Near and Distant Connection of Atmospheric Systems to Ocean Temperature Change in the Coastal California Current Region

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In studying hydrosphere, atmosphere, and biosphere interactions, it is useful to focus on specific subsystem processes and energy exchanges (forcing). Since subsystem scales range over ten orders of magnitude, it may be difficult to focus research on scales that will yield useful results in terms of establishing casual and predictive connections between more easily and less easily observed subsystems. In an effort to find pertinent scales, we have begun empirical investigations into relationships between atmospheric, oceanic, and biological systems having spatial scales exceeding 10^3 kilometers and temporal scales of six months or more. Reasons for this scale selection include:

- Significant changes at these scales (interannual events) can be detected and analyzed using established and actively updated data sets.
- Combining observations for interannual analysis allows sufficient numbers of observations to be grouped so that investigation results have reasonable statistical reliability.

Previous studies established connections between interannual fall-winter temperature changes in the coastal California Current region (Figure 1) and two widely separated locales of atmospheric forcing: remote atmospheric forcing from the Equatorial Pacific, and regional atmospheric forcing from the Northeastern Pacific (Norton and McLain 1993). Previous studies are reviewed and extended from the fall-winter period to a complete annual analysis. In addition, 700mb height anomaly fields are used to show relationships between atmospheric forcing over the North Pacific and ocean temperature change in the study region.

Data Series and Fields

A brief outline of data series development follows. Norton and McLain (1993) have previously provided a detailed description. For the ocean temperature series, 1.9×10^4 ocean temperature profiles were extracted from the U.S. Navy's Master Oceanographic Observations Data Set (McLain *et al* 1985) for the study region and sorted into six areas (Figure 1). Monthly mean anomaly values for 34 years (1953-1986) were computed at five depths from the profile information and divided by the standard deviation of the monthly means at each depth and for each of

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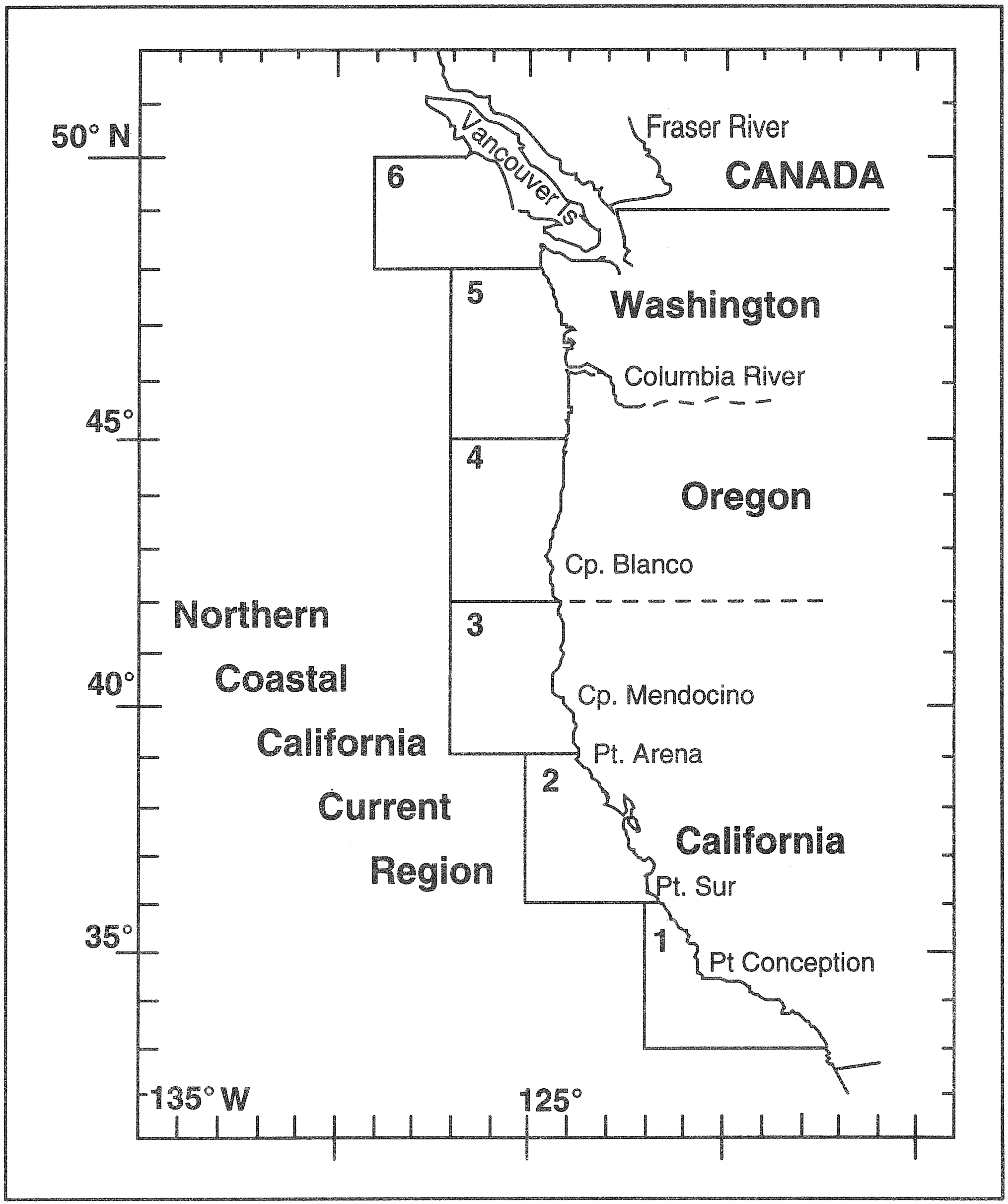

Figure 1. The northern coastal California Current region used in this study is a composite of the six subareas shown. Standardized monthly temperature anomaly values were obtained for each of the six subareas, then combined to give overall values representative of the entire area.

the six areas. This standardization allows intercomparison of depths and equal weighting between areas. Average unit magnitude in standardized anomaly is about 1.0°C above 50 meters, 0.6° at 100 meters, and 0.5°C below 150 meters.

For each depth, standardized anomaly values for the six subareas were averaged to give monthly anomaly values representative of the entire northern coastal California Current region. These monthly anomalies were then time-averaged over six months at each depth to give a single standardized anomaly value representing the entire 6-subarea region for fall-winter (September-February) and spring/summer (March-August).

Two monthly mean series of atmospheric sea level pressure (SLP) representing remote (Indonesian Low in the Equatorial Pacific at 12.4°S×130.9°W near Darwin, Australia) and regional (Aleutian Low in the North Pacific at 45°N×165°W) were used as forcing indicators. These single-point series were smoothed with a 6-month running mean as a preliminary processing step.

Quarterly (3-month average) 700mb height anomaly fields were used to study spatial variation of correlation coefficients (r) over the Pacific. The height anomalies were computed for the extra-tropical Northern Hemisphere as monthly means for 2°×2° areas, then averaged by month to give spring, summer, fall, and winter fields.

Interannual change values of ocean temperature, remote atmospheric forcing, and regional atmospheric forcing are used in all the following single atmospheric point analyses. For the current year, the interannual change value is found by subtracting the parameter value for the previous year (yr-1); *eg,* for a particular seasonal value of ocean temperature change, $D_{z,yr}$,

$$D_{z,yr} = A_{z,yr} - A_{z,yr-1},$$

where A is the combined standardized anomaly value for a given year, yr, at depth, z. Interannual change values are also referred to below as “interannual differences”.

Vertical Empirical Orthogonal Functions (EOFs) were derived from the 4×33 matrix having 0, 100, 200, and 300 meters as rows and 33 years of interannual differences at these depths as columns. Series of time varying coefficients (DEOFs) were computed from the input matrix and EOFs. Studies outlined in the next section deal only with EOFs for fall-winter.

In some years an atmospheric teleconnection may link changes in Equatorial Pacific sea surface temperature to SLP over the North Pacific (Rasmusson and Wallace 1983). This physical relationship causes North Pacific and Equatorial Pacific interannual difference series to have common variability, especially in winter. Correlation between the remote and regional atmospheric indicator series is easily demonstrated (Wallace and Gutzler 1981; McLain and Norton 1993). However, the present objective is to show discrete effects of North Pacific and Equatorial Pacific atmospheric forcing in regional ocean temperature change. To correct for the atmospheric teleconnection, each atmospheric series was linearly regressed on the other, and the residual series was used in place of the original series. These residual index series were used in Table 1.

Correlation of interannual temperature differences at 0m and 200m and 1st and 2nd EOFs to Atmospheric Forcing Indices.

Atm. Index	Correlation (r) and atm. leads/lags (+/-) in months 0m	200m	EOF1	EOF2
Eq. Pac. (12.4°S x 130.9°E)	.65, +6	.72, +6 .71, n.r.	.74, +5	.33, +7 .34, -5
No. Pac. (45°N x 165°W)	-.61, n.r.	-.20, n.r.	-.31, n.r.	-.66, n.r.

n.r. - lead/lag not resolved by present technique

Table 1. Correlation between atmospheric forcing indices and interannual ocean temperature change values for the fall-winter period. Values are correlation coefficients (r). Coefficients in the top row are positive, showing positive SLP anomaly at 12.4°S×130.9°E (Indonesian Low, remote forcing) to be correlated with positive temperature anomaly in the ocean study area. The bottom row has negative coefficients showing a reverse relationship between the ocean study area and SLP anomalies at 45°N×165°W (Aleutian Low, local forcing). For $|r| \geq 0.4$, significance levels are greater than 0.05 (Norton and McLain 1993).

Previous Studies

This section summarizes previous work by Norton and McLain (1993).

During fall-winter, remote forcing from the Equatorial Pacific atmosphere-ocean system and regional forcing from the North Pacific lead to interannual ocean temperature change along the west coast of the United States (Figure 1). Correlations between the subsurface temperature and the atmospheric index time series indicate that coherent ocean temperature changes extending from the surface to 300 meters depth indicate remote forcing from the equatorial atmosphere through the ocean. Correlations between time series of interannual ocean temperature change and series of equatorial interannual sea level pressure change at 12.4°S×130.9°E were as large ($r>0.6$) below 100 meters as at the surface. From 1954 through 1986, vertically coherent warming events occurred only during moderate to strong El Niño years as shown by Quinn *et al* (1987). The inference is that changes in the Equatorial Pacific atmosphere excite oceanic Kelvin waves, which travel to the eastern Pacific border and then poleward to higher latitudes where this influx of energy favors down-welling and warming. Ocean events associated with North Pacific SLP change at 45°N×165°W and direct atmospheric forcing have correlations that are greatest in the upper 50 meters. In general, changes in regional temperature below 100 meters depth are not significantly correlated with changes in North Pacific SLP indices. These results are illustrated in Table 1, which shows that correlation of temperature change in the study area with the equatorial atmosphere is greater at 200 meters than at the surface. At 200 meters and below, an additional oceanic response appears in phase with remote forcing. Correlation with the North Pacific forcing is clearly greater at 0 meters than at 200 meters (Table 1).

The first two vertical EOFs derived from the 4x33 matrix of interannual ocean temperature change in the upper 300 meters accounted for more than 92 percent of the variance. Column three of Table 1 shows that the first EOF (EOF1), which has nearly uniform loading over depth, is most closely correlated with Equatorial Pacific forcing. Column four shows that the second EOF (EOF2), which has greatest loading at 0 meters and sign reversal below 100 meters, is more closely correlated to regional atmospheric forcing.

The lag shown in the top row of Table 1 provides an additional distinction between regional and remote forcing. Positive lags in the top row suggest the signal related to equatorial forcing takes up to six months to reach the study region, which is consistent with the "remote" terminology and with the empirical studies of Enfield and Allen (1980) and Chelton and Davis (1982). The correlation of remote forcing at shorter lags (not resolved, or n.r., in Table 1) is consistent with observational and model studies of McCreary (1976), Huyer and Smith (1985), and Shriver *et al* (1991).

This study implied that interannual warming off the West Coast during fall-winter has two distinguishable geographical origins. The vertically-coherent signals related to the equatorial atmosphere-ocean system may result from propagating complex modal structures that combine to produce signals where vertical and horizontal propagation co-occur (Romea and Allen 1983).

Additional Results

The time variation in seasonal oceanic response modes (DEOFs) of the coastal California Current region during 1954 to 1986 are shown in Figure 2. Each year has two DEOF series values, with the spring/summer value given first. Vertical bars (DEOF1) show remote forcing response, and dots (DEOF2) show response to regional atmospheric forcing. Together, EOF1 and EOF2 account for more than 92 percent of the variance in both spring/summer and fall-winter series. Note that the relative magnitude of variance explained by EOF1 (>74%) and EOF2 (>12%) is reflected in the magnitudes of the left and right scales, respectively. Part of the unequal importance of EOF1 and EOF2 may be due to the averaging and differencing procedures, which select strongly for biennial processes that produce maxima in years following or preceding years with minima (Norton and McLain 1993). This event type is clearly seen in the DEOF1 series (*ie,* 1965-1966, 1972-1973). In general, effects of the first mode will conceal effects of the second mode at biennial scales, but when there is little ocean change forced by the first mode, the second mode becomes more important (*ie,* 1969, 1978).

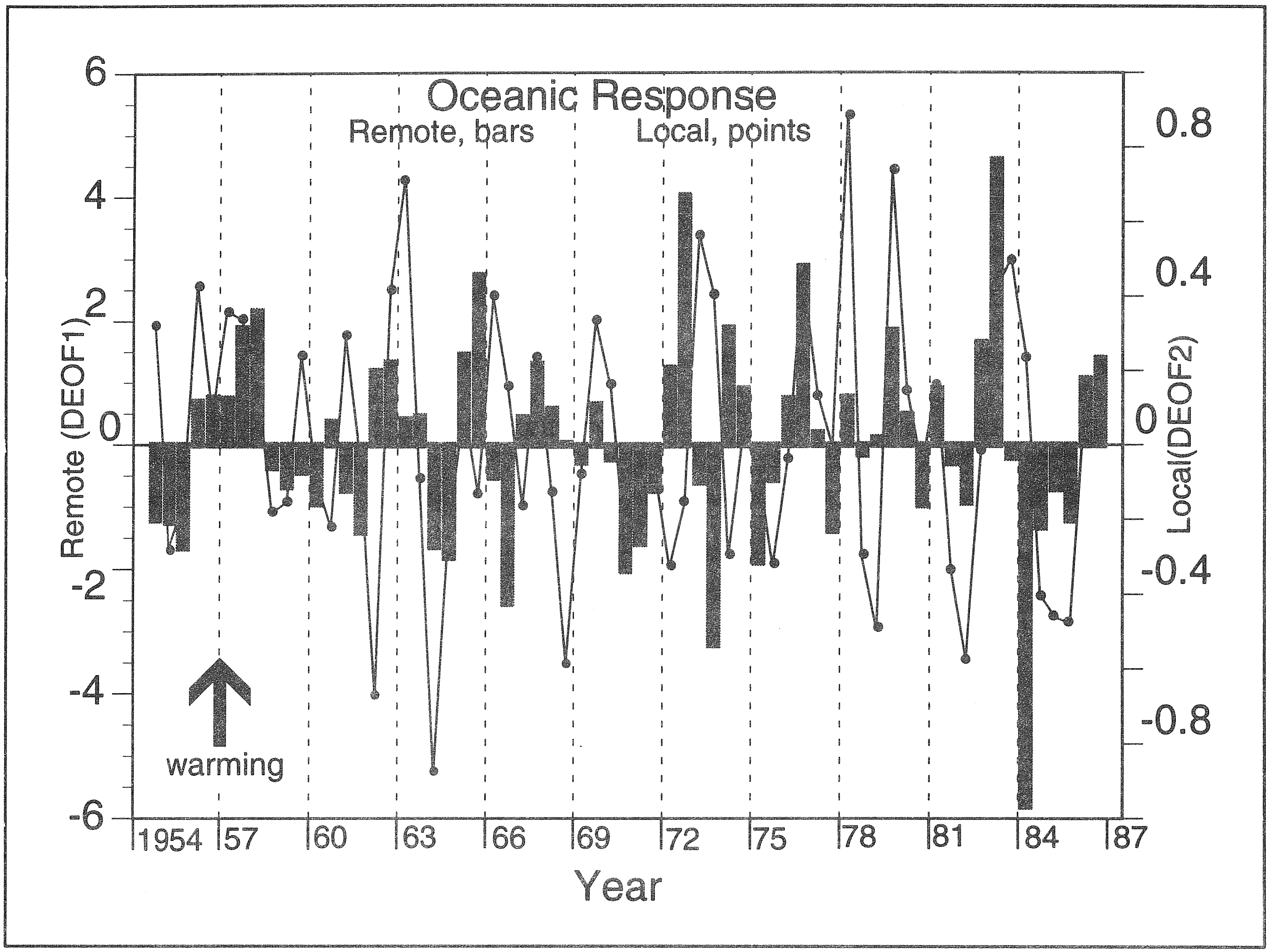

Figure 2. Northern coastal California Current response to remote (DEOF1) and local (DEOF2) atmospheric forcing from 1954 through 1986. The spring/summer value is plotted immediately to the right of the year tick at the bottom.

It is interesting to ask how well the DEOF series reflect environmental effects discussed by other researchers. Note that all moderate to strong El Niño events are represented by DEOF1 values exceeding 2.0 (1958, 1965, 1972, 1976, 1983) and that the largest warming signal in the series corresponds to the very extreme 1982-1983 event (Quinn *et al* 1987).

The most extensively documented California Current regional warming events of the series occurred in 1956-1958 and 1982-1983 (*eg*, Sette and Isaacs 1960; Wooster and Fluharty 1985). The 1956-1958 event was prolonged over three years when both EOF1 and EOF2 were in warming phase. Note that observation of anomalously warm ocean temperatures will lag the warming processes if warming begins during a cool ocean period, as in 1956 (Reid 1960). The timing of the 1982-1983 El Niño was quite different than the 1956-1958 event in that oceanic warming was intense for one year, followed by a cooling phase of similar magnitude and duration (Figure 2).

Selected references to California Current warm and cool events of interannual scale are shown in Table 2. Note that this report shows warming (ΔW) or cooling (ΔC) relative to the previous year. In contrast, references in Table 2 are most frequently to events that are warm or cool compared to an overall series mean. Nonetheless, the table suggests that most of the warming (ΔW) events identified by the DEOFs have been labeled as warm events by previous studies, and most of the cooling (ΔC) events have been labeled cool periods. The present material (Figure 2) may be used to compare the relative intensities of these events.

North Pacific Atmospheric Systems

Previous work showed that large-scale temperature changes in the coastal California Current region appear related to SLP changes at 45°N×165°W (Norton and McLain 1993). Oceanic changes related to this regional large-scale atmospheric forcing are represented by DEOF2 in Figure 2. Natural questions are:

- How are changes at 45°N×165°W related to atmospheric changes over the entire North Pacific?
- How are coastal ocean temperature changes in the study region related to atmospheric events throughout the North Pacific?

To address these questions, the correlation between DEOF2 and the height of fall (September, October, November) 700mb atmospheric pressure surface was mapped (Figure 3).

From Figure 3 it is evident that the time variation in DEOF2 is related to large-scale atmospheric conditions that extend over the entire North Pacific and North American continent. The area of over 5×10^7 km^2 has three primary regions of correlation, arranged in a pattern arcing from southwest to northeast. Regions of alternating sign may represent atmospheric Rossby waves associated with winter cyclogenesis over the North Pacific, temperature change in the coastal study region, and other phenomena throughout the global atmosphere-hydrosphere system (Rasmusson and Wallace 1983).

In Figure 3, the area of negative correlation with maximum near 50°N×160°W represents intensification or weakening of the Aleutian Low subsystem. Positive (negative) sea surface temperatures along the West Coast study area are correlated with negative (positive) height anomalies in the Aleutian Low. The pattern shown in Figure 3 is consistent with the relationship found for the single point (45°N×165°W) used by Norton and McLain (1993), suggesting that the single point used in previous studies was adequate in representing Aleutian Low variation. Correlation of winter 700mb height with fall-winter DEOF2, spring 700mb height with spring/summer DEOF2, and summer 700mb height with spring/summer DEOF2 gave similar results, with the major differences in the

Warming and Cooling years in the California Current Region

This Study Oceanic Response			Previous Studies		
Year	DEOF1	DEOF2	Source	Forcing	Ocean Observation
1955	ΔC	ΔC	Reid 1960	A	C
1956 - -57-58	ΔW	ΔW	Namias 1959, Stewart 1960, Reid 1960	A	ΔW, W
1962-63	-	ΔW	Namias 1963	A	W
1965	ΔW	-	Enfield &Allen 1980 Wyrtki 1975	O, A	W
1969	-	ΔW	Clark 1972	A	ΔW, W
1970-71	ΔC	ΔC	Norton et al. 1985 Emery & Hamilton 1985	O, A	C
1972	ΔW	-	Enfield & Allen 1980	O, A	W
1973	ΔC	ΔW	Emery & Hamilton 1985	A	C
1974	ΔW	-	Wyrtky 1977	O	-
1976	ΔW	ΔW	Norton et al. 1985	O, A	W
1977-78	-	ΔW	Chelton 1981	A	W
1979	-	ΔW	Norton et al. 1985	A	W
1983	ΔW	ΔW	Huyer &Smith 1985 Rienecker & Mooers 1986 Simpson 1992	O, A	ΔW,W
1985	ΔC	ΔC	Anon. 1986	-	ΔC, C
1986	ΔW	ΔW	Kousky 1987, Anon. 1987	O, A	W

ΔW - warming
ΔC - cooling
A - atmospheric forcing
O - oceanic forcing
C - ocean negative anomaly
W - ocean warm anomaly

Table 2. Comparison of warming and cooling events and selected references, which apparently refer to the same events. DEOF1 and DEOF2 (columns 2 and 3) are series of time varying coefficients. Forcing designations in column 5 may be implied by the references and not specifically mentioned.

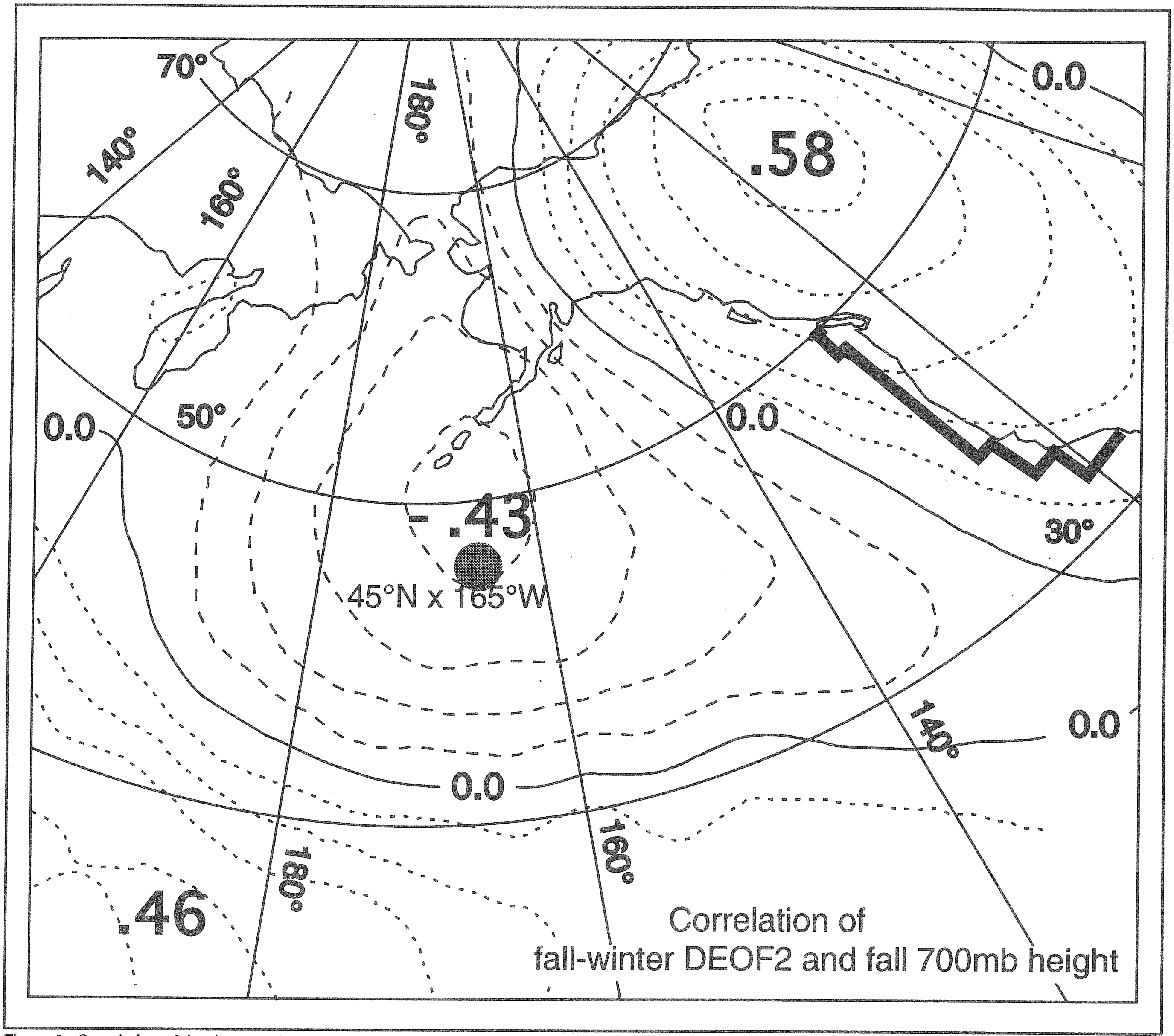

Figure 3. Correlation of the time-varying coefficients for the second EOF (DEOF2) for coastal ocean study area (heavy outline, right) with 700mb height field. Maximum correlations are shown in the largest bold numerals. Dotted and dashed contours show areas of positive and negative correlation, respectively.

magnitude of correlation maxima and minima. So, it appears that the spatial relationships shown in Figure 3 are consistent throughout the annual cycle. However, it is clear that other processes and forcing patterns are involved in changing the ocean temperature in the coastal study region, since upper ocean temperature change associated with EOF2 accounts for 18 percent of the total temperature change variance during spring/summer and 13 percent in fall-winter.

Correlation fields shown in Figure 3 indicate that anomalous west-to-east pressure gradients across the study area produce anomalous temperatures in the ocean surface layers. This is consistent with many previous studies (Table 2). Northward wind associated with such a gradient will lead to Ekman transport of generally warmer offshore water toward shore, creating an oceanic geopotential gradient favoring northward flow along the coast, which may lead to additional warming. Conversely, if the anomalous circulation pattern is reversed, southward wind would be more important in creating a cooler coastal ocean due to upwelling and increased influx of subarctic water from the north. However, wind-forced advection is not the only process creating regional atmospherically forced temperature anomalies in the coastal region. Anomalously strengthened (weakened) cyclonic atmospheric circulation may bring warmer (cooler), more (less) humid air into contact with the coastal ocean, which will lead to warming (cooling) in the ocean surface layers. Wind-forced mixing that penetrates the pycnocline leads to warming at depth and surface cooling. Curl effects associated with anomalous Aleutian Low development may be as important as Ekman transport in creating temperature anomalies in the coastal zone (Haney 1980, 1985; Rienecker and Ehert 1988)

In Figure 3, areas of positive correlation are found west of the date line south of 30°N and over the North American continent. These represent anti-nodes of the Aleutian Low, and overall this pattern strongly resembles the Pacific/North American (PNA) teleconnection (*eg*, Barnston and Livezey 1987). The greater correlation in the subtropical high and western Canada, as compared to the Aleutian Low, may be due to temporal mismatch in ocean DEOF2 (interannual difference) values and the atmospheric fields (single season).

For the single-point atmospheric indicator at 45°N×165°W, the association between coastal ocean temperature changes and the interannual difference of 6-month averages of sea level pressure corrected for the tropical to subarctic teleconnection had correlation coefficients exceeding 0.6 (Norton and McLain 1993). It should be noted that differencing reduces series autocorrelation so that the correlation coefficient values greater than 0.6 represent correlation of year-to-year events rather than longer climatic trends that tend to reduce degrees of freedom. Additional work will focus on comparing the ocean DEOFs with atmospheric fields that have been processed by procedures more similar to those used for the one-point indices.

Biological Interactions

Uda (1962) noted that cyclic abundance of similar commercial fish species on either side of the temperate and subarctic Pacific Ocean correspond to variations in intensity of recurring atmospheric patterns. He also found that boom and bust of commercial fisheries had reverse phasing on either side of the North Pacific. If the area of negative correlation in Figure 3 is taken as approximating the mean dimensions of the Aleutian Low's cyclonic circulation, it can be seen that an increase in the Low's intensity and extent would bring cooling conditions to the western subarctic Pacific. These same atmospheric conditions would bring warming conditions to the eastern subarctic Pacific and the study area (Namias 1959). If the processes that change ocean temperature are associated with species reproductive success in a similar way on either side of the Pacific, then a weakening of the Low would contribute to the success of warm water species in the western Pacific as cooling conditions associated with southward winds inhibited the success of similar species in the eastern Pacific. If the second temperature change mode (DEOF2) gives a time series of atmospherically forced oceanic variation at the eastern Pacific margin, then it might be expected from the work of Namias (1959) and Uda (1962) that a similar atmospherically forced mode would be found in the western Pacific and that these modes might be important in forcing environmental conditions that allow the biological effects described by Uda (1962).

Conclusion

Many studies (Table 2) have attempted to explain anomalous warming and cooling events along the West Coast of North America by considering either regional wind forcing or remote forcing through the ocean. The present work suggests that attempting to base interpretations on one forcing mechanism will fail because regional and remote ocean-atmosphere forces are both important and have characteristic oceanic responses.

Because of the tropical to mid-latitude atmospheric teleconnection (Wallace and Gutzler 1981; Rasmusson and Wallace 1983), negative or positive excursions by DEOF1 and DEOF2 frequently occur together (Figure 2). Note that the tropical El NIño teleconnection pattern in the North Pacific circulation (Rasmusson and Wallace 1983; Branston and Livezey 1987) is not unlike the correlation pattern with EOF2 shown in Figure 3. The existence of an intermittent atmospheric teleconnection makes it possible for statistically reasonable cases to be made for either forcing mechanism alone. However, considering only one forcing mode limits the possibility of a mechanistic description of warming and cooling events in the coastal California Current region. This, in turn, severely limits possibilities for establishing descriptions of biological and physical events with the precision needed to allow conservationally adequate exploitation of the marine environment.

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