# Interdecadal Variability in the Spatial Structure of Wind and SST in the California Current System

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## Introduction

The physical environment of eastern boundary current systems is rarely uniform in time. ENSO and other perturbations produce profound anomalies in the atmosphere and ocean on interannual to decadal and century time scales. Analogously, eastern boundary currents can be separated into discrete spatial regions, dominated by different physical processes, and presumably analogously different biological structure. These regions may be separated by sharp gradients in physical forcing and characteristics or by broad transition zones that extend over several degrees of latitude. The timing and intensity of large-scale climate events may not be coherent between regions.

To better understand how eastern boundary current ecosystems might respond to climate variability, it is crucial to describe their primary scales of spatial and temporal variability and discern the dynamics responsible for this variance, rather than treat eastern boundary currents as spatially homogeneous systems or use seasonally-averaged data to describe their climatology. The objective of this paper is to describe the temporal variability in the spatial texture of the California Current system, a major eastern boundary current system off the west coast of North America, to provide a base from which to evaluate the effect of climate change — in the recent past, at present, and for the future.

State-space statistical models are applied to long environmental time series of wind stress and sea surface temperature (SST) from the California Current (22-48°N) for the period 1946-1990. These data are expressed as monthly averages of the Comprehensive Ocean-Atmosphere Data Set (COADS) for 2° latitude boxes, which extend laterally from the coast to nominally 4° offshore. The models estimate a non-parametric and non-linear trend, a non-stationary and non-deterministic seasonal signal, and an autoregressive term (Schwing and Mendelssohn 1995). The models are applied to long time series of SST from selected coastal sites as well, for comparison to the COADS series.

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## Results

From the state-space model trend series, the California Current can be divided into three distinct geographical regions. The northern region (north of 40°N) features a rapid transition from strongly equatorward to poleward wind stress with distance north (Figure 1). The mean stress north of 44°N is poleward and has become increasingly poleward over time. The transition zone in wind stress has expanded southward over time, strengthening the zonal gradient in poleward stress. The California Current north of 40°N features spatially uniform mean SST (Figure 2). These SST trends show a series-length cooling tendency. This region of uniform SST has expanded southward over time as well.

Winds south of 40°N are equatorward and can be described in terms of central and southern regions (Figure 1). The central region (32-40°N) exhibits the greatest wind stress magnitudes in the California Current.

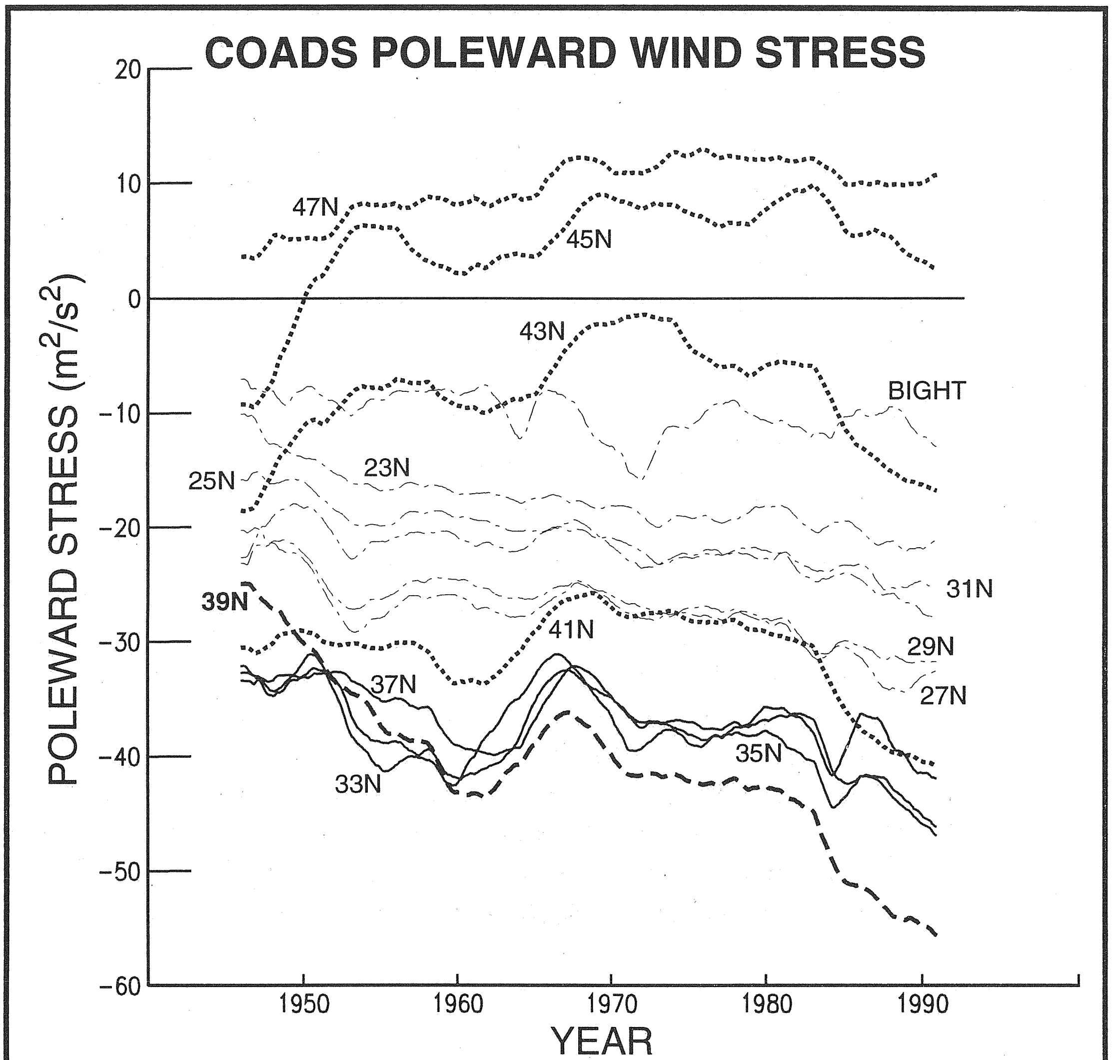


Figure 1 Time series of poleward wind stress trends for COADS boxes. Values denote center latitude of COADS boxes. Dashed-dotted lines represent time series from southern region (22-32°N). Solid lines represent time series from central region (32-40°N). Bold dotted lines represent time series from northern region (40-48°N). Bold dashed line represents 38-40°N time series.

Equatorward stress has intensified over time more here than in the northern and southern regions. This region features the greatest scales of interannual-to-decadal variation in stress (Figure 1) and SST (Figure 2) as well. Stress in the southern region (22-32°N) has become increasingly equatorward over time in a monotonic pattern, with relatively little interannual variation. Mean SST decreases consistently with increasing latitude in the central and southern regions. SST over about 30-38°N appears to warm rapidly in response to the 1957 and 1983 ENSO events as well as the well-documented 1976 regime shift (cf. Trenberth 1990). SSTs off Washington and Oregon (40-48°N) and most of Baja California (south of 30°N), on the other hand, take several months to years following the 1976 shift to warm by similar amounts.

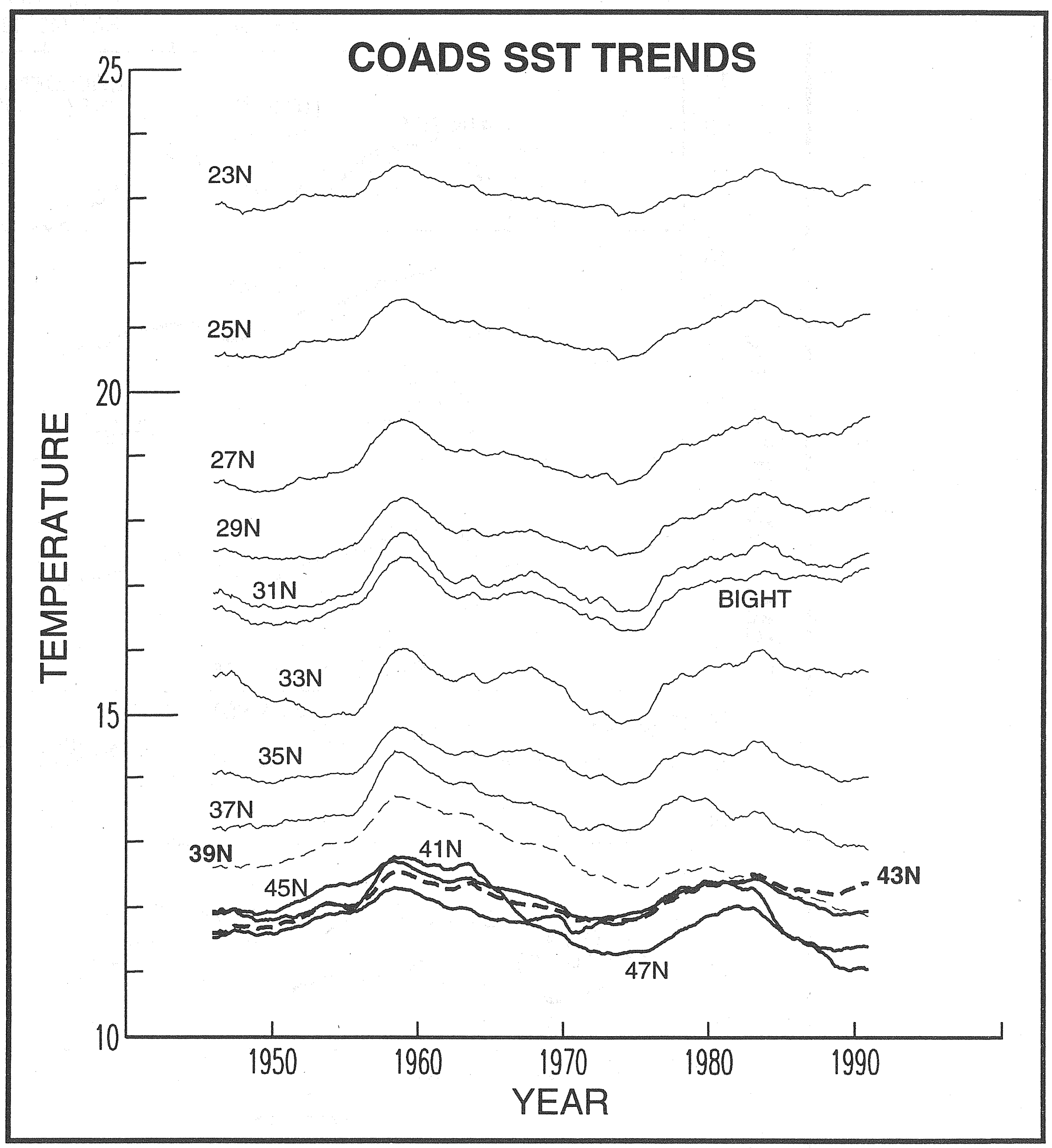


Figure 2 Time series of SST trends for COADS boxes. Fine lines denote time series south of 40°N. Bold lines denote time series north of 40°N. Fine and bold broken lines denote time series for 38-40°N and 42-44°N COADS boxes, respectively.

Although shore-based SST trends along the entire United States west coast display a significant warming tendency over the past several decades (Figure 3), the COADS (*ie,* California Current) SSTs show a cooling tendency north of 36°N (Figures 2 and 3). On shorter time scales, SST has decreased significantly since the 1983 ENSO north of about 34°N, but SSTs south of about 32°N have returned to near 1983 levels after a brief period of cooling following this event. The entire California

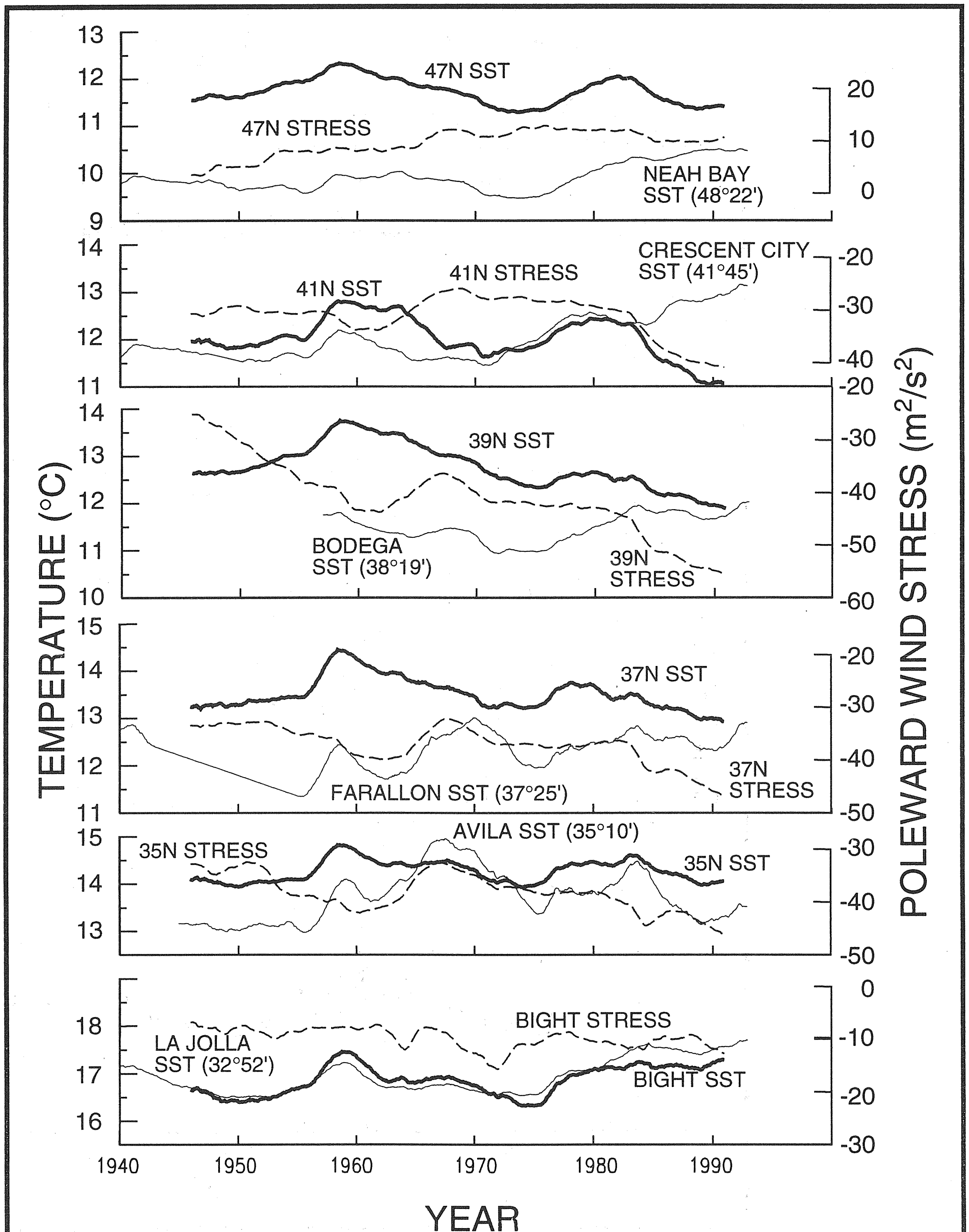


Figure 3 Trend time series of COADS SST and poleward wind stress, compared with selected nearby coastal SST series. Bold solid lines represent COADS SST series. Fine solid lines represent coastal SST series. Broken lines represent wind stress series. Location of time series shown in each plot.

Current warmed and cooled system-wide on decadal time scales prior to 1983, but displays a more heterogeneous pattern since 1983. A lack of correspondence between the 2° COADS and coastal SST time series north of about 34°N (Figure 3) suggests there is considerable cross-shelf as well as latitudinal variability in the California Current. This is confirmed by examination of the COADS data on 1° space scales (Schwing *et al* 1995).

SST trends are visually more correlated on interannual scales than wind stress trends. Major ENSOs and the 1976 regime shift dominate the SST trends series, particularly south of 38°N, but are not apparent in the wind trends. Instead ENSO wind variance is seen more clearly in the model autoregressive and error components of the state-space model, presumably because of the rapid atmospheric response to ENSO events. Multi-year perturbations in the wind trend series do occur (cf, 32-40°N, Figure 1) but are not coincident with ENSO or other documented large-scale atmospheric events. SST also shows decadal-scale periods of warm and cool anomalies that extend through the entire California Current. Wind stress anomalies are less extensive latitudinally and uncorrelated with local SST (Figure 3), suggesting that decadal-scale SST variability in the California Current is controlled by the basin- to global-scale pressure and wind fields, rather than local wind forcing.

## Discussion

The different regions of the California Current, as described above, and the likely relationship between wind forcing and SST on long time scales are illustrated in Figure 4. The figure shows the slopes (±99% C.I.) of linear fits to the time series of poleward stress and SST in each COADS box (*ie,* the linear tendency of each trend series). The correlation between poleward stress and SST is positive in much of the central region. A statistically significant tendency for increasing equatorward stress coincides with a cooling trend in SST. A reasonable explanation for this is that the increasing equatorward stress leads to greater offshore Ekman transport and more coastal upwelling that cools the surface waters of the California Current at these latitudes. This region coincides roughly with the geographic range of the upwelling maxima along the west coast. Increasing equatorward stress also would contribute to cooler SST through greater turbulent mixing of the upper ocean and could be associated with increased south- ward transport of cool water by the California Current. Changes in Ekman divergence and wind curl may be occurring as well. The influence of mixing and wind gradients on SST is the focus of ongoing analysis.

Outside of the central region, however, the trends in stress and SST are negatively correlated. Increasing equatorward stress coincides with warming SST south of 34°N, while greater poleward stress accompanies a cooling trend north of 44°N. The cooler SSTs off Oregon and Washington (north of 42°N) may be due to greater wind mixing (Schwing *et al* 1995). Greater poleward stress could be linked to a larger (gyre) scale pattern in atmospheric circulation, such as the documented intensification of the Aleutian Low in 1976, which could lead to fundamental changes in the region's ocean circulation. Long-term changes in wind curl could impact

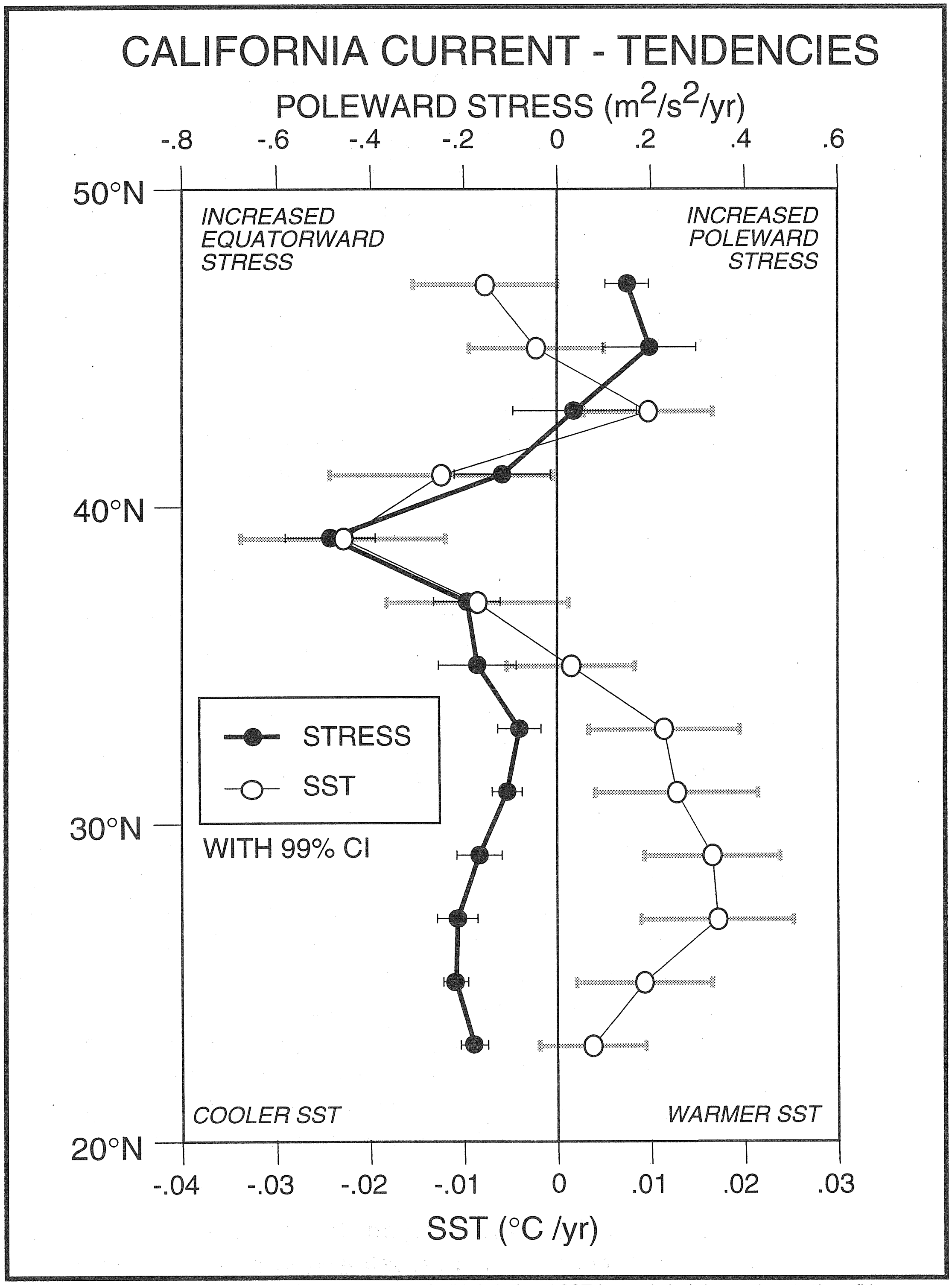


Figure 4 Slopes of a linear fit to COADS poleward stress (solid circles) and SST (open circles) time series. 99% confidence intervals shown by vertical bars (gray for stress, black for SST).

SST as well. We suspect that the transitional region between the Subarctic and California Currents could be extending southward, based on the expanding region of high northward wind stress divergence (Figure 1) and spatially uniform SST (Figure 2). This would be consistent with cooler SSTs.

The relationship between wind stress and SST in the southern region is less straightforward. Roemmich and McGowan (1995) present results consistent with ours for southern California, and speculate that increasing stratification over the last 45 years (due to an increasing heat flux from the atmosphere into the upper ocean) has led to shallower upwelling and a smaller "cooling" effect from increasing upwelling- favorable stress. The extension of this idea to the region farther north implies a different dynamical balance, such that increased stratification of surface water, a consequence of atmospheric warming, is overwhelmed by the contribution of wind in driving more cool water from ocean depths into, and/or vertical mixing of, the surface layer of the California Current.

It is apparent that over the last several decades, surface waters in the California Current south of 34°N have experienced a different set of forcing conditions from those farther north. Not only are the tendencies of wind and SST different in these regions of the California Current, but the changing linear relationship between stress and SST implies that the primary mechanisms that drive variability in SST, and probably the general ocean circulation, on decadal time scales is fundamentally different in these regions. It is not possible to develop a more firm conclusion about the mechanisms leading to these tendencies without a more thorough three-dimensional analysis of the temporal variability of wind vector fields over the north Pacific Ocean. A complex interaction of spatially as well as temporally varying Ekman transport, wind mixing, and direct heating appears to be responsible for the long-term fluctuations in SST in the California Current.

The temporal and spatial variability of the physical environment of the California Current must be considered when analyzing changes in the biological structure of this and other eastern boundary current ecosystems. Roemmich and McGowan (1995) have found that zooplankton biomass off southern California has decreased by 80% since 1951, while the surface layer has warmed by more than 1.5°C over the same time. They suggest this decrease is due to an increase in stratification of the surface layer, which has led to a shallower, hence lower nutrient, source of upwelling. However, their observations, which are in accord with our analysis of COADS data in the southern region, are restricted to south of 35°N. The results reported here show that regional differences in environmental variability have existed in the California Current over the last five decades; therefore it is conceivable that analogous differences in biological productivity have occurred as well. Specifically, Roemmich and

McGowan note a correlation between declining zooplankton biomass and increasing near-surface temperature and stratification. This model implies that biomass could be increasing in the northern California Current in association with the cooling tendencies of the COADS SST series.

Some of the observed substantial anomalies (*eg,* 1965-75, Figure 3) in the California Current are unrelated to well-defined climate events such as ENSO. Nevertheless, these periods of unusual environmental conditions are likely to have significant ecosystem consequences. "Warm" years, when conditions off California are similar to those during ENSO events despite the absence of an equatorial ENSO signal, are linked to poor recruitment of central California rockfish, while "cool" years feature enhanced recruitment (S.V. Ralston, Tiburon, NMFS, pers. comm.). Extreme year classes of several species of fish over large geographical areas tend to occur in association with unusual environmental conditions (Hollowed and Wooster 1992).

The results presented here clearly demonstrate the highly variable nature of the California Current environment in time and space, and argue against oversimplifying eastern boundary current climate change as a constant linear trend, or in terms of a record from a single location. The distinct latitudinal regionalization and cross-shelf variability of the California Current wind and SST fields has key implications for ecosystems studies as well as fisheries management. For example, which time series or regions are more important to study in terms of defining a stock's environment? Regional differences also mean that widespread stocks, or stocks that are highly migratory over their life history, face a spatially heterogeneous changing climate. Fisheries scientists must evaluate the relative environmental differences in each region, as they pertain to the climate signal and its variability, and compare them to a species' distribution and behavior as a function of life stage, to fully understand the consequences of climate change on populations. Widespread stocks also may display a very different long-term variability from species whose domain is limited to one of the homogeneous regions of the California Current described here.

In closing, the long-term trends described here cannot be considered without considering changes in seasonal patterns. Mendelssohn and Durand (1995) provide an eloquent discussion of how climate change can be interpreted in a number of ways. Schwing and Mendelssohn (1995) highlight an example of how seasonal changes over long time scales can have a clear signal that is independent of patterns in the model trend series described here. State-space models are a powerful tool for separating interannual-to-interdecadal fluctuations in environmental time series from seasonal patterns of variability. The results presented here demonstrate the importance of evaluating the entire spectrum of temporal and spatial variability, rather than simply at global climate scales, when examining long-term environmental fluctuations. This will improve our understanding of the linkages between long-term variations in atmospheric forcing and the coastal ocean's response to this variability on regional scales, and ultimately an improved assessment of the impact of climate variability on living marine resources.

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