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Expressions of 1976–1977 and 1988–1989 Regime Shifts in Sea-Surface Temperature off Southern California and Hawai‘i[1]

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Abstract: Sea-surface temperatures off southern California from Scripps Pier and from Koko Head, Hawai‘i, were examined to determine what impact regime shifts that occurred in 1976–1977 and 1988–1989 had on environmental conditions at each location. Cumulative sums were employed to enhance the detection process. The cumulative sum time histories revealed major turning points at both locations at the time of the 1976–1977 event. At both locations, increases in temperature were indicated, consistent with the phase change in the Pacific Decadal Oscillation that took place at that time. The cumulative sums also indicated major turning points at both locations during the 1988–1989 event. A new procedure called the method of expanding means was employed to determine the long-term impact of these events. By comparing means before and after a given event it is possible to observe the magnitude of the change and to what extent it is sustained. For the 1976–1977 regime shift, temperatures increased rapidly and remained consistently higher, by ~1°C for 2–3 yr at Scripps Pier. This increase occurred over a period of approximately 7 months and accounts for more than half of the total warming that has occurred at that location since 1920. At Koko Head, a similar response was observed with a sustained increase of approximately +0.5°C. The oceanic response to the 1988–1989 event was quite different. At Scripps Pier, temperatures before and after this event did not show any tendency to converge to significantly different values out to periods of 2–3 yr. At Koko Head, mean temperatures did converge to slightly different values after 1 yr, with mean values being consistently lower after this event (~−0.4°C). It was shown that in some cases changes associated with these events could be identified in the original data, but without the help of cumulative sums, it is usually not possible to make a clear distinction between changes of interest and other sources of variability. Finally, decorrelation time scales for the records at both locations were estimated and found to be on the order of a year, implying spatial scales that are at least synoptic (tens to hundreds of kilometers).

Decadal Climate Variability manifests itself in several ways. According to Miller and Schneider (2000), Decadal Climate Variability can take the form of gradual drift, smooth oscillations, or steplike changes. Regime shifts are part of Decadal Climate Variability because they are steplike in nature and have time scales that are commensurate with Decadal Climate Variability. Thus, regime shifts imply sustained changes in the climatological and/or biological states of the system. According to Mantua (2004:180), a regime shift or change corresponds to “a relatively brief time period in which key state variables of a system are transitioning between different quasi-stable attractors in phase space.” In referring to the ecological aspects of regime shifts, Bakun (2004:974) defined them as “a

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persistent radical shift in typical levels of abundance or productivity of multiple components of the marine biological community structure, occurring at multiple trophic levels and on a geographical scale that is at least regional in extent." Changes that signify a regime shift are often far smaller than those associated with other more common climatic events and so their detection and localization are often difficult, and it may take years to decades before their occurrence can be firmly established.

Regime changes are important for a number of reasons. First, they affect biodiversity. If biodiversity is reduced, then the system is more susceptible to invasion by foreign species. Second, they are important because they can reflect overfishing and other anthropogenic influences (Bakun 2004). Consequently, regime shifts are important for fisheries management. Third, regime shifts are related to climate change and thus have an impact on marine weather.

A number of regime shifts have been reported in the North Pacific since the early 1900s, although their occurrence has been detected as far back as circa 1600 (Gedalof and Smith 2001). Well-documented regime shifts occurred in the North Pacific in 1925 (e.g., Beamish et al. 1999, Overland et al. 1999), in 1939 (Ware 1995, MacCall 1996), in 1946–1947 (Beamish et al. 1999, Overland et al. 1999, Peterson and Schwing 2002), in 1976–1977 (e.g., Ebbesmeyer et al. 1991, Graham 1994, Miller et al. 1994, McGowan et al. 1998, Hare and Mantua 2000, Bakun 2004), in 1988–1989 (e.g., Hare and Mantua 2000, Rebstock 2002), and in 1999 (e.g., Greene 2002, Chavez et al. 2003, Peterson and Schwing 2003).

In this study, we examined coastal observations of sea-surface temperature off the coasts of Hawai'i and southern California during regime shifts in the North Pacific that occurred in 1976–1977 and 1988–1989. The regime shift in 1976–1977 is quintessential, according to Bakun (2004), because it had a major impact on most, if not all, climatic and ecosystems indicators. The 1976–1977 regime shift took place during the winter of 1976 and 1977 (Miller et al. 1994, Hare and Mantua 2000). The 1988–1989 regime shift was an event that took place during the winter of 1988 and 1989. According to Hare and Mantua (2000), this event was unique in the sense that its primary manifestations were biological because it was, for the most part, limited to certain components of the North Pacific ecosystem.

The Pacific Decadal Oscillation is closely related to regime changes in the North Pacific. The Pacific Decadal Oscillation is a cyclic pattern of climatic variability that has periods of 15–20 yr on shorter time scales and 50–70 yr on longer scales (Minobe 1997). The Pacific Decadal Oscillation index is a measure of the Pacific Decadal Oscillation and is defined as the first principal component of the sea-surface temperature anomaly over the North Pacific, north of 20° N. Changes in the sign or phase of the Pacific Decadal Oscillation often correspond to regime changes in the North Pacific. During the 1976–1977 regime shift, for example, the phase of the Pacific Decadal Oscillation changed from negative to positive (e.g., Ebbesmeyer et al. 1991). Although the Pacific Decadal Oscillation is often useful in helping to identify regime changes, its origins are not well understood (e.g., Mantua and Hare 2002). Another climate-related indicator called the North Pacific Gyre Oscillation has recently been introduced that correlates well with changes in salinity, nutrients, and chlorophyll (Di Lorenzo et al. 2008). According to Di Lorenzo et al., fluctuations in the North Pacific Gyre Oscillation are driven by regional- and basin-scale variations in wind-driven upwelling and horizontal advection. The North Pacific Gyre Oscillation may play an important role in forcing global-scale decadal changes in marine ecosystems. Ultimately, it may prove to be a better indicator of Decadal Climate Variability and regime shifts than the Pacific Decadal Oscillation.

Regime shifts are often subtle and our understanding of them is limited. It is our goal to shed more light on identifying, localizing, and characterizing these events through the use of coastal observations at far-removed locations around the Pacific basin. Unlike most climatic data that have been averaged extensively in space and/or time, coastal observations are often acquired daily or weekly at single locations and so allow us to examine these events in much greater detail. Using data acquired daily or weekly, we can observe when these events are initiated, how they evolve, and when they are terminated.

MATERIALS AND METHODS

A number of methods for detecting regime shifts in marine ecosystems were presented and discussed by Mantua (2004). Identifying and localizing regime shifts constitute a problem in change point detection (Basseville and Nikiforov 1993). Basseville and Nikiforov found that of all the algorithms they tested, the CUmulative SUM (CUSUM) performed as well as, or better than, most in detecting change points. As a result, we employed cumulative sums to detect and localize regime shifts in the time series of sea-surface temperatures that are employed in this study.

Breaker (2007) discussed both the strengths and weaknesses of cumulative sums in detecting regime shifts. He found that at several locations along the west coast of North America cumulative sums of sea-surface temperature often produce a distinct pattern that appears to be characteristic of regime shifts. During several regime shifts, the cumulative sum trajectories from two locations, one off central California and the second off southern California, were highly synchronized and nearly identical in form. Although the cumulative sum patterns during regime shifts, in most cases, indicate correctly whether an increase or decrease in temperature has occurred, estimates of the change magnitude were consistently high. These events have time scales on the order of 6 months, and they often consist of two change points, one that signals the onset of the event and a second that signals its termination. As a result, it was found that standard tests of significance may not be appropriate for determining whether or not regime shifts are statistically significant. It was concluded that testing regime shifts for statistical significance is a problem that may be more closely related to pattern recognition, where more appropriate tests could be applied.

The cumulative sum can be expressed as

$$S_c = \sum_{i}^{n} (x_i - \bar{x}), \qquad (1)$$

where x_i represents the ith observation; $\bar{x}$, the mean of x from $i = 1$ to n; and S_c is the cumulative sum over the interval specified (e.g., Hawkins and Olwell 1998). By removing the global mean, the resulting cumulative sum time history is constrained to start and end at zero. Changes in the mean level of the time series are reflected as changes in the slope of the cumulative sum when it is plotted versus time, where the magnitude of the slope is proportional to the change in the mean. When the change in slope is positive, an increase in the mean is indicated, and, conversely, when the slope becomes negative, a decrease in the mean has occurred. Because slopes are additive, the slope, m_{RS}, associated with a particular event can be estimated according to

$$m_{RS} = m_T - m_{AC} - m_{LTD} \qquad (2)$$

where m_T is the observed slope, m_{AC} is the slope associated with the annual cycle, and m_{LTD} is the slope associated with any long-term drift or trend. Cumulative sums are sensitive to initial conditions. Specifically, the time that the summation is started can also affect the slope of the cumulative sum (Breaker 2007). The statistical properties of cumulative sums differ greatly from those of the original data. When cumulative sums are calculated, serial correlation is considerably increased, contributing to nonstationarity and distortion of the slopes associated with change points. However, cumulative sums improve the signal-to-noise ratio associated with change points that characterize regime shifts and so enhance the detection process. For the 1976–1977 event at Scripps Pier off southern California, for example, the improvement in signal-to-noise ratio was greater than 7 deciBels (dB), or almost one order of magnitude.

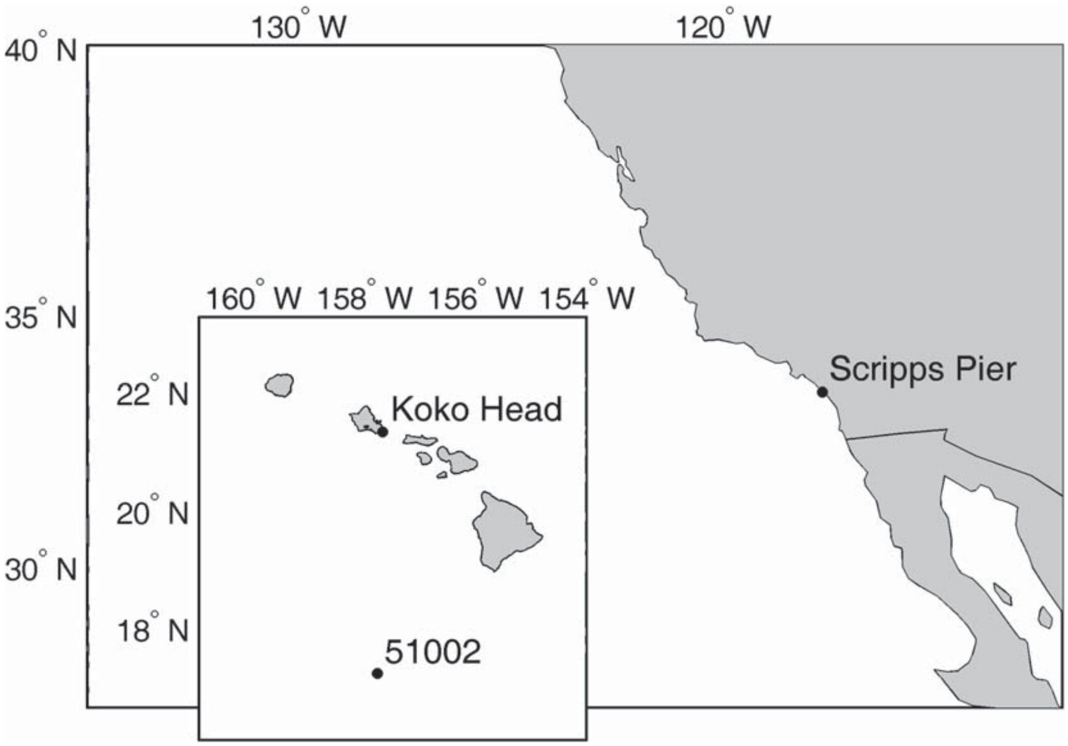

FIGURE 1. A map of the study area showing the three locations where sea-surface temperature data were acquired for this study. These locations are Scripps Pier, located just north of San Diego, in southern California; Koko Head, located on the east coast of O'ahu, Hawai'i; and National Data Buoy Center Environmental Data Buoy 51002, located southwest of the Hawaiian Islands.

The sea-surface temperature data used in this study are from the following locations: Scripps Pier at La Jolla, off southern California; the National Data Buoy Center (NDBC) Environmental Data Buoy 51002 located southwest of the Hawaiian Islands; and Koko Head, located along the east coast of O'ahu. These locations are shown in Figure 1. The observations from Scripps Pier are daily and extend from 1 January 1920 through 31 December 2004, a period of 85 yr. Thus, for an interval of 85 yr, the value of n used in equation (1), in this case, is $85 \times 365 = 31025$ (the leap days have been removed). The data from Koko Head, O'ahu, are weekly and extend from 1 January 1956 through 31 December 1990. Thus, the interval for the weekly data at Koko Head is 35 yr, and the value of n used in equation (1), in this case, is $35 \times 52 = 1820$. Finally, the data from NDBC buoy 51002 are hourly but have been daily-averaged for the period from 1 October 1988 through 31 July 1989. Because regime shifts are of relatively short duration there is always the possibility that an instrumental change might be taken for an environmental change due to a regime shift. Simulations using cumulative sums have shown that the time scale associated with an instrumental change is far shorter than the time scales associated with any of the regime shifts we have observed.

In calculating cumulative sums to detect change points or regime shifts, it is important to remove or reduce the influence of the annual cycle where the annual cycle is a major source of variability. The annual cycle often distorts or suppresses the change points that signify a regime shift. Consequently, we removed the mean annual cycle in each case before calculating the cumulative sums. To calculate the mean annual cycle, we calculated the mean value for each day of the year, taken over the number of years in the record. The mean annual cycle was next repeated for each year. This replicated version of the mean annual cycle was then subtracted from the original data, producing a new residual time series where the influence of the annual cycle had been considerably reduced. Finally, the global mean was removed from the residuals before the cumulative sum was calculated. By first removing the mean annual cycle, a turning point pattern specifically associated with regime shifts was produced in the cumulative sum time history that appears to be unique (Breaker 2007).

RESULTS AND DISCUSSION

The data from Scripps Pier are shown as a two-way layout in Figure 2*a*, with month of the year given along the ordinate and the

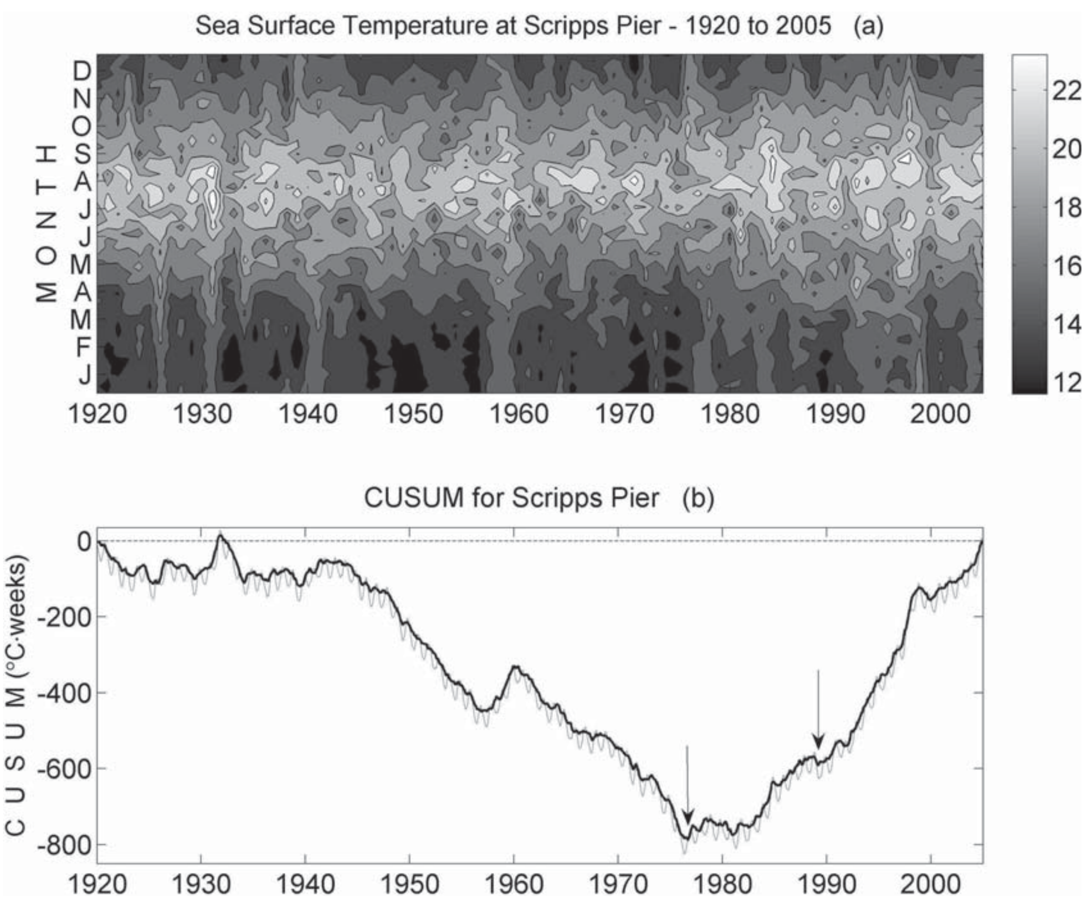

FIGURE 2. The upper panel (*a*) shows a two-way layout of weekly sea-surface temperature at Scripps Pier, by month, along the *y*-axis and, by year, along the *x*-axis. The period extends from 1 January 1920 through 31 December 2004. The warmest temperatures occurred between June and September. The lightest areas correspond in most cases to El Niño warming episodes. The lower panel (*b*) shows a cumulative sum (CUSUM) of the data shown in (*a*). The lighter trace shows the cumulative sum based on the original data, and the darker trace shows the cumulative sum with the mean annual cycle removed. In both cases, the global means were removed before the cumulative sums were calculated. The vertical arrows identify regime shifts that occurred during 1976–1977 and 1988–1989.

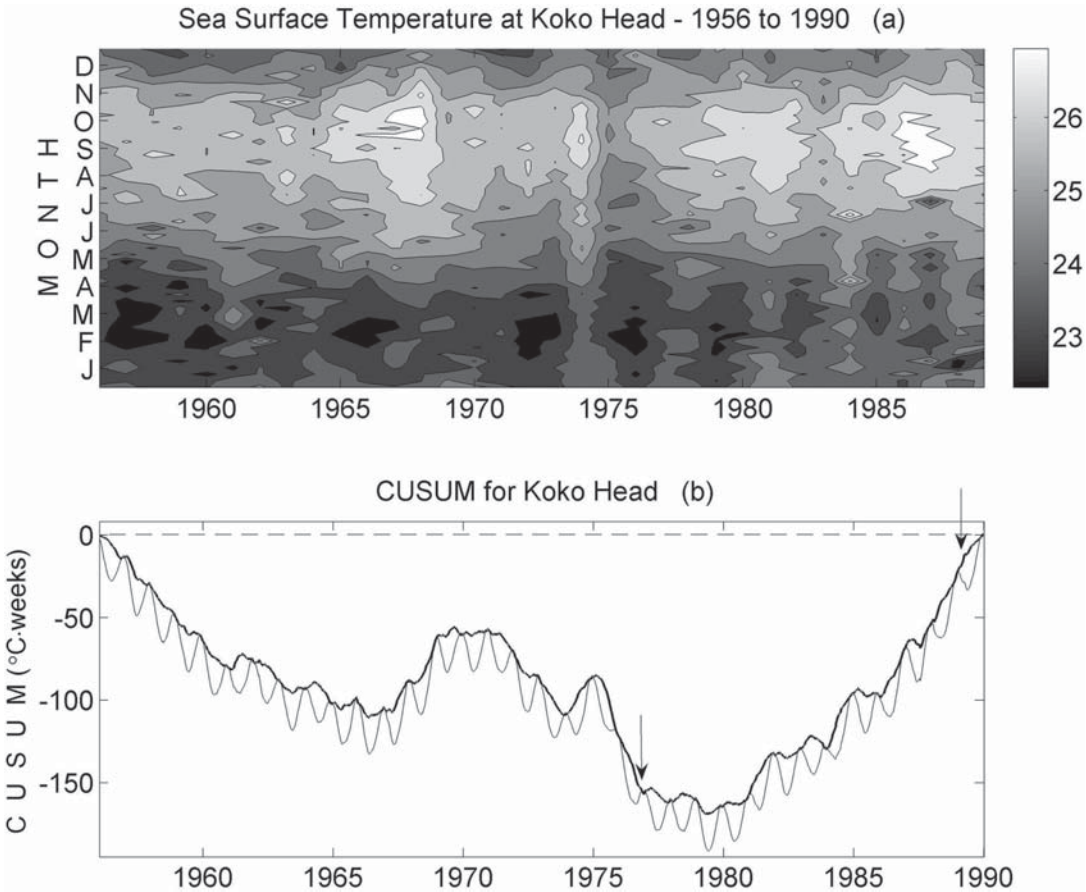

Figure 3. The upper panel (*a*) shows a two-way layout of weekly sea-surface temperature at Koko Head, Hawai'i. The period extends from 1 January 1956 through 31 December 1990. The warmest temperatures occurred between July and November. The lower panel (*b*) shows a cumulative sum (CUSUM) of the same data. The lighter trace shows the cumulative sum based on the original data, and the darker trace shows the cumulative sum with the mean annual cycle removed. In both cases, the global means were removed before the cumulative sums were calculated. The vertical arrows identify the regime shifts that occurred during 1976–1977 and 1988–1989.

year itself along the abscissa. On a seasonal basis, the greatest warming occurred between June and September. The areas of lightest shading indicate periods of warming that were primarily due to El Niño episodes. Major El Niño episodes that appear in the record occurred in 1930, 1957–1958, 1982–1983, 1992–1993, and 1997–1998. The corresponding cumulative sum is shown in Figure 2*b*, with (lighter trace) and without (darker trace) the mean annual cycle. El Niño–related warming during the late 1950s is particularly evident. The events of primary interest in this study, the first in 1976–1977 and the second in 1988–1989, are indicated by vertical arrows. The data from Koko Head are shown in a second two-way layout in Figure 3*a*. The most intense warming occurred between July and November, but warming specifically due to El Niño episodes is not as apparent in this case, although the warming during the early to mid-1980s is almost certainly El Niño–related. The corresponding cumulative sum is shown in Figure 3*b*. Because the record is shorter and the range of values over which the cumulative sum extends is smaller, it is much easier to see the influence of the annual cycle in this case. Again, the two events of interest are indicated by vertical arrows. In the following sections, the mean annual cycle has been removed before calculating the cumulative sums in all cases.

To detect and localize the 1976–1977 and 1988–1989 events, we started by examining the cumulative sum time histories (i.e., cumulative sums) during the periods when they were reported to have occurred. As stated earlier, the first event occurred during the winter months of 1976 and 1977, according to Miller et al. (1994) and Hare and Mantua (2000). According to Hare and Mantua, warming was observed over a broad band along the Pacific coast of North America during this event, whereas a large portion of the central Pacific was, on average, -0.8 to -1.0°C cooler. Following Breaker (2007), we looked for a unique pattern or change point, or a pair of change points, separated by at least several months during the winter of 1976–1977. Figure 4*a* and *b* shows the cumulative sums at Scripps Pier and Koko Head during this event. This event was previously identified by Breaker (2007) for the record at Scripps Pier and is bounded by the vertical dark, dashed lines in Figure 4*a*. Although we cannot precisely identify the beginning and end of this event, similar patterns have been observed at other locations and for other events (Breaker 2007). There are two change points (indicated by dark arrows), separated by approximately 7 months, that essentially capture this event. The timing and duration of this event are in close agreement with the results of Miller et al. (1994) and Hare and Mantua (2000).

An event during the same period is shown in the cumulative sum of sea-surface temperature at Koko Head (Figure 4*b*), but it has a somewhat different appearance, making its detection and localization slightly more difficult. During the last four months of 1976, there are two changes in slope, a weak turning point in September (first dark arrow), followed by a major turning point in December (second dark arrow). We highlight this period with gray, dashed boxes in Figure 4*a* and *b*. It falls within the vertical dark, dashed lines that bracket the event at Scripps Pier, indicating that it occurs at about the same time at both locations. If we have localized the event at Koko Head correctly, it is clear that its orientation, unlike the orientation of the cumulative sum pattern at Scripps Pier, is strongly affected by the prevailing slope of the cumulative sum that precedes it. Thus, we have estimated the slope, as shown by the thin, gray, dashed line, and subsequently subtracted it from the cumulative sum in accordance with equation (2). The results are shown in Figure 6*a*. Slope corrections in some cases make it easier to identify certain events but become increasingly important if the actual increase (or decrease) in mean level is to be estimated. Based on the direction of change or sign of the cumulative sum at Scripps Pier, an increase in temperature is indicated. At Koko Head, the major change point in December 1976 also suggests an increase in mean level because the slope changes abruptly and becomes strongly positive (Figure 4*b*).

The second event occurred during the winter of 1988–1989 and has been reported on numerous occasions (e.g., Mackas 1995, Overland et al. 1999, Watanabe and Nitta 1999, Hare and Mantua 2000). Although minor cooling was observed off the coast of California during this regime shift, there was a broad region of warming over much of the central North Pacific (Hare and Mantua 2000). To detect and localize the 1988–1989 event, we once again examined the cumulative sums slightly before, during, and after the period when this event was reported to have occurred (Figure 5). The cumulative sum for Scripps Pier (Figure 5*a*) shows a rather sudden decrease late in 1988 that most likely indicates the onset of this event, followed by a major turning point in early 1989 that points to its termination (Breaker 2007). These change/turning points are again indicated by dark arrows. The region of interest is enclosed by vertical dark, dashed lines. Based on the separation of the two turning points, we estimate the duration of this event to be approximately 6 months. Its timing is consistent with the results of Hare and Mantua (2000).

In Figure 5*b*, we observe what is almost

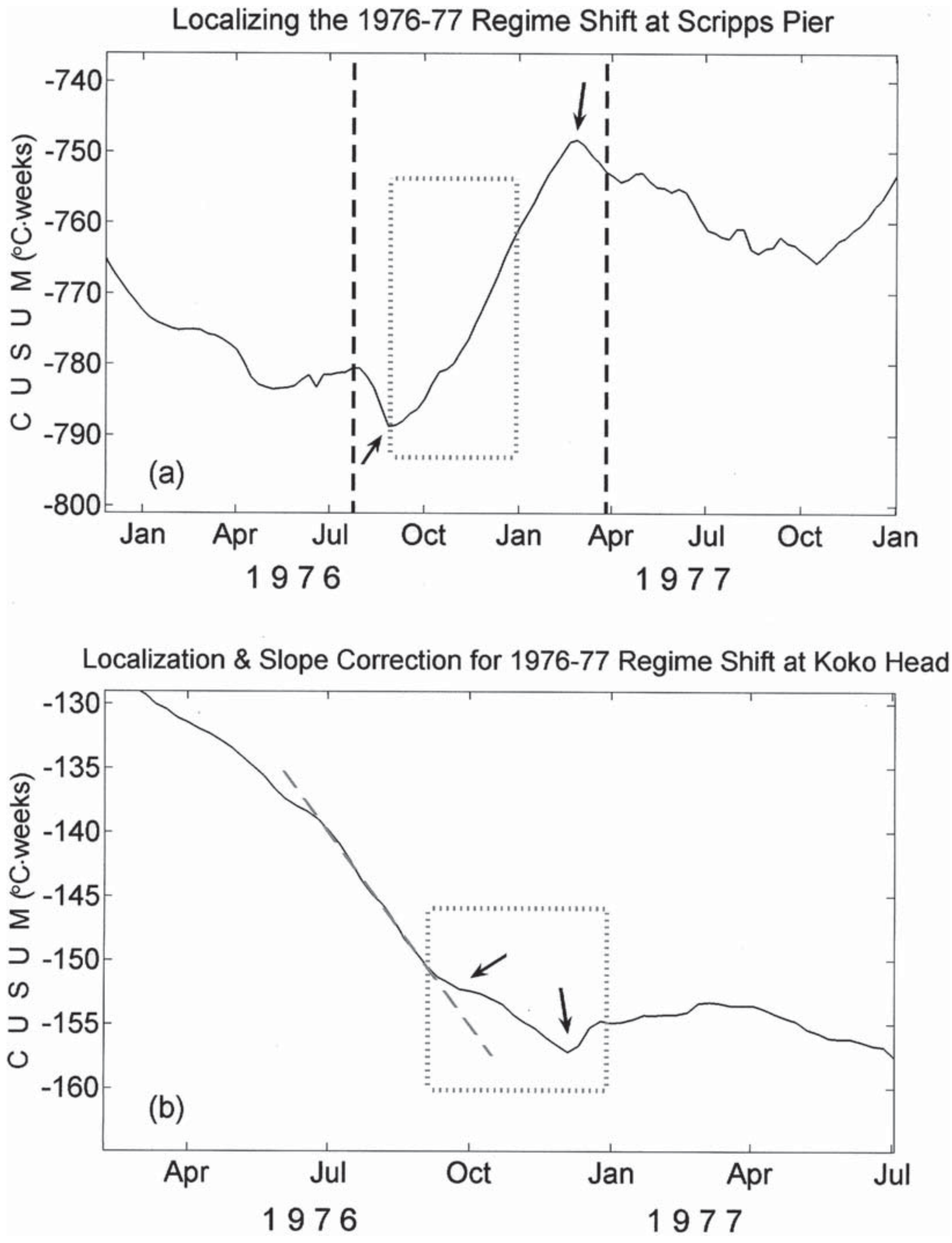

FIGURE 4. The upper panel (*a*) shows the cumulative sum (CUSUM) at Scripps Pier for the period from early 1976 through 1977. The change points (indicated by dark arrows) within the dark, dashed lines identify the transition period associated with the 1976–1977 regime shift. The gray, dashed box shows the period for the same event at Koko Head, Hawai'i. The lower panel (*b*) shows the cumulative sum at Koko Head for the period from early 1976 through mid-1977. The gray, dashed box shows the cumulative sum pattern associated with the 1976–1977 event. The dark arrows indicate the turning points that locate the approximate beginning and end of this event. The thin, gray, dashed line shows the slope of the cumulative sum just before the event. In Figure 6*a*, this event is shown with the slope removed.

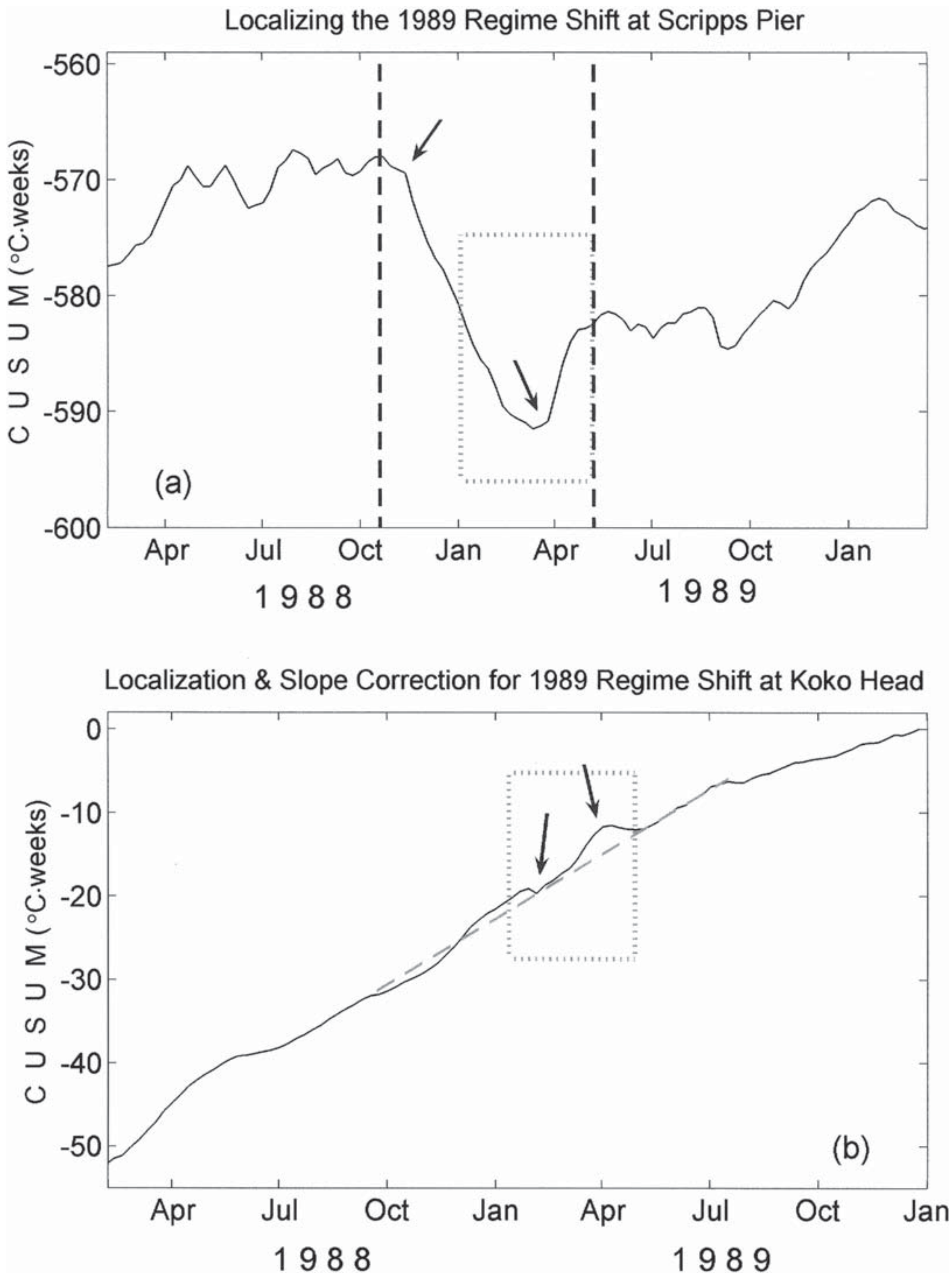

FIGURE 5. The upper panel (*a*) shows the cumulative sum (CUSUM) at Scripps Pier for the period from early 1988 through early 1990. The regime itself is bracketed by the vertical dark, dashed lines, and the dark arrows indicate the turning points that locate the beginning and end of this event. The gray, dashed box shows the period for the same event at Koko Head, also shown in the panel below (*b*). In Figure 5*b*, the overall period at Koko Head extends from early 1988 to 1990, but the event itself is shown within the gray, dashed box. Dark arrows indicate the approximate beginning and end of this event. The thin, gray, dashed line shows the slope of the cumulative sum just before, during, and after the event. In Figure 6*b*, this event is shown with the slope removed.

certainly the same event at Koko Head, which extends from January through April 1989 (enclosed in the gray, dashed box). The amplitude of this event is relatively small, but the pattern is distinct and similar to the patterns we observed during other regime shifts. Because this pattern is superimposed on large-scale drift in the cumulative sum time history, we calculated the linear slope during the period shown by the thin, gray, dashed line and subsequently removed it from the cumulative sum (Figure 6*b*). We show the period of this event in gray, dashed boxes in Figures 5*a* and *b*. Like the 1976–1977 regime shift, this event occurred at the same time at both locations, although its duration appears to be somewhat shorter at Koko Head than it was at Scripps Pier.

The original and slope-corrected cumulative sums for the 1976–1977 and 1988–1989 regime shifts at Koko Head are shown in Figures 6*a* and *b*, respectively. Because the events at Koko Head are weaker and not as well defined as they are at Scripps Pier we have zoomed in slightly to take a closer look at them. It is somewhat easier to identify the beginning and end of these events in the slope-corrected versions and thus to estimate their durations. For the 1976–1977 regime shift (Figure 6*a*) we estimate its duration to be approximately 4 months. By comparing this event with its signature at Scripps Pier, we also see that its amplitude is smaller by almost an order of magnitude ($\sim$40°C·weeks versus $\sim$4°C·weeks). For the 1988–1989 regime shift (Figure 6*b*), the slope correction affects the magnitude of this event to a considerable degree, although the overall pattern is retained. In this case, we estimate its duration to be between 2 and 3 months. Again, its amplitude, compared with its amplitude at Scripps Pier, is small, almost an order of magnitude smaller ($\sim$20°C·weeks versus $\sim$2.5°C·weeks).

In examining these events, it is possible, although not likely, that we have not localized and identified them correctly. However, no other events whose cumulative sum patterns were even roughly similar to the patterns we have ascribed to them could be found within a year or more of the dates that are given for these events. Previous results have shown that the patterns associated with specific events appear to be well preserved between central and southern California, and that they are usually in phase (Breaker 2007). A comparison of the cumulative sum time histories from Scripps Pier and Hawai‘i show that they are approximately in phase but that the corresponding patterns are not as well correlated. The duration of these events appears to be roughly half as long and their amplitudes far smaller at Koko Head than they are at Scripps Pier. Finally, although the large changes in the cumulative sums at Scripps Pier suggest that the corresponding changes in sea-surface temperature may be relatively large, as we will see, such changes do not necessarily translate into long-term, sustained changes in the state of the ocean.

It is usually assumed that regime shifts lead to long-term (i.e., sustained) changes in the state of the system, whether these changes are biotic, abiotic, or both in nature. When we look at the cumulative sum in Figure 2*b*, for example, the long-term trend before the 1976–1977 regime change is essentially negative, whereas the long-term trend following this event is positive. This dramatic turning point during the 1976–1977 regime shift occurs notwithstanding the end constraint for the cumulative sum to return to zero at the end of the record. The long-term impact of this event sets it apart from most, if not all, of the regime shifts that have been reported since the early 1900s.

As stated earlier, regime changes tend to be subtle. According to Kerr (1992) and MacCall (1996), regime shifts are usually smaller than year-to-year fluctuations and may involve several parts of the climate system, and so recognizing them is often difficult and may require a decade or longer before a positive identification can be made. Thus, it is not surprising that it is difficult to determine the long-term (i.e., sustained) impact of most regime shifts. It is not clear that these events do lead to long-term changes in the system in all cases. In some cases, it is possible that changes associated with a particular event may be only temporary and thus their impact would be minimal. Also, some environmental

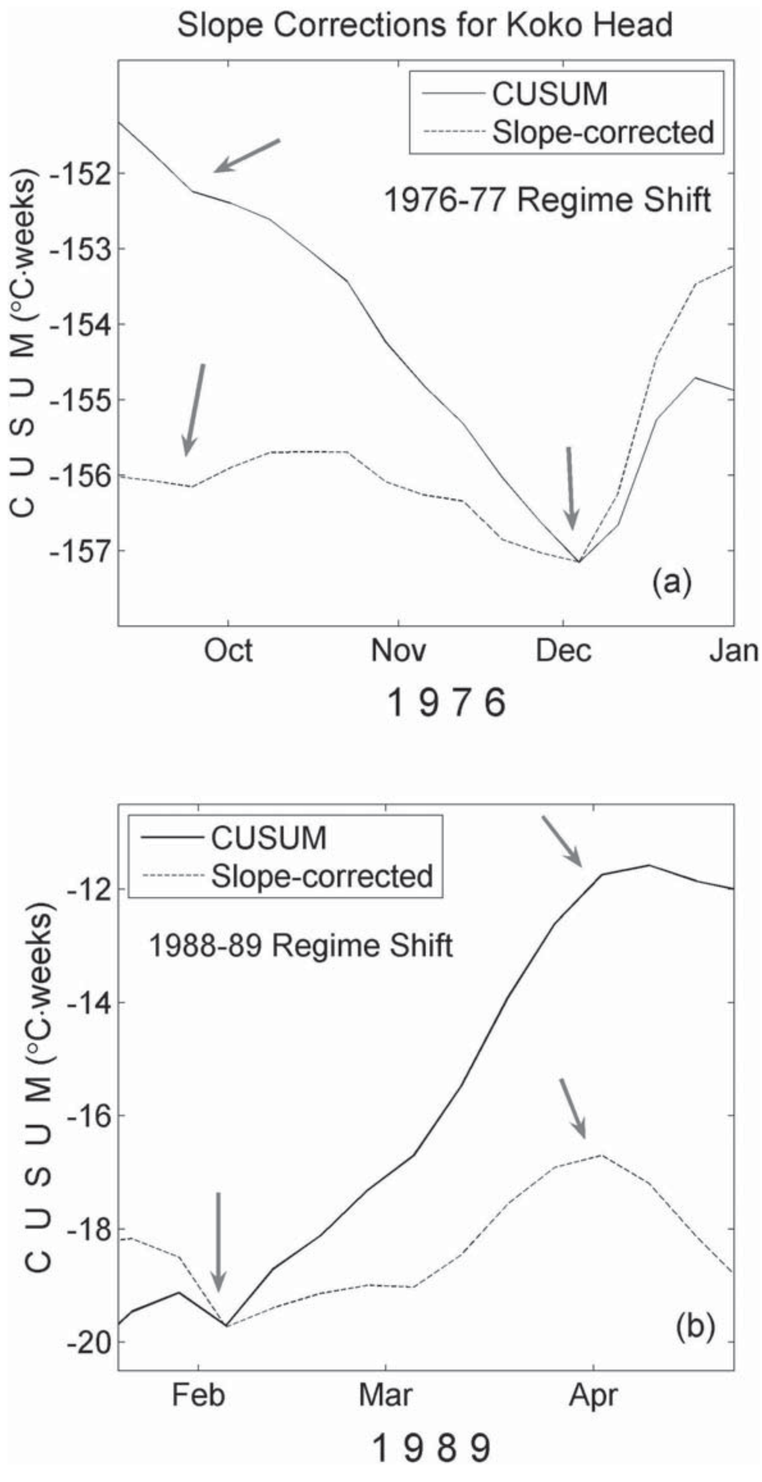

Figure 6. The original (solid lines) and slope-corrected (dashed lines) cumulative sums (CUSUM) are shown for the 1976–1977 regime shift at Koko Head in (*a*), and for the 1988–1989 regime shift at Koko Head in (*b*). Gray arrows indicate the major turning points that help to delimit these events. See text for details.

parameters may be more sensitive to such changes than others. In our study, we were limited to sea-surface temperature as a proxy for system behavior.

To explore the long-term impact of regime shifts, we have developed a procedure that provides us with a glimpse of whether or not long-term changes have occurred. We refer to this procedure as the method of expanding means. First, we take the original data and remove the mean annual cycle. Next, we estimate the center point of a particular regime shift. In the case of the 1976–1977 regime shift, for example, the midpoint of this event could be taken as the first week in January 1977. Then, the mean values of temperature are calculated starting at the midpoint and progressing forward and backward in time. At each step in moving away from the center point, another value is added to the length of record that is used to calculate the mean in each direction. Because we add a new value at each step when the mean is calculated, it seems natural to call this procedure the method of expanding means. As a computational algorithm, it takes the following form in the forward direction:

$$\bar{x}_i = \frac{1}{(j_2+1)} \sum_{j_1}^{j_2=j_2+1} x_j \tag{3}$$

for $i = 1, 2, \ldots, i_{max}$, $j_1 = 0$, and $j_2 = 0, 1, \ldots, i_{max} - 1$. In the reverse direction:

$$\bar{x}_i = \frac{1}{(|j_2|+1)} \sum_{j_1}^{j_2=j_2+1} x_j \tag{4}$$

for $i = -1, -2, \ldots, -i_{max}$, $j_1 = 0$, and $j_2 = 0, -1, \ldots, -i_{max} + 1$, where $\bar{x}_i$ is the mean summed over the first i values, i_{max} represents the maximum length over which the expanding means are calculated, and j_1 and j_2 are the indices that locate the midpoint of a given event that is assumed to start at zero. We have assumed that the best place to start calculating the expanding means is at the midpoint of a regime shift, but we have not demonstrated that this is necessarily true. This question is addressed in Appendix 1.

Confidence limits that correspond to the standard error have also been calculated and take into account, at least approximately, the loss in degrees of freedom due to serial correlation. The details of the procedure used to estimate the loss in degrees of freedom that permit us to establish more realistic confidence limits can be found in Emery and Thomson (1997) and so are not repeated here. Confidence in the calculated means should increase with each step because the sample size likewise increases. Our goal is to see if the means eventually converge to stable values that do not change appreciably beyond a certain point and whether or not there are significant differences in these values beyond that point. Finally, because few values are involved in calculating the means initially, and the starting location occurs at the midpoint of a regime shift, the first several months are usually periods of rapid change where stable estimates of the long-term means cannot be obtained.

How to select i_{max} is an important question. The processes are not necessarily stationary, and so the local mean may change appreciably over the length of the record. Thus, when we continue to expand the means over longer and longer intervals, they often wander, yielding differences in the forward and reverse directions that change with time. To obtain guidance in selecting i_{max}, we have calculated autocorrelation functions for the data from Scripps Pier and Koko Head to estimate the decorrelation time scales associated with changes in the process. It is essential to remove the mean annual cycle from the original data before the calculation is performed because the annual cycle dominates the autocorrelation function, and the function will not approach zero if it is not removed. Both records also contain small, long-term positive trends that have been fitted to the data and then removed before calculating the autocorrelation functions. The autocorrelation functions for Scripps Pier (Figure 7*a*) and Koko Head (Figure 7*b*) are very similar and exhibit an exponential decay that is characteristic of a first-order, autoregressive process (Chatfield 1999). We see no influence from the annual cycle, suggesting that our procedure for addressing this problem has been reasonably effective. Both decay curves approach zero at

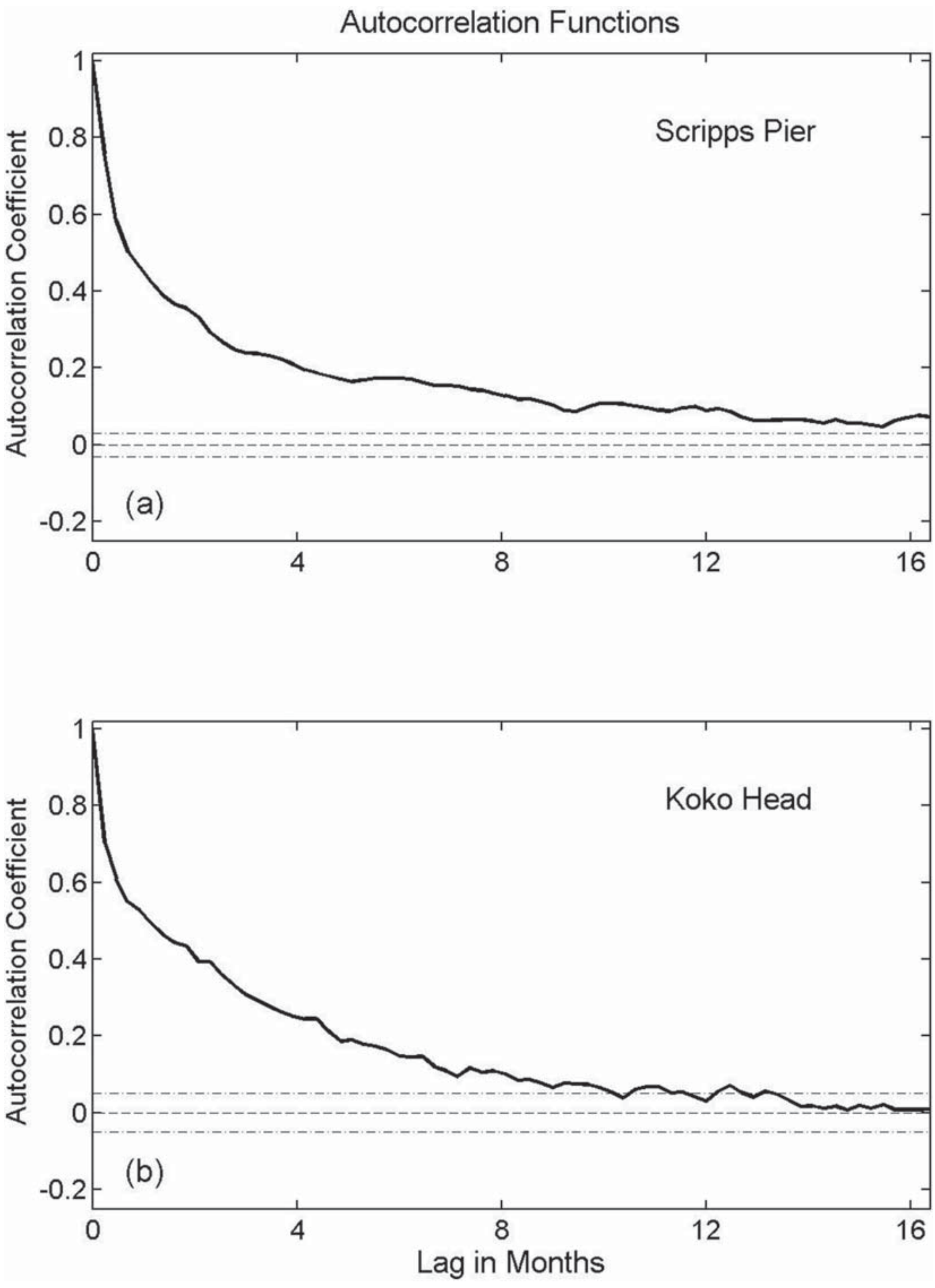

FIGURE 7. Autocorrelation functions for the weekly data at Scripps Pier (*a*), and Koko Head (*b*) are shown. The dash-dot lines just above and below zero correspond to the upper and lower 95% confidence limits. Values that fall outside these limits are significantly different from zero. In both cases, the correlation decay curves approach 1 yr or slightly longer before they are no longer significant. Thus, we estimate the decorrelation times to be on the order of 1 yr. See text for details.

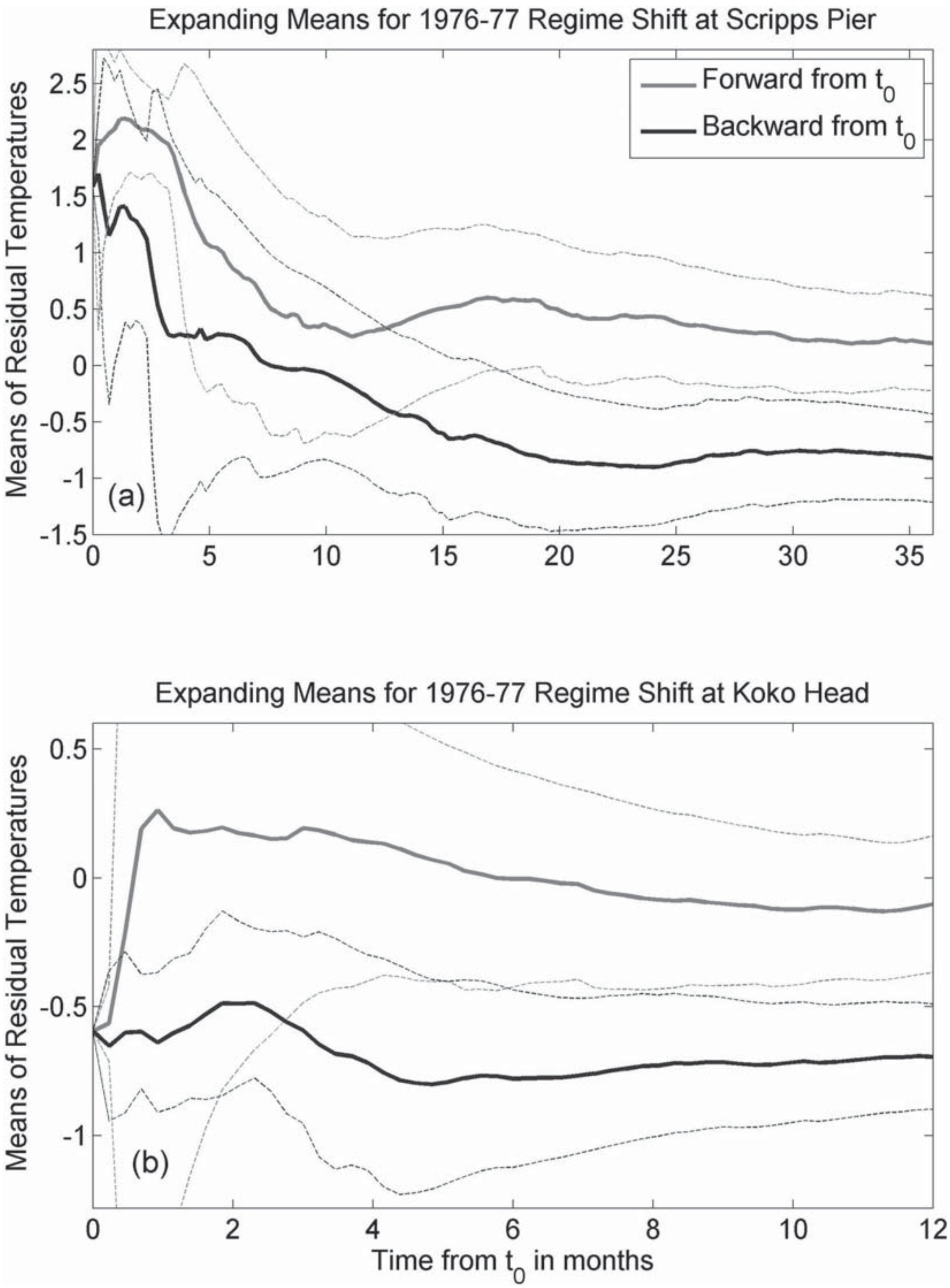

Figure 8. Expanding mean temperatures are shown in the forward (gray) and reverse (black) directions starting at the time of the 1976–1977 regime shift for Scripps Pier (*a*) and Koko Head (*b*). The dashed lines correspond to the standard error of the mean and thus provide a measure of uncertainty in the mean values that are calculated. Differences in the means before and after the event provide an indication of how well the changes due to this regime shift are sustained and, thus, an indication of its overall impact. See text for details.

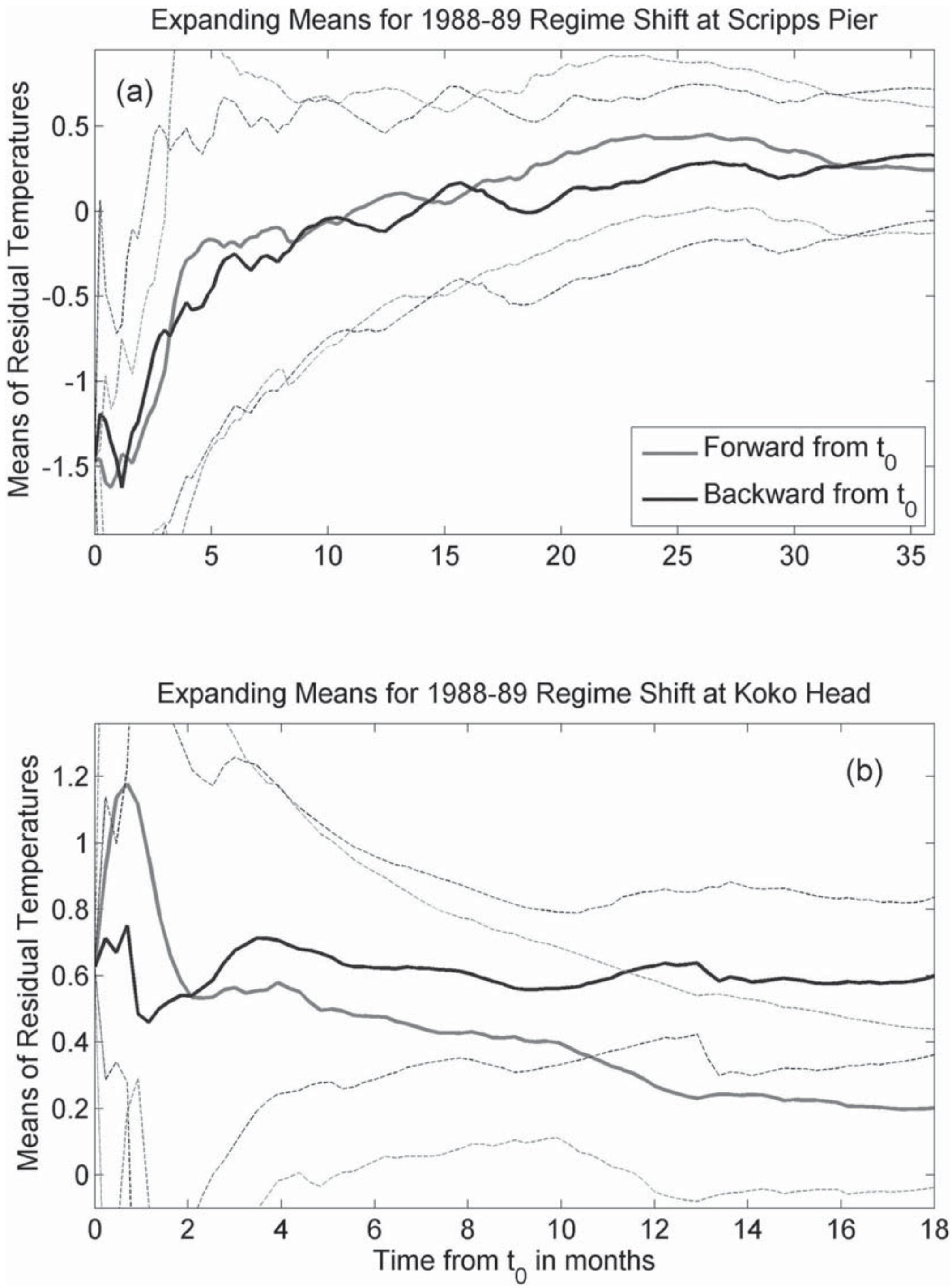

FIGURE 9. Expanding mean temperatures are shown in the forward (gray) and reverse (black) directions starting at the time of the 1988–1989 regime shift for Scripps Pier (*a*) and Koko Head (*b*). The dashed lines correspond to the standard error of the mean and thus provide a measure of uncertainty in the mean values that are calculated. Differences in the means before and after the event provide an indication of how well the changes due to this regime shift are sustained and, thus, an indication of its overall impact. See text for details.

lags of approximately 1 yr or slightly longer. This decorrelation time scale represents our estimate of the time during which the process may be considered to be stationary. At longer time scales, the mean and variance, for example, may vary significantly. Finally, our choices for i_{max} have been guided, at least in part, by these results.

In Figure 8, the expanding means for the 1976–1977 regime shift are shown for Scripps Pier (Figure 8*a*) and Koko Head (Figure 8*b*). The standard error of the mean is shown by the dashed lines in each case. They express our uncertainty in estimating the mean. As the sample size increases, the uncertainty tends to decrease, and thus the dashed lines gradually converge as we approach i_{max}. At Scripps Pier, the expanding means are always higher in the forward direction out to an i_{max} of 36 months. After roughly 20 months, the expanding means start to converge to stable values. Beyond about 30 months, the mean values do not change significantly. At this point there is a significant difference in the mean temperatures before and after the event that approaches $+1.0°C$. Thus, out to at least 3 yr, there appears to be a significant, sustained increase in temperature. In fact, this increase in temperature represents more than half of the total increase in sea-surface temperature at Scripps Pier since 1920. At Koko Head (Figure 9*b*), there is a smaller but still significant increase in temperature before and after this event out to a period of at least 1 yr. The difference at this point is approximately $+0.5°C$. The relatively large and sustained increases in temperature at both locations are consistent with the phase change in the Pacific Decadal Oscillation that occurred at this time (Mantua et al. 1997, Mantua and Hare 2002) and the vast body of literature that is related to this event.

The expanding means for the 1988–1989 regime change are shown for Scripps Pier and Koko Head in Figures 9*a* and *b*, respectively. Unlike the regime shift in 1976–1977, the expanding means at Scripps Pier are similar out to at least 1.5 yr (~18 months) before and after this event. Beyond approximately 18 months, values in the forward direction are slightly higher than in the reverse direction, but after ~30 months the differences become even smaller. Thus, it is difficult in this case to infer that an appreciable change has occurred. The expanding means for Koko Head (Figure 9*b*) convey a different picture. After about 2.5 months, the expanding mean in the reverse direction is consistently higher than its value in the forward direction, consistent with a sustained decrease in temperature that approaches $-0.40°C$ by the 13th month. Hare and Mantua (2000) indicated that minor cooling was observed off the coast of California during this event, but a broad region of warming was observed over much of the central North Pacific. Thus, our results are not necessarily consistent with those of Hare and Mantua.

There is one school of thought that argues that if the signal of interest can be detected only after some method of signal processing has been applied (often, very sophisticated), and yet there is not the slightest indication of its existence in the original, unprocessed data, it might be wise to reexamine the methodology. We concur with this philosophy and so asked whether it is possible to observe these events in the original data, recognizing that some guidance may be required from our previous analyses? We first examined the original data at Scripps Pier and Koko Head during the 1976–1977 event (Figure 10). In Figure 10*a*, the original weekly-averaged data at Scripps Pier from mid-1976 through mid-1977 reveal two rather abrupt dips or decreases in temperature as shown by the vertical arrows. If we compare these locations with the cumulative sum in Figure 4*a*, the first arrow corresponds approximately to the major turning point in August 1976, and the second arrow corresponds approximately to the peak in the cumulative sum in February 1977. Because the two events observed in the original data coincide rather closely with the major inflection points in the cumulative sums, they almost certainly reflect the same event. At Koko Head (Figure 10*b*), a major peak occurs in December 1976 and is again indicated by a vertical arrow. If we compare

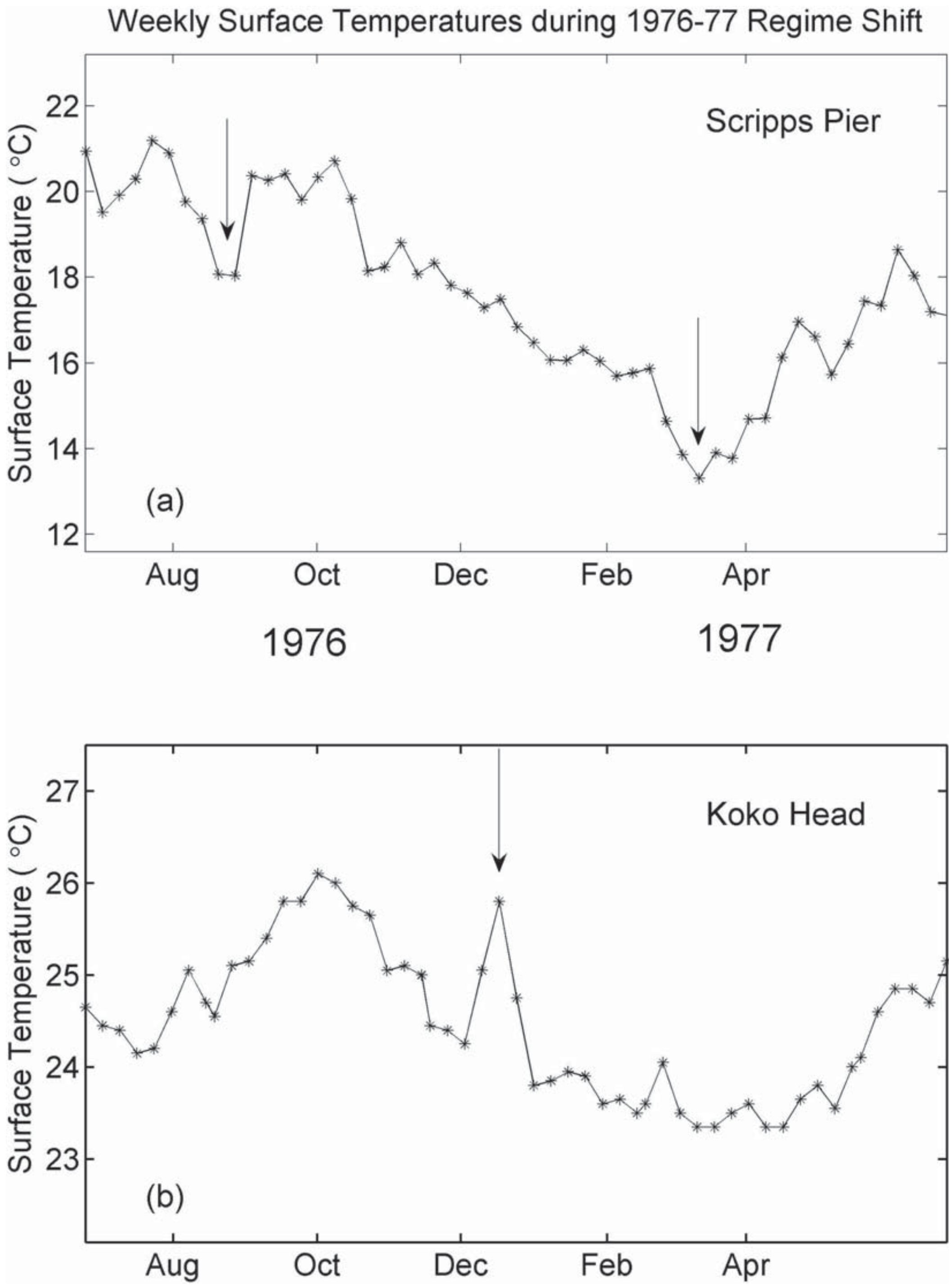

FIGURE 10. The original weekly sea-surface temperature data plotted during the period of the 1976–1977 regime shift at Scripps Pier (*a*) and at Koko Head (*b*). The vertical arrows correspond to change points in the corresponding cumulative sums shown in Figures 4 and 6. The changes in sea-surface temperature indicated by the arrows show that in some cases indications of these events can be observed in the original data.

the location of this peak with the cumulative sum in Figure 4*b*, it occurs within about 2 weeks of the major turning point that also occurs in December 1976 (indicated by the second arrow that points to the deepest depression). They most likely reflect the same event.

In Figure 11, the original data from Scripps Pier (*a*), Koko Head (*b*), and daily-averaged sea-surface temperatures from NDBC buoy 51002 (*c*), located southwest of Hawai'i (Figure 1), are shown. The NDBC buoy was not deployed until after the 1976–1977 event. In the original data at Scripps Pier (Figure 11*a*), there is a sudden increase in temperature in March 1989 that corresponds very closely to the major change in slope (i.e., turning point) in the cumulative sum shown in Figure 5*a* (indicated by the second arrow). The sudden dip in February 1989 indicated by the vertical arrow in Figure 11*b* at Koko Head corresponds to the time where the major change point occurs in the cumulative sum shown in Figure 5*b* (indicated by the first arrow). In Figure 11*c*, there is a short but obvious drop in temperature indicated by the arrow in February 1989 that again corresponds almost exactly to the time of the first turning point in the cumulative sum at Koko Head (Figure 5*b*). The second arrow in April 1989 coincides with the peak or highest point in the cumulative sum in Figure 5*b*.

We conclude that in some cases it may be possible to identify changes in the original data that correspond to the events of interest, and we find that reassuring. However, without the help of cumulative sums, it may be difficult to distinguish these events from many other sources of variability that naturally affect the variable of interest. One of the most important properties of cumulative sums is their ability to effectively suppress most sources of short-term variability, while accentuating change points in the data.

CONCLUSIONS

Sea-surface temperatures from Scripps Pier, off southern California, and from two locations near Hawai'i have been examined to determine how these observations were affected by two well-documented regime shifts in the North Pacific, one in 1976–1977 and one in 1988–1989. Cumulative sums were calculated to assist in detecting and localizing these events. We conclude that cumulative sums were useful in achieving the primary goals of this study.

The duration of the 1976–1977 event off southern California was approximately 7 months, whereas its duration off Hawai'i was closer to 4 months. The 1988–1989 event lasted approximately 6 months off southern California, and off Hawai'i it lasted approximately 2–3 months. Because of our ability to estimate the duration of these events rather precisely using cumulative sums, we must conclude that the durations of both events were much shorter off Hawai'i than they were off southern California.

A new procedure called the method of expanding means was introduced to examine the magnitude of the change associated with regime shifts and how well the change is sustained. Based on the results of this study we conclude that this method is well suited to determining both the magnitude and sustainability of these events and thus their impact.

Based on our analysis of the 1976–1977 regime shift at Scripps Pier off southern California, we conclude that as much as half of the total warming that has occurred off southern California since 1920 took place during that event.

Based on the results of a time scale analysis of the data from Scripps Pier and Hawai'i, the corresponding spatial scales are on the order of tens to hundreds of kilometers. Thus, we conclude that although the data come from single locations, our results apply to areas that are regional in extent.

We conclude that in some cases, the events examined in this study can be identified in the original data but that cumulative sums are usually required to make a positive identification.

Finally, we conclude that it has only been possible to obtain the results presented in this study because the observations that were

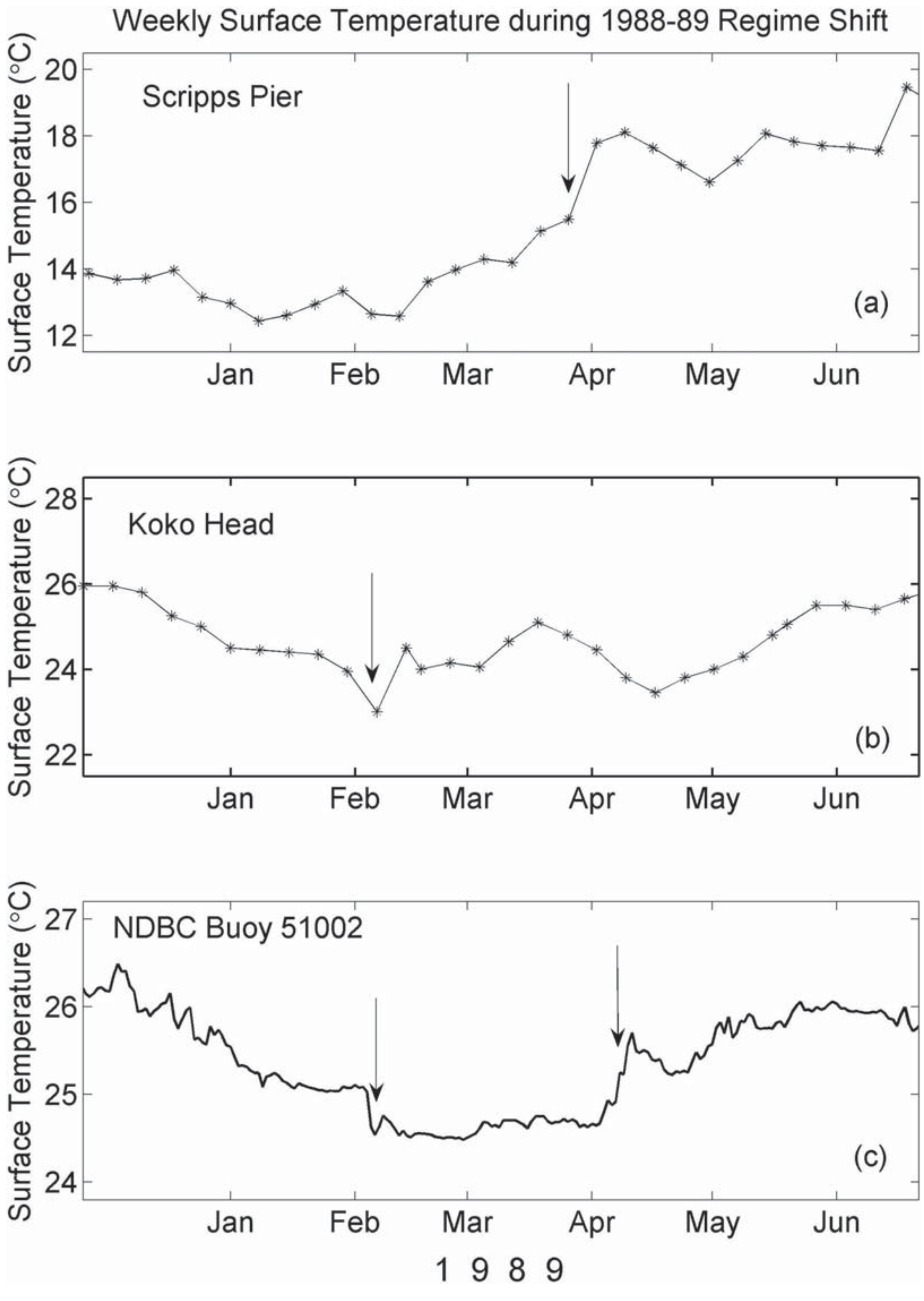

Figure 11. The original weekly sea-surface temperature data plotted during the period of the 1988–1989 regime shift at Scripps Pier (*a*), at Koko Head (*b*), and at NDBC buoy 51002 (*c*). The vertical arrows correspond to change points in the corresponding cumulative sums shown in Figures 5 and 7. Thus, the changes in sea-surface temperature indicated by the arrows show that there are also indications of this event in the original data.

employed have been acquired either daily or weekly at single locations and that spatial or temporal averaging may completely obscure the events of primary interest.

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Appendix 1

On Selecting the Starting Point for Calculating the Expanding Means

It was initially assumed that the best place to start calculating the expanding means was at the midpoint of a regime shift. However, we provided no evidence to support this assumption. To address this question we produced a synthetic time series that approximately simulates the observed data. First, we generated a normally distributed random sequence of 1,000 with a variance of 1.5. Then we added serial correlation based on a first-order autoregressive process with a lag-one autocorrelation of 0.9. Then a unit step increase from 10.0 to 11.0 was inserted at the midpoint of the sequence. The final sequence is shown in the top panel of Figure A1. Expanding means were then calculated in the forward and reverse directions starting at the midpoint, out to values of ± 300 about the midpoint. The results are shown in the middle panel of Figure A1. The expanding means settle down and converge to the correct values rapidly when we start the calculations at the midpoint of the sequence where the step occurs. Next, we started the calculations at locations before and after the step to show how the expanding means converge in these cases, compared with the first case (bottom panel of Figure A1). In one case the calculations were started before the step at sample number 400 (dashed, gray), and in the second case, the calculations were started after the step at sample number 550 (dotted, black). It is clear from this comparison, where the differences between the forward and backward (reverse) expanding means are shown, that convergence to the magnitude of the step (+1.0) occurs more rapidly when the expanding means are calculated from the step itself than for times before or after the step.

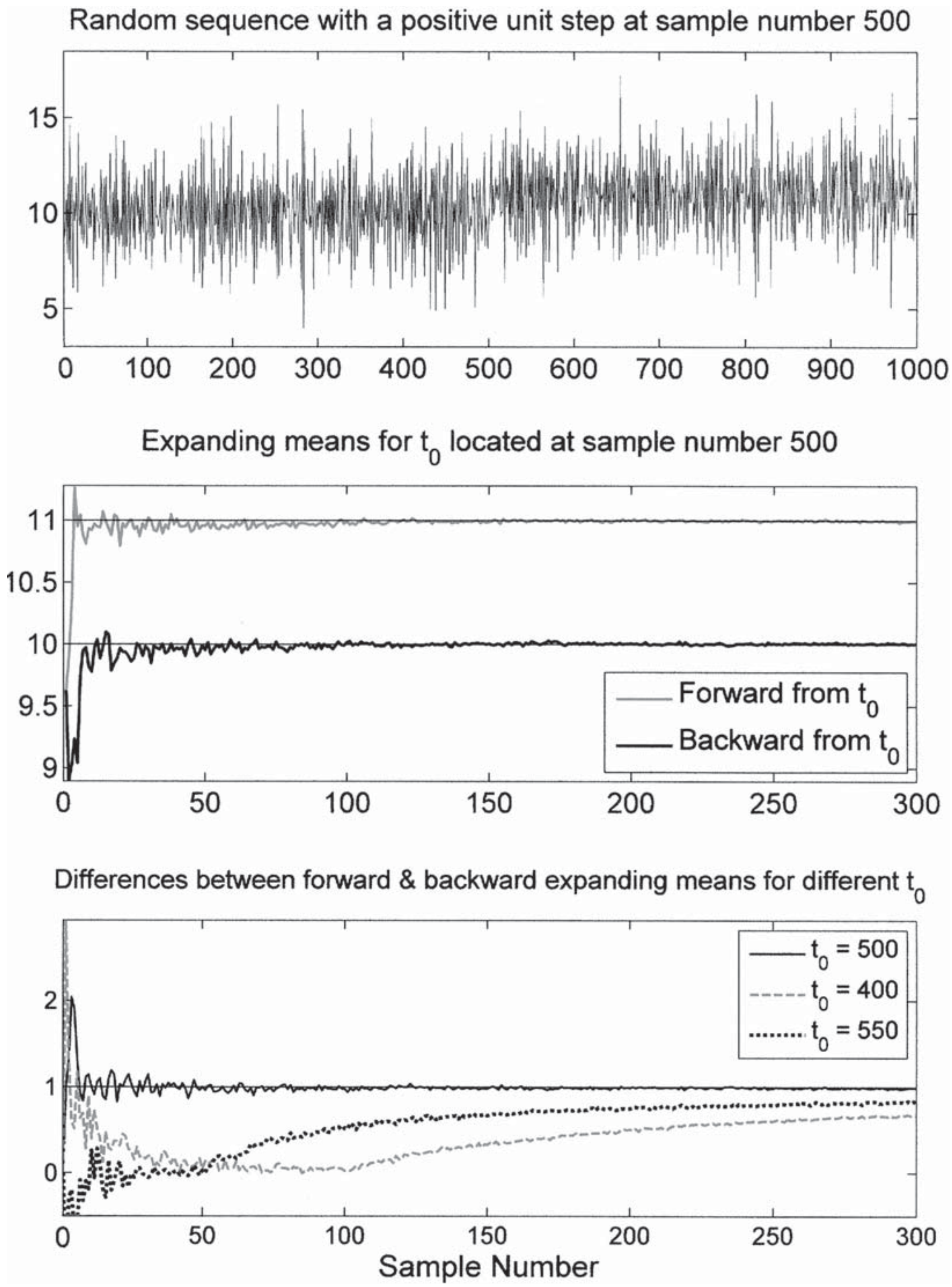

FIGURE A1. The top panel shows a normally distributed random sequence of 1,000 with a variance of 1.5 units, to which serial correlation and a unit step (from +10.0 to +11.0) located at the midpoint of the sequence have been added. The middle panel shows the expanding means calculated in the forward (light gray) and reverse (dark gray) directions from the location of the step (i.e., the midpoint) out to values of ±300 from the midpoint. The bottom panel shows the differences between the forward and reverse expanding means for starting locations of 500 (solid, black), 400 (dashed, gray), and 550 (dotted, black) out to values of ±300 from each starting point. See Appendix 1 for details.