

EL NIÑO AND RELATED VARIABILITY IN SEA-SURFACE TEMPERATURE ALONG THE CENTRAL CALIFORNIA COAST

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Abstract. Sea-surface temperature along the central California coast contains interannual variability primarily associated with El Niño episodes. Sea-surface temperatures at Granite Canyon from 1971 to 1985 reveal four periods of sea-surface warming which coincide with tropical El Niño occurrences. El Niño related increases in sea-surface temperature at Granite Canyon are examined using two-way layouts of the monthly means and standard deviations, an anomaly analysis, and empirical orthogonal functions. These techniques were well-suited to the task of isolating and enhancing the El Niño influence. Two-way layouts of the monthly means and standard deviations, the mean annual anomaly for the El Niño years, and empirical orthogonal functions indicate that El Niño related warming is seasonal, being strongest in the fall and winter and weakest during the spring. Analysis of shorter term variability suggests that a recently discovered 40- to 50-day oscillation in sea-surface temperature along central California, and spring transitions to coastal upwelling may be related to, or at least influenced by, El Niño episodes at mid-latitudes. Finally, sea-surface temperatures at Pacific Grove, inside Monterey Bay, are not as representative of oceanic conditions along central California as are the observations acquired at Granite Canyon. However, sea-surface temperature at Pacific Grove is a useful indicator of events and processes that occur in and around Monterey Bay.

Introduction

Oceanic variability on interannual time scales is of major importance along the west coast of North America [Hubbs, 1948; Roden, 1963]. El Niño episodes contribute strongly to this variability at mid-latitudes along the California coast [Enfield and Allen, 1980; Chelton and Davis, 1982; Chelton et al., 1982]. This variability is manifested in the California Current System (CCS) at the surface and at subsurface levels to depths of several hundred meters [Rienecker and Mooers, 1986]. It is clearly revealed in a number of physical properties including coastal wind [Norton et al., 1985], sea level [e.g., Enfield and Allen, 1980], alongshore currents [Huyer and Smith, 1985], salinity [e.g., McGowan, 1984], and sea-surface temperature [e.g., Breaker and Mooers, 1986].

Sea-surface temperature at various coastal locations has been examined in a number of studies of long-term variability in the CCS. From spectral analysis of multiyear records of sea-surface temperature (and salinity) Roden [1961] found that most of the nonseasonal variance in these properties is concentrated at frequencies below one cycle per year. Based on a statistical analysis of 26 years of sea-surface temperature acquired along the west coast of the United States, Roden [1963] concluded that (1) the only significant periodicity in sea-surface temperature was due to the annual cycle, (2) non-

annual fluctuations of extreme temperatures were reasonably coherent over distances of several hundred km, and (3) the magnitude of the largest extremes in temperature increased with increasing return period. More recently, McLain et al., [1985] concluded that El Niño related anomalies in sea-surface temperature are often spatially coherent from Chile, in the southern hemisphere, to British Columbia, in the northern hemisphere. These anomalies may occur quasi-simultaneously off Peru and California.

Based on 12 years of daily sea-surface temperatures acquired in Granite Canyon along the central California coast (Figure 1), Breaker et al., [1984] found that (1) El Niño influence on coastal sea-surface temperature produces higher-than-average temperatures during the fall and winter, (2) during El Niño episodes, mean annual sea-surface temperature are significantly

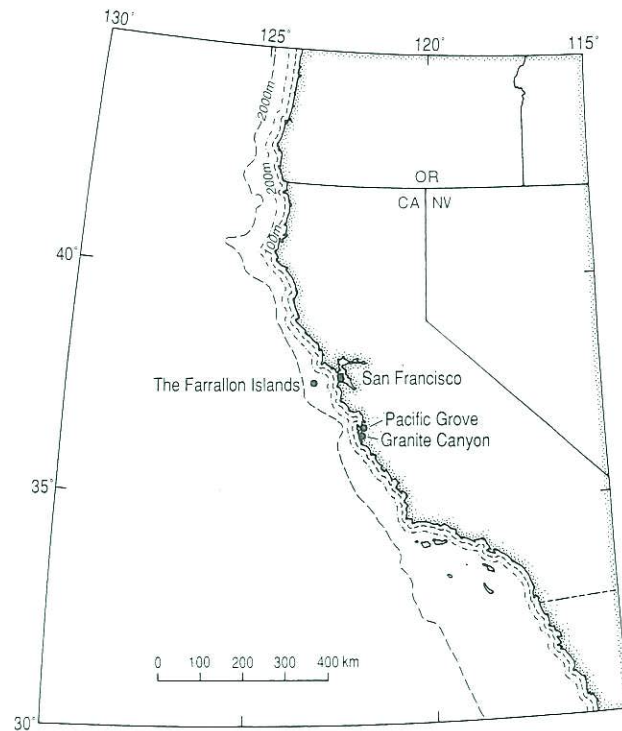


Fig. 1. Locations of the sea-surface temperature acquisition sites at the Farrallon Islands, Pacific Grove, and Granite Canyon along the central California coast.

higher than normal (0.5–1.0 °C), and (3) because of their frequency of occurrence, duration, and intensity these episodes must be considered a major contributor to interannual variability in sea-surface temperature at mid-latitudes along the California coast. Breaker and Mooers [1986] found over the 12-year period from 1972 through 1983 that El Niño influence along the central California coast was present approximately 30 percent of the time.

In the present study several analyses of sea-surface temperature data acquired at Granite Canyon are presented in an effort to provide better resolution of the El Niño episodes that occur. Also of major interest is the seasonal dependence associated with the El Niño signal. Primarily because El Niño related variability is inherently nonperiodic, but also because our data span only four El Niño episodes, the data used in this study are not well suited to standard spectral analysis techniques. Consequently, we consider alternate analysis methods to accomplish our objectives. These analyses include (1) two-way layouts of the monthly means and standard deviations, (2) an anomaly analysis, and (3) empirical orthogonal functions (EOFs). Possible connections between El Niño episodes and shorter term variability, including (1) the recently discovered 40- to 50-day oscillation in sea-surface temperature [Breaker and Lewis, 1988] and (2) the often abrupt spring transition to coastal upwelling, are considered. Finally, the representativeness of sea-surface temperature acquired at Pacific Grove is considered through comparisons with the data from Granite Canyon.

The Data

Daily sea-surface temperatures have been acquired by the California Fish and Game Commission's Marine Culture Laboratory at Granite Canyon, located 11 km north of Point Sur and about 25 km south of Pacific Grove (Figure 1), since March 1, 1971. Granite Canyon has an excellent exposure to the deep ocean with the Continental Shelf extending only 6 km offshore at this location. Because of its proximity to deep water the influence of the predominant semidiurnal tide is expected to be small. The daily observations are taken at approximately 1600 UT.

Daily sea-surface temperatures have been acquired since January 1, 1919 (except for 1940), at the Hopkins Marine Station in Pacific Grove. This monitoring site is located inside Monterey Bay in relatively shallow water.

Temperatures at both locations are read to the nearest 0.1 °C using a calibrated immersion thermometer. Measurement accuracy is reported to be plus or minus 0.2 °C [Scripps Institution of Oceanography Reference 81–30,

1981]. Leap days that occurred during 1972, 1976, 1980, and 1984 have been removed from the data at both locations. Because the calculations contained herein have been performed over the past 4 years, a period over which the Granite Canyon time series itself has increased in length, the record lengths for the various analyses presented vary slightly. However, it is felt that these slight differences in record length (12 versus 15 years, in the extreme) should not significantly affect the results.

Interannual Variability at Granite Canyon

The time series of daily sea-surface temperature at Granite Canyon starting on March 1, 1971, and ending on February 28, 1985, is shown in Figure 2. Each El Niño episode occurring between 1971 and 1985 is indicated by a vertical arrow (1972–1973, 1976–1977, 1979–1980, and 1982–1983). The 1972–1973 El Niño was classified as a strong episode based on a variety of environmental indicators off the Peruvian coast [Quinn et al., 1978]. According to the same indicators, the 1976–1977 El Niño was classified as an episode of moderate intensity. By any standard the 1982–1983 El Niño episode was exceptionally strong. Even the relatively weak El Niño of 1979–1980, which was mainly observed in the western and northeastern Pacific [Donguy et al., 1982], can be identified in the raw data.

Abrupt decreases in temperature also occurred in 1973, 1977, 1980, 1981 and correspond to the spring transition to coastal upwelling. The spring transition is a major event along the coasts of California and Oregon in certain years that signals the seasonal change from nonupwelling to upwelling conditions [Huyer et al., 1979]. A discussion of the spring transition in sea-surface temperature along the central California coast was presented previously [Breaker and Mooers, 1986].

To examine El Niño influence on sea-surface temperature on a seasonal and an annual basis two-way layouts of the monthly mean values and the corresponding standard deviations within each month were calculated for the period from March 1, 1971, to March 1, 1983 (Figures 3 and 4). These two-way layouts were constructed as follows: The distribution of monthly means (standard deviations) by month and year are plotted along each of the two horizontal axes and their magnitudes along the vertical axis, yielding a three-dimensional display. Relatively high values of the monthly means generally coincide with each of the El Niño episodes (indicated by large dots). These higher monthly means also tend to occur during the fall and winter between September and February. The monthly means were also

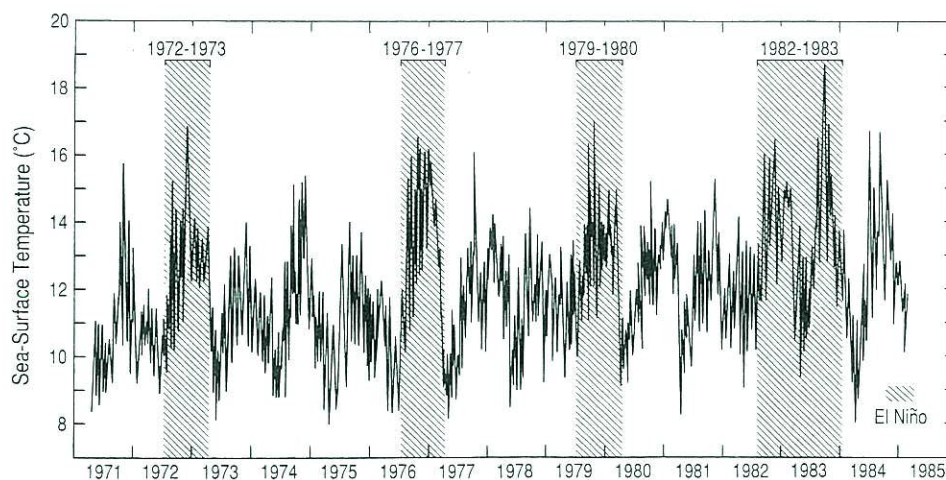


Fig. 2. Daily sea-surface temperatures at Granite Canyon from March 1, 1971, to March 1, 1985. El Niño episodes occurring during this period are indicated by vertical arrows.

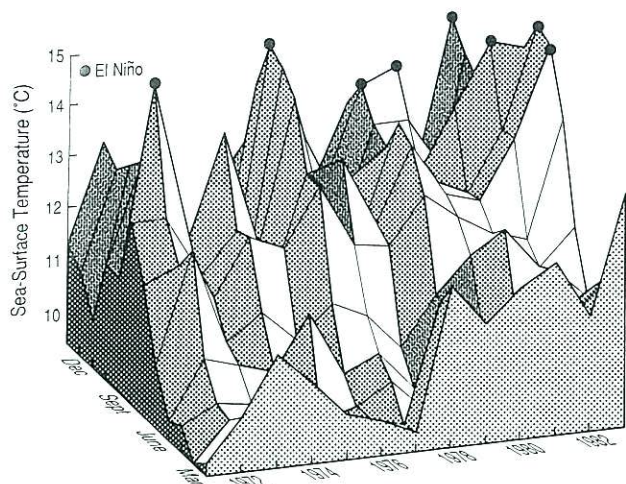


Fig. 3. Two-way layout of monthly mean sea-surface temperatures from March 1, 1971, to March 1, 1983. Large dots identify peak values associated with El Niño episodes.

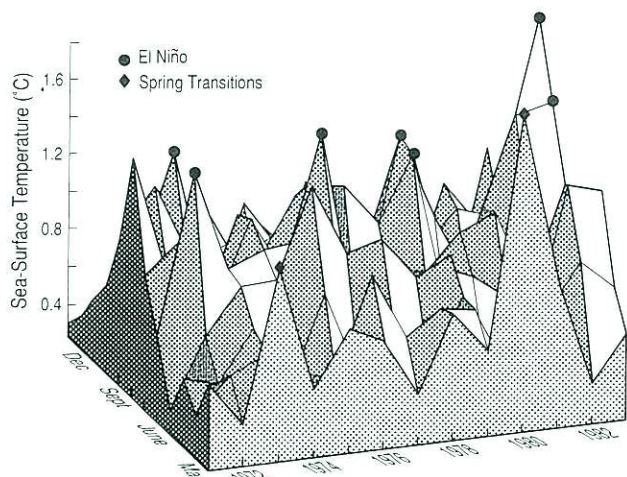


Fig. 4. Two-way layout of within-month standard deviations of sea-surface temperature from March 1, 1971, to March 1, 1983. Large dots identify peaks associated with El Niño episodes. Diamonds identify peaks associated with spring transition events.

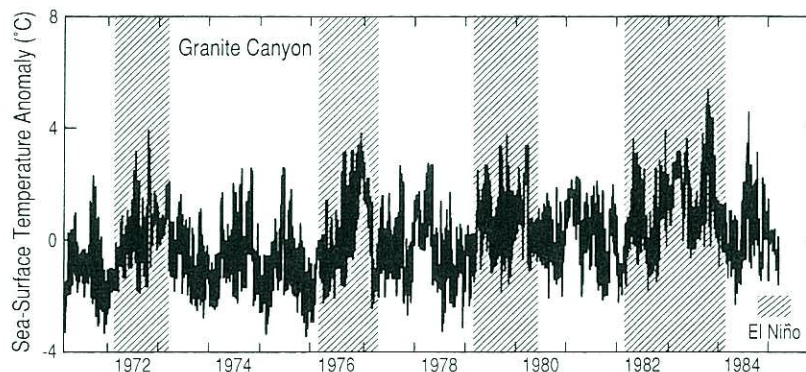


Fig. 5. The daily anomaly in sea-surface temperature at Granite Canyon from March 1, 1971, to March 1, 1985. The periods of El Niño influence are indicated by the cross-hatching.

averaged across months (not shown). From 1972 to 1983 higher annual mean temperatures (on the order of 2 °C) occurred during the El Niño episodes.

Figure 4 shows the two-way layout of within-month standard deviations. Although the background variability is higher in this case, higher standard deviations often occurred during the previously identified El Niño periods and again during the fall and winter (large dots). Particularly high standard deviations occurred in the latter half of 1982. Additionally, larger standard deviations occurred in March 1973 and March 1980 (diamonds). Major spring transitions to coastal upwelling occurred in those months, events which undoubtedly contributed to these high values (see section on Spring Transitions).

The data from Granite Canyon are now analyzed with respect to the anomaly in sea-surface temperature based on the departure from the mean annual cycle calculated over the 14-year period from March 1, 1971, to March 1, 1985. First, the anomaly itself is determined. Then a mean annual anomaly is calculated for the El Niño years to examine the seasonal dependence of the El Niño signal. Finally, the anomaly is integrated over the length of record to provide a cumulative anomaly versus time. The integrated anomaly is calculated in order to enhance longer term variability in the data.

The anomaly in sea-surface temperature is shown in Figure 5, and the mean annual cycle upon which it is based is shown in Figure 6 (upper panel). The anomaly reveals significant positive departures during the El Niño years with the greatest positive departures (up to plus 5 °C) occurring during 1983. Positive anomalies are not restricted to the El Niño years, as indicated by the positive values that occurred during 1974 and 1984. The positive anomaly in 1984, however, may still be related to the 1982–1983 episode even though its primary signature in the tropics was essentially no longer detectable [Quiroz, 1984].

The mean annual cycle in sea-surface temperature at Granite Canyon (smoothed using a triangular weighting function with nine weights) indicates an annual range of about 3.5 °C. Minimum values occur during April and May when coastal upwelling is maximum, and maximum values occur during the early fall when solar heating and the onset of the Davidson Current combine to produce maximum temperatures. These processes, in their entirety, suppress the annual range of temperatures along the central California coast when compared with the annual range sea-surface temperatures at similar latitudes further offshore [Reid et al., 1958].

The annual anomaly (smoothed as before) has been calculated for the El Niño years (Figure 5) and shows a strong seasonal dependence (Figure 6, lower panel). A positive anomaly greater than 1 °C occurs from October through February with a maximum in October. A sudden decrease in the anomaly occurs at the beginning of March and coincides with the spring transition to coastal upwelling (see section on Spring Transitions). Even during the period of seasonal upwelling, however, sea-surface temperatures are slightly above normal (approximately 0.3 °C).

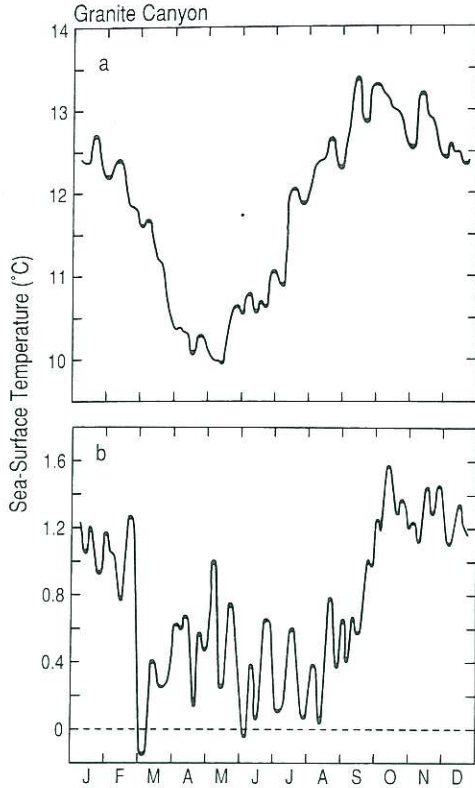


Fig. 6. Mean annual cycle in sea-surface temperature at Granite Canyon smoothed using nine weights with a triangular taper (upper panel). The mean annual anomaly in sea-surface temperature at Granite Canyon for the El Niño years (see previous figure) smoothed using nine weights with a triangular taper (lower panel).

The integrated anomaly is shown in Figure 7 (upper panel). In calculating the integrated anomaly some phase shift has most likely been introduced with respect to the original time series. However, alignment of the original time series with the integrated series indicates that this phase shift is small (on the order of a month or less). The integrated anomaly is negative throughout the period of observation except during 1984 and 1985. Over the period 1971–1985 the integrated anomaly gradually decreases until 1976 and by 1979 begins to increase. Abrupt increases in the integrated anomaly also occurred during each of the El Niño events.

To better isolate the El Niño occurrences, a second-degree polynomial was fitted to the integrated anomaly using the method of least squares and then removed, yielding the residual time series shown in the lower portion of Figure 7.

Removal of the polynomial trend clearly accentuates the El Niño occurrences. Rapid but similar increases in the integrated anomaly occur during each El Niño period, which help to delineate and characterize these events. In each case these abrupt increases last for about 8 months and have overall amplitudes that vary between plus 200 degree days (1979–1980 episode) and plus 450 degree days (1982–1983 episode). The double hump associated with the 1982–1983 episode illustrates the relatively long duration of this event.

The second degree polynomial provided a good fit to the data (goodness-of-fit nearly equal to 90 percent), obtaining only slight improvements in the fit for higher degree polynomials. As a result, the long-term trend in the integrated anomaly suggests that sea-surface temperatures at this location were generally increasing over the 14-year period, since differentiation of

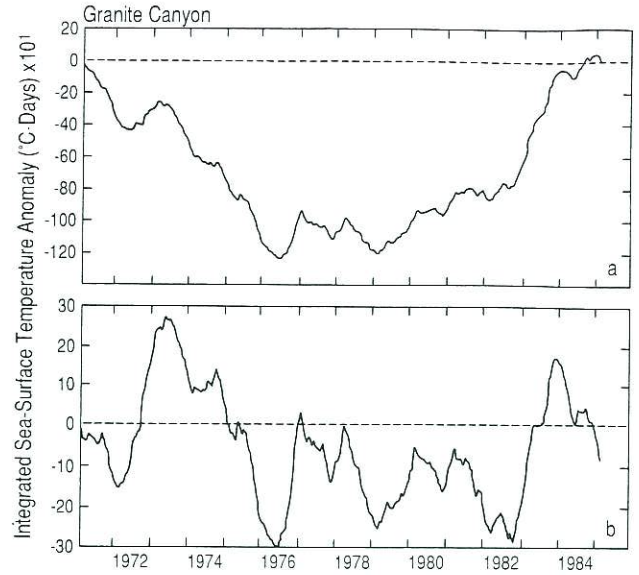


Fig. 7. Integrated anomaly of sea-surface temperature at Granite Canyon (March 1, 1971, to March 1, 1985) based on the mean annual cycle (upper panel). Removal of a second degree polynomial (fitted by least squares) from the data yields the residuals shown below (lower panel).

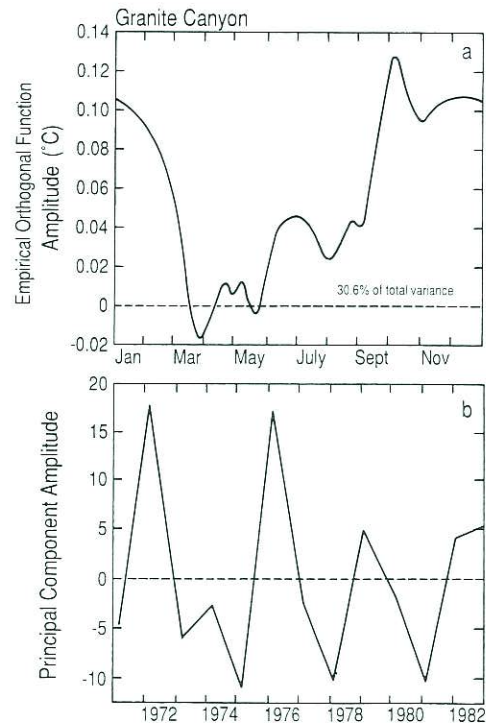


Fig. 8. First empirical orthogonal function (EOF) eigenvector (upper panel) and principal components (lower panel) of sea-surface temperature at Granite Canyon from March 1, 1971, to March 1, 1983 (adapted from Breaker and Mooers [1986]). The 12-year record was broken up into 12 one-year time series in order to calculate the EOFs. The first EOF has been smoothed.

a second degree equation (i.e., the polynomial function that is used to approximate the integrated anomaly) yields a first degree equation with a positive slope, and thus temperatures that increase with time. This interpretation agrees with the results of Breaker et al. [1983] who found a statistically significant positive linear trend for the first 12 years of data at Granite Canyon.

A time domain EOF analysis of the first 12 years of daily sea-surface temperatures at Granite Canyon (March 1, 1971, to March 1, 1983) provides an alternate basis for examining El Niño influence along the central California coast (Figure 8, adapted from Breaker and Mooers [1986]). Each year was treated as a separate time series in this analysis. A long-term trend and a mean annual cycle were first removed before the EOFs were calculated. The first EOF, which accounted for about 31 percent of the total variance, shows that most of the variance occurs between October and February. That this seasonal increase in variance occurs during El Niño periods is shown by the time varying EOF amplitudes that have peaks in 1972, 1976, and 1979. These results are consistent with the previous two-way layouts and the annual anomaly. In fact, the shape of the first EOF is very similar to the shape of the annual anomaly, even to the extent of reproducing the peak that occurs in October.

Interestingly, a similar EOF analysis, which included data to March 1, 1984, did not resolve the El Niño influence as well as the original 12-year analysis that only partially included the 1982–1983 event. In particular, the variance associated with the first EOF was not clearly concentrated between October and February, a result most likely due to the fact that the 1982–1983 episode spanned a period of at least two years, and that its influence was strongly felt during the spring and summer of 1983.

Forty to Fifty-Day Oscillations in Sea-Surface Temperature

Forty to fifty-day oscillations in sea-surface temperature have recently been detected along the central California coast [Breaker and Lewis, 1988]. Spectral analysis of sea-surface temperature at Granite Canyon and Pacific Grove both indicate the presence of these oscillations. Spectral analysis of

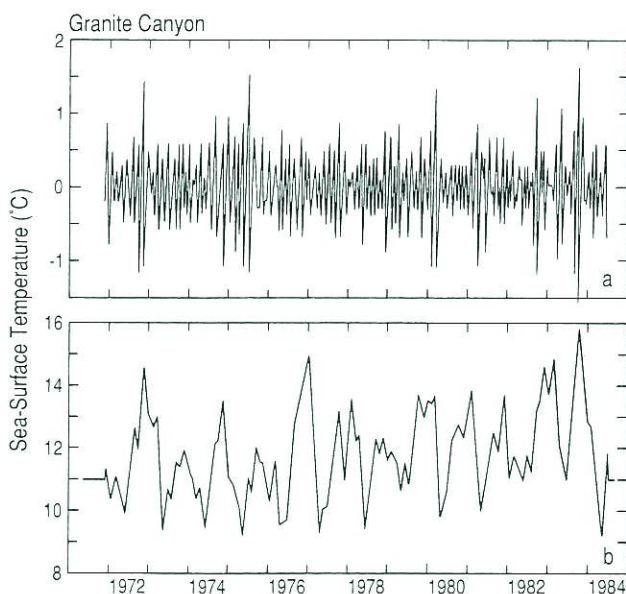


Fig. 9. Sea-surface temperature at Granite Canyon from March 11, 1971, to June 25, 1984, filtered within a pass-band extending from 0.0143 cycles per day (i.e., 70 days) to 0.0333 cycles per day (i.e., 30 days). A lowpassed version of this series is shown for comparison (lower panel); after Breaker and Lewis, [1988].

sea-surface temperature at other locations along the California coast indicate that this oscillation may not be present off southern California (below approximately 34° N.), but that it is present at least as far north as Point Arena (approximately 39° N.).

Breaker and Lewis showed that these oscillations are most likely forced by the local winds. Winds at 850 mb in the eastern Pacific also reveal oscillations in the 30- to 60-day range, oscillations which may originate in the tropics [Knutson and Weickmann, 1987].

To demonstrate the possible connection between the 40- to 50-day oscillation in sea-surface temperature off central California and El Niño occurrences, Breaker and Lewis compared a band-pass filtered version of sea-surface temperature at Granite Canyon centered at 47 days with a smoothed version of the same series (Figure 9). Peak amplitudes associated with the 40- to 50-day oscillation (i.e., the band-pass filtered data) occurred in 1972, 1975, 1980, 1983 and generally coincide with the El Niño episodes during that period. A clear exception occurred in 1975 where the 40- to 50-day peak precedes the 1976–1977 El Niño by at least one year.

If a connection does, in fact, exist between the intensity of the 40- to 50-day oscillation in sea-surface temperature off central California and El Niño episodes, an exact correspondence in time between these phenomena should not necessarily be expected since the 40- to 50-day oscillation appears to originate in the atmosphere, whereas mid-latitude El Niño warmings are the result of both atmospheric and oceanic linkages [Wallace, 1985].

Spring Transitions

Frequently the change from winter (nonupwelling) to spring (upwelling) conditions occurs abruptly along the west coast of the United States. This change, which is referred to as the spring transition [Huyer et al., 1979], usually occurs between February and April. The transition is characterized by an abrupt decrease in sea-surface temperature on the order of 3 °C and lasts for about a week. This event has been uniquely identified in sea-surface temperature in about half of the years since 1971 at Granite Canyon.

A spring transition occurred in March 1980, and the daily sea-surface temperatures for that year are shown for Granite Canyon, Pacific Grove, and the Farallon Islands (Figures 1 and 10). A sudden, large drop in sea-surface temperature occurred during March at each location. On closer inspection, however, the time of occurrence is later and the magnitude of the drop is less at Pacific Grove compared to Granite Canyon and the Farallon Islands. This event starts more-or-less simultaneously at Granite Canyon and the Farallons, but its onset is delayed by almost 10 days at Pacific Grove. Following this event cooler temperatures, which are primarily attributed to coastal upwelling, persist for several months at each location.

Spring transitions also occurred in 1973 and 1977 and are shown separately with the 1980 spring transition at Granite Canyon (Figure 11). Although the spring transition in 1977 is not as pronounced as the ones occurring in 1973 and 1980, a rather abrupt decrease in sea-surface temperature does occur during the last week of February in that year. In each case these spring transitions follow El Niño episodes. Part of the explanation for the occurrence of these relatively intense spring transitions lies in the fact that anomalously warm waters were present along the central California coast just prior to the seasonal change to coastal upwelling (see Figure 5, for example). Thus relatively large decreases in temperature might be expected to accompany these particular spring transitions. However, it is not clear why they should have occurred so abruptly, an attribute that additionally added to their intensity. We note that a clearly identifiable spring transition in sea-surface temperature did not follow the 1982–1983 episode (although a more gradual and lesser decrease in temperature can still be seen during the spring of 1983, see Figure 2). The lack of a distinct spring transition during the spring of 1983 may have been due to the overall intensity of this episode. Due to its intensity, coastal upwelling was significantly weaker during the spring and summer of 1983, and, thus coastal sea-surface temperatures remained higher than normal during that period.

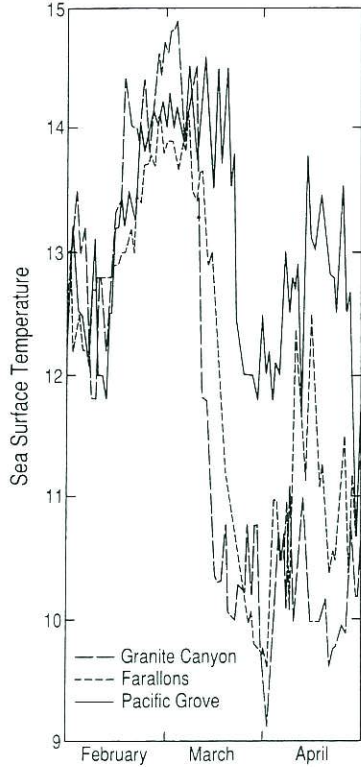


Fig. 10. Spring transition in daily sea-surface temperature during March 1980 at Granite Canyon, Pacific Grove, and the Farallon Islands. The abrupt decrease in sea-surface temperature associated with the 1980 spring transition occurred at Granite Canyon and the Farallon Islands approximately 10 days before it occurred at Pacific Grove.

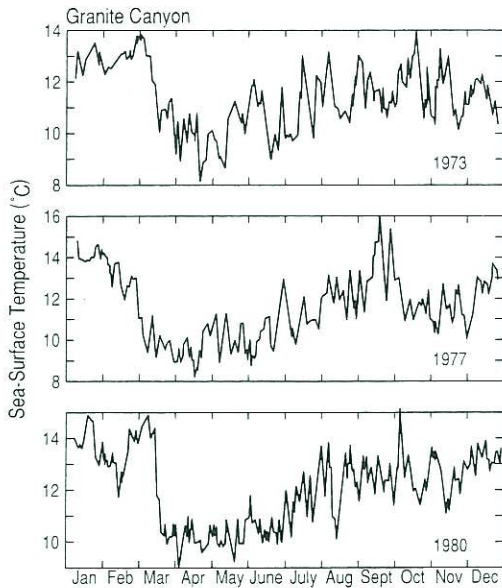


Fig. 11. Spring transitions in sea-surface temperature at Granite Canyon following the 1972-1973, 1976-1977, and 1979-1980 El Niño episodes.

Sea-Surface Temperature at Pacific Grove

Sea-surface temperatures at Pacific Grove have been used extensively in studying oceanic variability along the west coast of the United States because of its location along the central California coast, and because daily observations have been acquired almost continuously there since 1919 [Robinson, 1957; Robinson, 1960; Roden, 1961; Roden, 1963; List and Koh, 1976]. Robinson [1960] and Roden [1963], for example, both demonstrated that these data reflect interannual variability along the central California coast.

Although sea-surface temperature at Pacific Grove reflects interannual variability, variability that is often related to El Niño occurrences, its sheltered location inside Monterey Bay reduces its sensitivity to these occurrences and increases its sensitivity to events and processes that occur locally.

A comparison of slightly smoothed sea-surface temperatures at Granite Canyon and Pacific Grove for the same 12-year period (March 1, 1971, to March 1, 1983) shows the reduction in sensitivity to El Niño warmings at Pacific Grove compared to Granite Canyon (Figure 12). Both series have been smoothed using a cosine-tapered smoothing function with 81 weights. The peak-to-peak variations from one year to the next are greater at Granite Canyon than at Pacific Grove. Because the annual peaks in temperature often reflect El Niño influence, we tabulated peak values from each series and calculated the associated entropies (not to be confused with the entropy from thermodynamics). The entropy provides a quantitative measure of information content [Schwartz, 1959]. In this case these entropies were based on the probabilities of occurrence of the peak temperatures within a specified range, and thus may be expressed as

$$H = -\sum_{n=1}^N p(n) \text{Log}_e p(n) \tag{1}$$

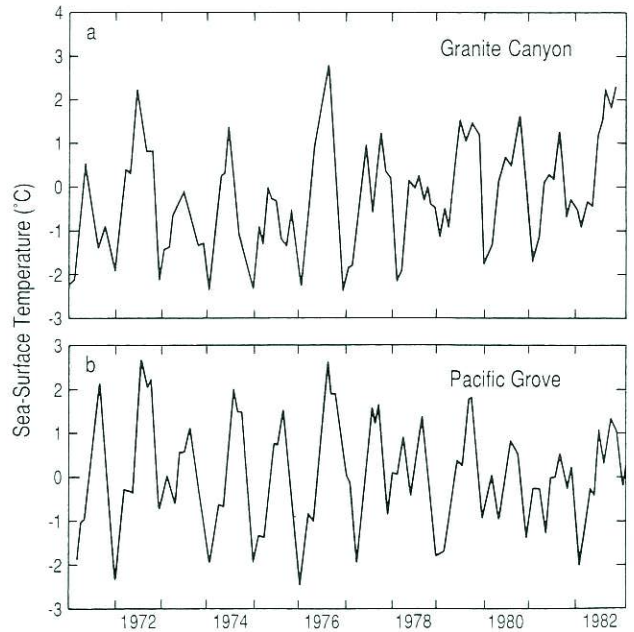


Fig. 12. Smoothed daily sea-surface temperatures at Granite Canyon and Pacific Grove for the period March 1, 1971, to March 1, 1983. The smoothing was accomplished using a cosine-tapered weighting function with 81 weights.

where

H = Entropy
 $p(n)$ = Probability of occurrence of a peak temperature
 N = Number of temperature intervals

The calculated entropy for Pacific Grove is 1.01 and for Granite Canyon 1.35. Thus the information content with respect to the annual peak values in sea-surface temperature is higher at Granite Canyon than at Pacific Grove. To the extent that El Niño episodes contribute to the spread of the annual peaks in sea-surface temperature at each location these entropies provide a quantitative indication of their relative importance. However, because of the relatively small sample size involved (i.e., Figure 12), confidence in these values of H is not high. Because the sampling distribution for H is unknown it is not possible to estimate the significance of this quantity.

The annual peaks in temperature from each record also indicate that the difference between the temperatures averaged for 1972, 1976 and 1982, and the average of the remaining years for each location is over 50 percent greater at Granite Canyon than at Pacific Grove.

The phase relationship between daily sea-surface temperatures at Pacific Grove and Granite Canyon is also examined. Based on a cross-correlation analysis of 15 years of coincident sea-surface temperatures, March 1, 1971, to March 1, 1986 (Breaker and Broenkow, 1988, in preparation), significant lags occur between these locations indicating that (1) Pacific Grove leads Granite Canyon by almost 2 months with respect to the annual cycle, and (2) Granite Canyon leads Pacific Grove by about 5 days after the annual cycle and its harmonics are removed (Figure 13). The earlier occurrence of the annual peak in the cycle at Pacific Grove most likely reflects the

importance of local heating inside Monterey Bay. That Granite Canyon leads Pacific Grove by about 5 days after the annual cycle was removed indicating the time required for oceanic signals to transit Monterey Bay.

These results suggest that both the amplitude and phase of the oceanic signals received at Pacific Grove, as manifested in sea-surface temperature, are strongly influenced by the particular location of this monitoring site.

Final Remarks

Several analyses of sea-surface temperature at Granite Canyon were presented to help identify and resolve El Niño related variability and its associated seasonal dependence. These analyses included two-way layouts of the monthly means and standard deviations by month and year, an analysis of the anomaly in sea-surface temperature, and an EOF analysis (the result of the EOF analysis were published previously by Breaker and Mooers [1986]). Two-way layouts of the monthly means and standard deviations of sea-surface temperature, the mean annual anomaly for the El Niño years, and the EOF analysis clearly revealed the seasonal nature of El Niño related warmings along the central California coast. The El Niño signal is strong during the fall and winter and weakest during the spring.

Forty-to-fifty day oscillations and spring transitions also occur in sea-surface temperature along the central California coast. Both processes may be linked to, or at least influenced by, El Niño episodes at mid-latitudes. Sea-surface temperatures at Pacific Grove were found to be less sensitive to El Niño warming events than sea-surface temperatures acquired at Granite Canyon. However, sea-surface temperatures at Pacific Grove do reflect the variability associated with events and processes that occur in and around Monterey Bay.

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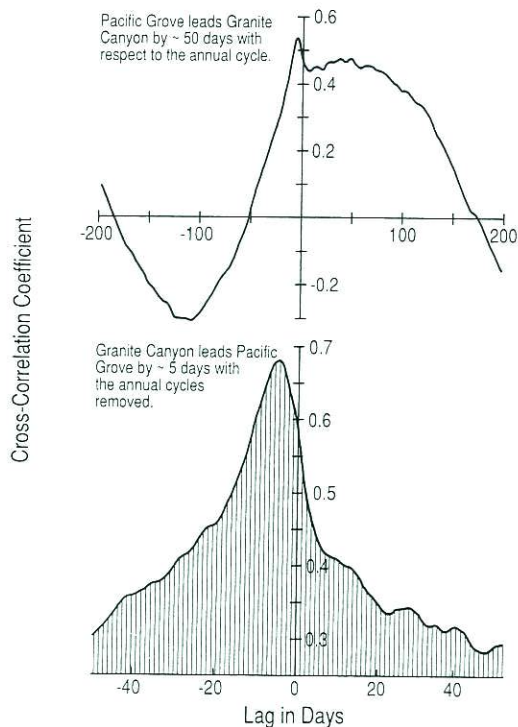


Fig. 13. Cross-correlograms of sea-surface temperature between Granite Canyon and Pacific Grove for the period March 1, 1971, to March 1, 1986. The upper-panel shows the cross-correlogram for the original data and the lower panel, the cross-correlogram for the original data less the annual cycle and its second harmonic; after Breaker and Broenkow [1988].

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