm event in the Pacific in 1982-83, it was thought that similar Atlantic warm events might have occurred following earlier Pacific warm events. To examine this question, we made time series of monthly mean SST for the years 1946 to 1979 by 5° blocks for the eastern tropical Pacific and Atlantic from the

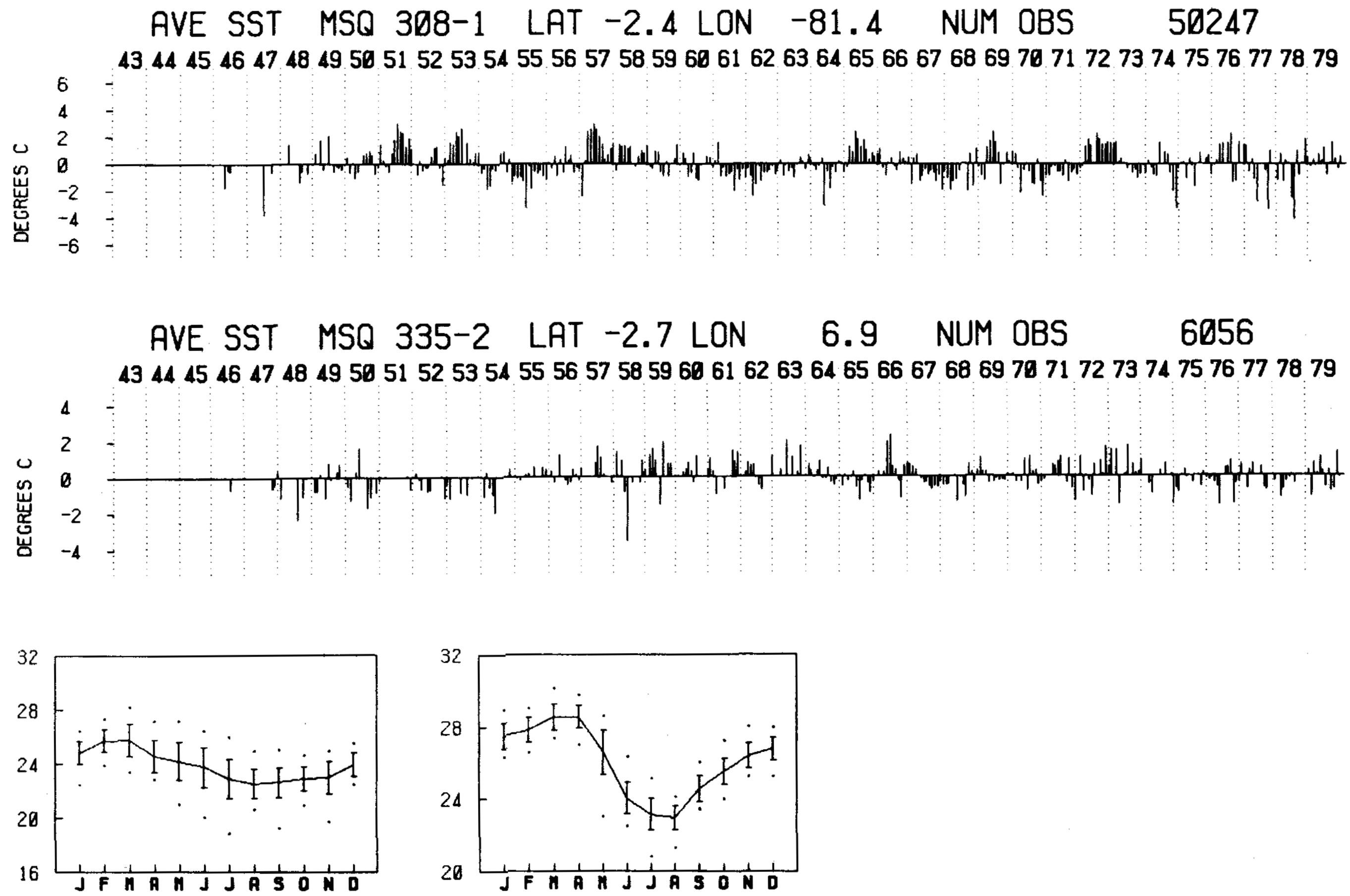

Figure 8. Time series of anomaly of SST in 5° blocks in eastern tropical Pacific (*upper*) and Atlantic (*lower*) oceans for the years 1943 to 1979. Mean annual cycle of SST and range and standard deviation of interyear variability are shown in small boxes (Pacific, *left*, Atlantic, *right*). Areas are Marsden 5° blocks 308-1 off Ecuador in the eastern tropical Pacific (0° to 5°S, 80° to 85°S) and 335-2 off Gabon in the eastern tropical Atlantic (0° to 5°S, 5° to 10°E).

Consolidated Data Set of Fleet Numerical Oceanography Center (FNOC). This data set comprises marine weather reports from two sources: (1) historical logbook reports in the TDF-11 data file from the National Climatic Data Center for the years 1946 to about 1976, and (2) the reports received in real time by FNOC for 1971 to 1979. Time series of SST anomalies (Figure 8) were made for an area off Ecuador (Marsden 5° block 308-1) and an area off Gabon in the tropical Atlantic (5° block 335-2). Although the Atlantic data are very sparse, there is no obvious lag relationship between the two series.

The most obvious difference between the Atlantic and Pacific SST time series is the generally greater persistence of anomalies in the tropical Pacific relative to the tropical Atlantic. We examined this in greater detail by computing autocorrelation functions for the two series (Figure 9). The autocorrelation function of the Atlantic series drops to less than 0.1 in 3 months, whereas it takes 8 months in the Pacific. The slower response time in the Pacific reflects the larger size of the Pacific and the greater energy required to displace the thermocline vertically.

CONCLUSIONS

Although sampling density was extremely nonhomogeneous, we computed monthly mean SSTs and anomalies from the long-term mean for series of 3° blocks along the coast in the eastern boundary current systems of the Pacific and Atlantic oceans. From these data, anomalous warm and cold events can be seen in all four major eastern boundary current systems. In the Pacific, coherent anomalies can extend over great stretches of coast from Chile to British Columbia, causing the California and Peru current systems to have similar SST anomalies simultaneously. Other local anomalies can occur in the California and Peru currents as well. There was less coastwise coherence of SST anomalies in the Atlantic than the Pacific, and thus the Canary and Benguela current systems do not generally have similar SST anomalies simultaneously.

Two major hypotheses for formation of anomalous

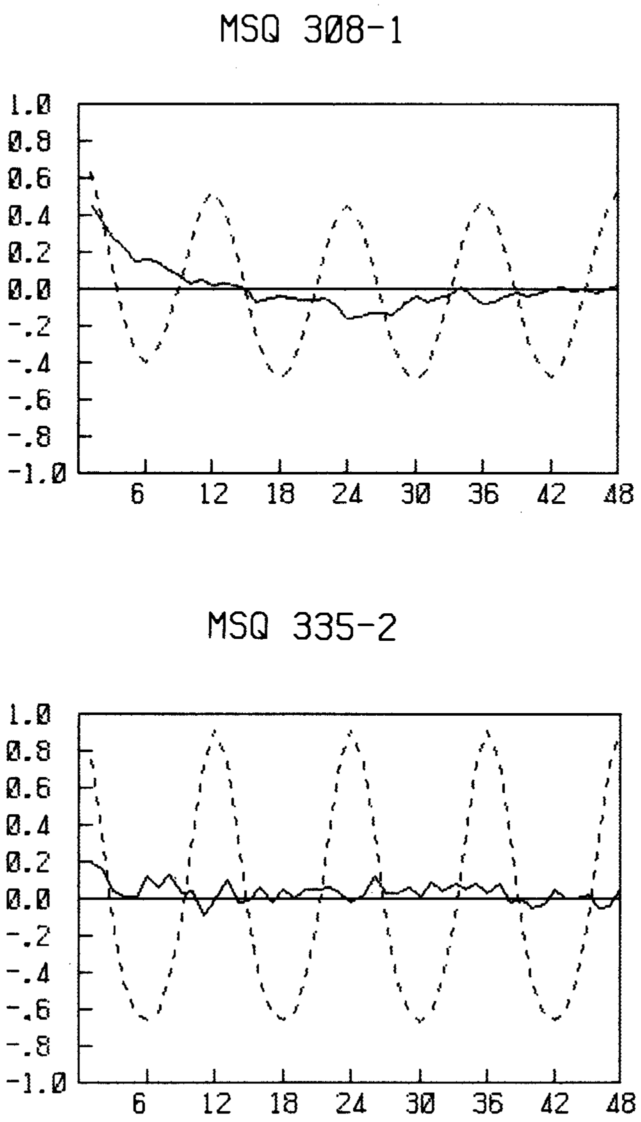

Figure 9. Autocorrelation function of monthly mean SST anomaly series for lags up to 48 months in 5° blocks in the eastern tropical Pacific (*upper*) and the eastern tropical Atlantic (*lower*). The dashed curves are the autocorrelation functions of the original SST time series, and the solid lines are the autocorrelation functions of the time series of SST anomalies.

warm events in the California Current have been suggested: (1) onshore transport of warm surface waters by strong southwesterly winds warms the surface water and depresses the thermal structure; (2) poleward-propagating coastally trapped waves from tropical El Niño events cause depressions of the thermocline to propagate poleward. Propagating coastally trapped waves narrow and lose energy with distance poleward from the tropics and do not explain the observed large coastwise anomalies. Onshore transport may occur in the same year as tropical warming events and cause local reinforcement of the effects of propagating coastally trapped waves in midlatitudes. Local heating by solar radiation is a third possible hypothesis for formation of anomalous warm events.

Two important effects of the anomalous warming events have biological significance: (1) geostrophic adjustments to the deepened thermal structure cause an intensification of normal seasonal poleward flow over the continental shelf. This intensification causes increased advection of warm water poleward and allows warm-water organisms to extend their ranges poleward. (2) A thickened surface layer reduces the ability of upwelling-favorable winds to upwell nutrients into the lighted surface waters, lowering the biological productivity.

An extremely anomalous warming event occurred in the California and Peru current systems during 1982-83. Off California exceptionally strong onshore transport of warm waters from offshore reinforced propagating coastally trapped waves from an exceptionally strong tropical El Niño. Anomalies were as large as +4°C at the surface and as large as +5° to +6°C at 100 m (Brainard and McLain in press), reflecting a deepening of the thermocline along the coast by 50 to 100 m. Off California the biological productivity of the surface waters was greatly reduced, and strong poleward flows advected many warm-water species northward.

SST anomalies in the Canary Current during 1971-84 have been relatively small but showed a general warming trend similar to that observed in the Pacific. Anomalies in the Benguela Current were extremely persistent and were positive during the years 1971-78 and cool during 1979-83. Anomalies then became strongly positive in early 1984, possibly because of an intrusion of equatorial water. There was no obvious lag relationship of SST anomalies in the Atlantic following similar warm events in the Pacific. SST anomalies are generally more persistent in the tropical Pacific than in the tropical Atlantic, but anomalous conditions in the Benguela Current can persist for five or more years.

The interannual variability of SST fluctuations in eastern boundary current systems is high near the frontal regions where the eastern boundary currents leave the coast. SST gradients are strong in these regions, and interannual variability of SST is locally high because of interannual variations in the seasonal migration of the fronts. Interannual variability of SST is higher in the Southern Hemisphere than in the Northern Hemisphere, but the anomalies in the Southern Hemisphere tend to be more persistent. Thus SSTs in the Northern Hemisphere tend to vary about a mean state, whereas Southern Hemisphere anomalies tend to switch between different regimes, lasting for a year or longer.

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