Kelvin-Wave-Induced Anomalous Advection and the Onset of Surface Warming in El Niño Events

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ABSTRACT

The initial surface warming of the 1982 El Niño event was of quite different timing and pattern from that associated with most El Niño events; strong anomalous warming occurred first in July along the equator and subsequently along the South American coast. We show here that a simple advective model for tropical ocean surface warming can produce anomalous sea-surface temperature (SST) fields like those found in the first few months of the 1982 El Niño. The model physics assumes that the existing SST field is advected by anomalous currents to produce the anomalous warming, and that the anomalous currents are those induced subsequent to the passage of downwelling Kelvin wave front(s). With the initial SST field taken to be that of July 1982, the anomalous eastward currents of the model lead to a satisfactory prediction of the evolution of anomalous SST for several months. Numerical experiments with a fully nonlinear and thermally active ocean model support the physical relevance of the more idealized study.

The anomalous horizontal advection model can also account for the initial SST evolution during the more common type of El Niño event. The reason that a similar anomalous current field can produce two such different warming patterns is that the gradients of SST along the equator have strong seasonal variation. If anomalous eastward currents are generated along the equator between February and April, when the climatological zonal SST gradient is small, little equatorial warming will occur and so coastal warming is observed first; this is the case in most El Niño events. But if the same anomalous currents occur later in the year, when there is typically a strong zonal temperature gradient, strong equatorial surface warming will occur prior to coastal warming, as happened in 1982. The pattern of SST changes resulting from remote westerly wind changes in the tropical Pacific thus is very strongly linked to the annual cycle of SST.

1. Introduction

An important new test for any theory of the El Niño–Southern Oscillation (ENSO) cycle is posed by the unusual behavior of the tropical Pacific during 1982, when the sea-surface temperature (SST) increased in a fashion unlike the composite of most previous events. The composite picture of SST evolution in previous events has been presented by Rasmusson and Carpenter (1982) based on three-month averages and six events between 1949 and 1976 (Fig. 1). According to the composite scenario, anomalous surface temperature (in the sense of departure from the climatological seasonal cycle) typically first exceeds 1°C in March–April along the western tropical coast of South America just south of the equator. By September–October, the maximum anomaly has increased and the region of anomalously warm water extends out along the equator, sometimes to the Dateline.

In the 1982 event there was no anomalous coastal warming in the boreal spring (henceforth, all seasons refer to the Northern Hemisphere); instead, anomalously warm temperatures first appeared along the equator in late summer, and subsequently intensified and spread to the east. By the end of 1982, the anomaly occupied a region quite similar to that seen at the same time period in the composite picture. Fig. 2 shows the 1982 event according to F. Miller's analysis (personal communication, 1983). (Note that, because different SST analyses use different data and different SST climatologies, differences of 2°C between analyses of the 1982 event are common and should not, in our opinion, be accorded undue significance. The results of Fig. 2 should thus be used to form a large-scale picture of the changes in SST from month-to-month.)

Major atmospheric as well as oceanic changes occur during the period of surface warming, and understanding the full ENSO cycle will require that the coupled atmosphere–ocean system be examined. While some preliminary studies have been made which jointly use simple models for the ocean and atmosphere (McCreary, 1983; Philander, 1983), they make specific assumptions about the mechanisms which act to change the surface temperature and winds; these assumptions

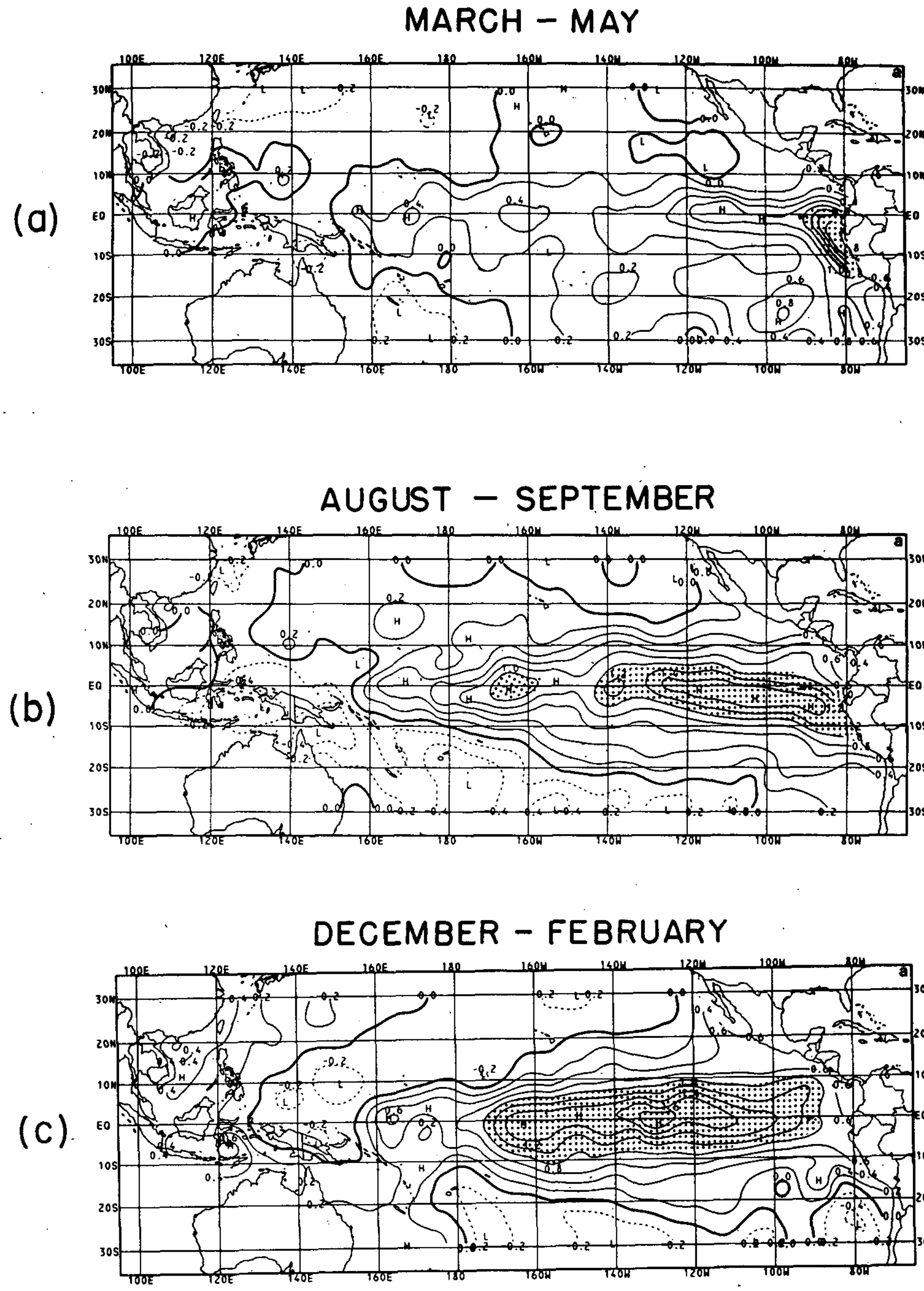


FIG. 1. Composite analysis of El Niño warming based on three-month averages of SST anomalies; from Rasmusson and Carpenter (1982). Contour interval is 0.2°C; stippled areas have anomalous SST greater than +1.0°C.

deserve further scrutiny in light of recent work (Gill, 1983; Schopf and Harrison, 1983; Schopf, 1983). Here we investigate the more limited problem of explaining the initial evolution of SST in the composite and 1982 types of El Niño events using thermally and dynamically consistent ocean models, and assuming that the behavior of the atmosphere is roughly known.

We argue that the initial (first 3–4 months) surface warming of both types of ENSO event can be produced by a single process associated with the passage of downwelling Kelvin wave fronts. We also show that the seasonal cycle of SST in the equatorial Pacific provides the key to understanding the differences between the two patterns. The mechanism is anomalous ad-

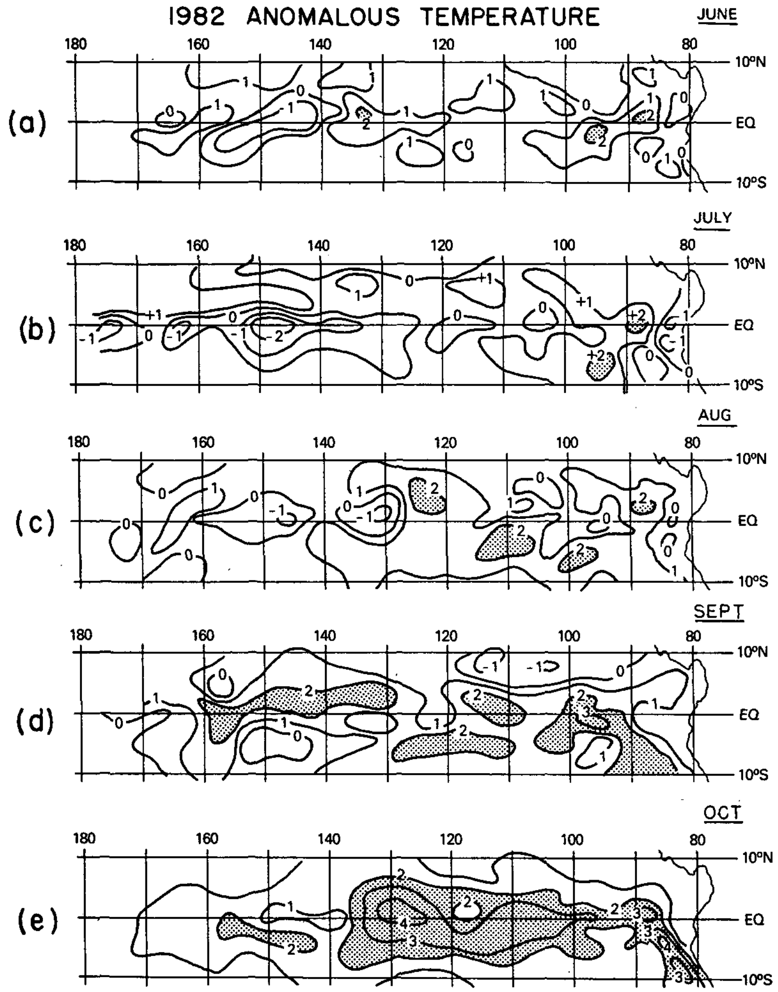


FIG. 2. Monthly-mean SST anomalies for July through October 1982 as prepared by F. Miller. Contour interval is 1°C; stippled areas have anomalous SST greater than +2.0°C. Note that the composite SST anomalies (Fig. 1) are much smaller than those of the 1982 event, both because the 1982 event was unusually intense and because of the averaging which took place in forming the composite.

vection, hypothesized by Gill (1983) to describe much of the surface warming of the 1972 El Niño, and found responsible for most of the warming in the series of idealized but nonlinear numerical experiments described by Schopf and Harrison (1983).

These results presume the existence of anomalous atmospheric westerly winds in the central or western equatorial Pacific to force the hypothesized downwelling Kelvin wave fronts. There is recent evidence that anomalous westerly winds in the equatorial Pacific do precede most events; Luther *et al.* (1983; hereafter LHK), discuss one type of anomalous wind variability, while Barnett (1983) discusses another. A true theory for the onset of an ENSO event requires some process (mechanistic or random) to produce the anomalous winds. No theory of the onset of the ENSO cycle exists at present.

2. Downwelling Kelvin waves and anomalous advection

The importance of horizontal advective processes in mean tropical SST balances has long been known, but their connections to anomalous behavior have only recently become clearer. Philander (1981) pointed out that advective warming could be induced following Kelvin wave frontal passage in the presence of a mean zonal SST gradient, and Gill (1983) was lead by a process of elimination to assume that horizontal advection is a dominant factor in his single layer model reconstruction of the 1972 surface warming. According to linear equatorial wave theory (e.g., Cane and Sarachik, 1976), a stationary regionally confined westerly wind anomaly blowing on an otherwise quiescent ocean forces downwelling Kelvin waves of different vertical modal structures to propagate eastward from the forcing region at different speeds (the lower the mode, the faster the speed). At a given location east of the forcing region the anomalous surface current is zero until the first Kelvin wave front arrives. At that time an acceleration is set up which creates an anomalous eastward surface current ($u' > 0$). Subsequent evolution of the anomalous surface flow is determined by the integrated forcing along the wave characteristics for previous time, and the arrival of other waves.

If the region of anomalous forcing moves eastward, the details of the current changes are altered, but the basic flow evolution is similar. The Appendix offers a discussion of the linear dynamics of an expanding wind patch relevant to the problem of interest, and shows that the current acceleration can be quite abrupt or rather slow. We note that if the wind forcing is confined to the ocean mixed layer (where the stability is neutral), westerly surface stress will contribute to eastward surface flow in all of the low-order vertical modes. See Weisberg and Tang (1983) for further discussion of the relevant linear theory.

When a downwelling Kelvin wave front impinges upon the eastern boundary of the basin, some of its energy moves poleward along the boundary as a coastal Kelvin wave front and some is reflected westward as a much more slowly-propagating Rossby wave front. South of the equator along the boundary, an anomalous southward surface current ($v' < 0$) is accelerated behind the coastal Kelvin wave front, in a manner similar to that observed for the zonal current along the equator. The anomalous vertical velocity is downward near the surface ($w' < 0$), both along the coast and the equator.

A usefully simplified heat equation linearized about the conditions at a particular time is

$$\frac{\partial T'}{\partial t} = u'\frac{\partial \bar{T}}{\partial x} - v'\frac{\partial \bar{T}}{\partial y}, \qquad (1)$$

where overbars denote the pre-existing conditions, and primes denote departures from these conditions. Eq. (1) describes what we shall call the "anomalous advection" balance. Despite the simplifications, (1) was found to be an adequate basic balance for the SST changes observed in the fully nonlinear and thermodynamically active model studies described by Schopf and Harrison (1983). They found that immediately along and adjacent to the eastern coast the effects of meridional and vertical advection may not be easy to separate, but along the equator (1) is especially useful. Note that when the anomalous advection balance holds, SST will change only when both an anomalous current and a non-orthogonal SST gradient exist.

3. Anomalous advection and El Niño initial surface warming

In order to examine the implications of this balance to the initial surface warming in El Niño events, we must consider the SST gradients in the El Niño region and their seasonal variations.

Recent analyses of the climatological SST from merchant ship surface data (Reynolds, 1982) are presented in Fig. 3. Along the equator during February through May, $\partial T/\partial x$ is generally very weak and negative (perhaps -2×10^{-7} °C m^{-1}), but it is much more strongly negative in summer and fall (perhaps -10^{-6} °C m^{-1}). South of the equator along the South American coast, the meridional temperature gradient is strong and quite variable spatially. Often $\partial T/\partial y$ is positive just south of the equator, but it always becomes positive somewhere north of 10°S and then negative somewhat farther south.

Given u' and v' fields from our assumed dynamics and this SST information, we can now examine the SST changes that are predicted by the anomalous advection balance. Note that the changes depend critically on the time of the year in which the Kelvin wave front passes. Wave passage in February through May will produce very little equatorial SST change (0.3°C month^{-1} if $\partial T/\partial x$ is -2×10^{-7} °C m^{-1} and u' is 0.5

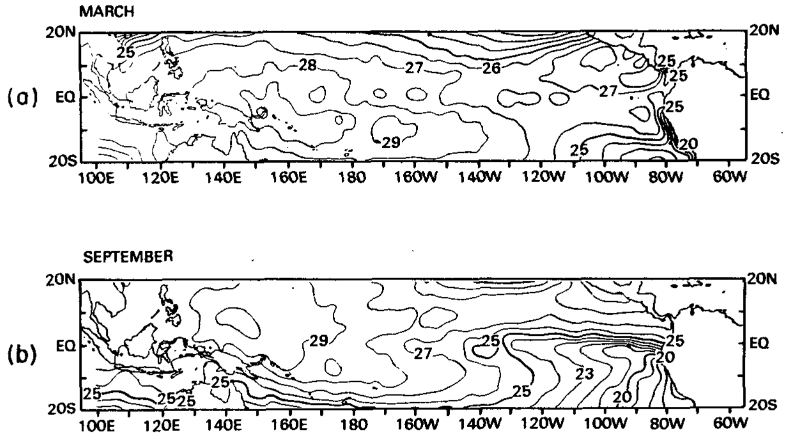
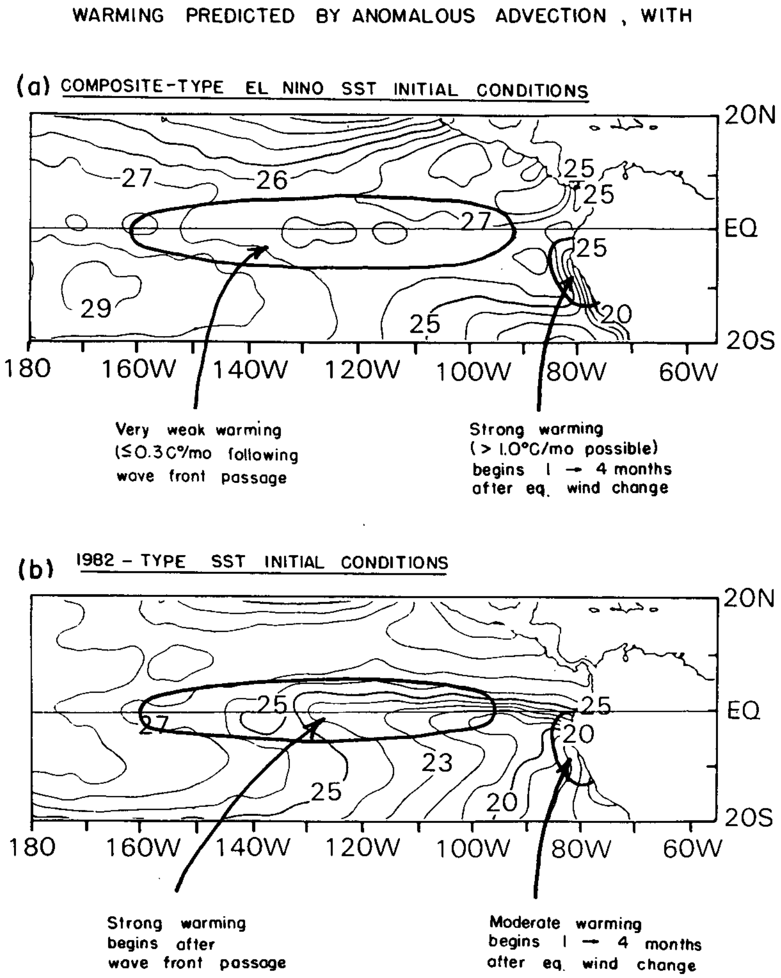


FIG. 3. Climatological SST for March and September; from Reynolds (1982).

m s^{-1}). The same anomalous current situation in July, when the gradient is more like -10^{-6} °C m^{-1}, will produce substantial equatorial SST warming (~ 1.5°C $month^{-1}$).

Coastal warming will be produced by anomalous meridional advection where $\partial T/\partial y$ is positive (since $v' < 0$). The details of the warming will vary with time of year, but generally warming is expected between the equator and perhaps 15°S with the greatest warming between 10°S and a few degrees south of the equator (where $\partial T/\partial y$ is positive and greatest). It is not straightforward to estimate the magnitude of the anticipated coastal warming from anomalous advection because the maximum gradient is not easy to estimate, but certainly it can be comparable to the maximum equatorial warming rate.

Thus the timing and location of the initial warming in the composite El Niño events and in the 1982 event are consistent with the anomalous advection model, whose predictions are sketched in Fig. 4. Nearly unmeasurable equatorial warming will occur in the wake of one or more downwelling Kelvin wave fronts, propagating through the eastern Pacific in the period February through April, but there will be substantial South American coastal warming from one to several months later (depending on the wave front phase speed). The initial warming should continue until other oceanic or atmospheric factors change the circulation or the local forcing. This corresponds to the initial months of the composite El Niño scenario. If, however, the downwelling wave fronts propagate through the eastern Pacific later in the year, there should be substantial equatorial SST warming one to several months prior to the onset of South American coastal warming. This corresponds to the initial SST evolution of the 1982 El Niño event.


WARMING PREDICTED BY ANOMALOUS ADVECTION, WITH

(a) COMPOSITE-TYPE EL NINO SST INITIAL CONDITIONS

Very weak warming (≤0.3C°/mo following wave front passage

Strong warming (> 1.0°C/mo possible) begins 1 → 4 months after eq. wind change

(b) 1982 - TYPE SST INITIAL CONDITIONS

Strong warming begins after wave front passage

Moderate warming begins 1 → 4 months after eq. wind change

FIG. 4. Schematic description of the timing and location of SST changes expected from the anomalous advection model. (a) The composite El Niño situation, with Kelvin wave front propagation near the beginning of the year; the first strong warming will occur at the coast. (b) The 1982 El Niño, with Kelvin wave front propagation near mid-year; the first observable warming will occur along the equator.

4. Model studies of the 1982 initial warming

We can examine the 1982 event further in light of these ideas. Ship and island wind data indicate that there was a major westerly change in the zonal wind near the Dateline at the equator in late June 1982; the wind shifted from generally weak (2–5 m s^{-1}) easterlies to weak-to-moderate (up to 8 m s^{-1}) westerlies over a period of less than a month, and the westerlies then persisted for several months (Sadler and Kilonsky, 1983). The anomalous surface winds appear to have moved from west to east during this time. Such a change should force one or more of the hypothesized downwelling Kelvin wave fronts and, because the change was so large, a substantial anomalous eastward surface current.

a. Anomalous Advection Results for 1982

A very simple model to study the relevance of anomalous advection to the initial equatorial SST changes of the 1982 event can be constructed as follows:

1) A cubic spline fit to the July 1982 equatorial SST field gives the initial SST condition, and the anomalous current is initially zero.

2) The anomalous current is quickly accelerated to 0.6 m s^{-1} eastward after a first mode Kelvin wave front traveling at 2.5 m s^{-1} eastward passes the longitude of interest (see the Appendix). It is assumed that this wave front was at the Dateline at the end of June.

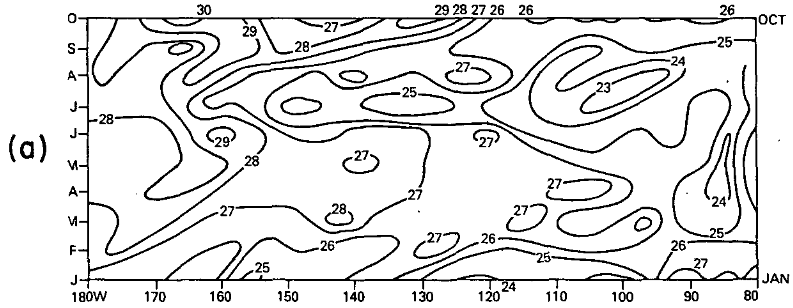
3) The initial SST field is advected by the anomalous current to predict the evolution of SST.

4) The predicted SST anomaly is obtained by subtracting a spline fit to climatology from the advected SST field.

The abrupt change in current is caused by the eastward movement of the forcing, on the basis of the results summarized in the Appendix. Figure 5a shows the evolution of 1982 SST along the equator and Fig. 5b shows the time evolution of the anomalies as determined from the data in Fig. 2. Figs. 6a and b present the predicted SST and its anomaly between July and October 1982 according to the above anomalous advection model. The amplitude and spatial structure are in good general agreement.

This very simple type of model also can be used to illustrate the importance of the time of year on the effects of such an anomalous advection event. We repeated the above calculation using February 1982 data for the initial SST field. The predicted SST and its

1982 SST ALONG EQUATOR



1982 SST ANOMALIES ALONG EQUATOR

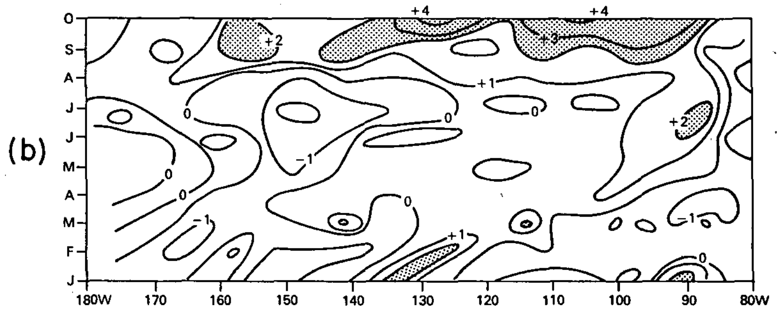


FIG. 5. Equatorial time–longitude sections for 1982 of (a) SST as derived from F. Miller's data, and (b) anomaly of SST as obtained from the data in Fig. 2. Stippled areas have anomaly greater than +2.0°C.

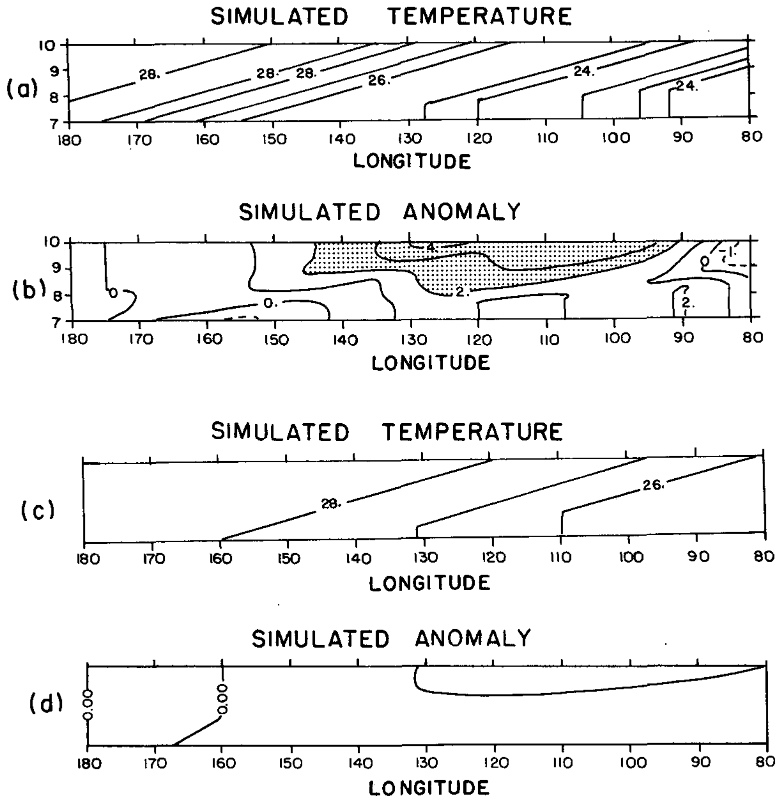


FIG. 6. Equatorial time–longitude behavior predicted by a simple anomalous advection model using 1982 conditions. (a) SST obtained with Kelvin wave passage in mid-year; July initial SST conditions. (b) SST anomaly from (a). (c) SST obtained with Kelvin wave passage in February–March; February initial SST conditions. (d) Change in SST from February. Wave frontal speed is taken to be 2.5 m s^{-1}; particle velocity behind the wave front is taken to be 0.60 m s^{-1}. See text for further explanation.

anomaly is shown in Figs. 6c and d, and must be considered unmeasurable with the usual sparse set of SST observations in this region. If the strong forcing anomaly of 1982 had occurred around the beginning of the year, there would have been no significant equatorial SST signal from Kelvin wave passage along the equator.

Clearly the anomalous advection mechanism can reproduce much of the initial equatorial SST evolution of the 1982 event. The use of plausible wave front speeds and anomalous surface current speeds leads to a satisfactory description of amplitudes, positions and timing of the SST changes.

b. Nonlinear numerical model results

To examine the importance of the mechanism further, it is necessary to turn to a numerical model system that predicts SST and currents from first principles. The ideal experiment would be to initialize a physically complete model to June 1982 conditions for the atmosphere and ocean, and then introduce the 1982 wind changes and follow the evolution of SST. With the ocean models and data available to us, such initialization is not possible. Instead we spun up the model to an initial state which reproduces many of the SST characteristics of June 1982, and then introduced a wind anomaly grossly similar to that of 1982.

The model is as described in Schopf and Harrison (1983), but with the surface heat flux parameterized as in Schopf (1983). Primitive equation dynamics are used in two thermally active layers, whose interface is determined through mixed-layer physics. The temperature field affects the pressure force in the model and is determined through three-dimensional advection, turbulent mixing and surface heating. The basin is rectangular, extending from 20°S to 20°N, and covering 75° of longitude (80–155°W).

In Fig. 7 we present the initial SST pattern which was generated by driving the model with south-southeasterly winds ($\tau^x = -0.025$ N m^{-2}, $\tau^y = 0.05$ N m^{-2}). There is a manifestation of both coastal upwelling due to the southerly component, and equatorial upwelling due to the zonal stress. To model the wind forcing of the 1982 event, we imposed a zonally confined uniform westerly wind anomaly whose eastern edge was at the model western boundary on day zero, but moved eastward by 35° over 35 days. The movement of the patch

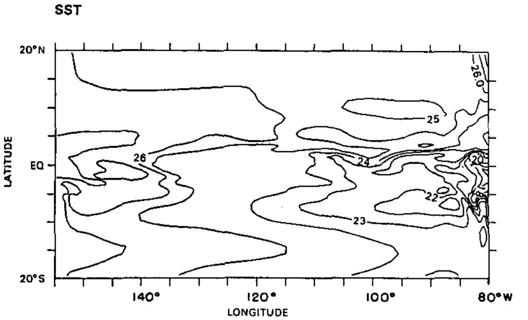


FIG. 7. Initial SST conditions for the numerical model of the 1982-like warming. The model was spun-up for three years with constant south-southeasterly winds of 0.056 N m^{-2}. See text for further explanation.

was stopped after 35 days, leaving anomalous winds between 120°W and the western boundary.

Anomalous advection can be the result of remote and local wind changes; any change in u' and v' can produce SST changes. When the wind changes are well to the west, the anomalous currents will be given at least qualitatively by the free Kelvin wave kinematics. However, when there are local and remote changes, as appears to have been the case in the 1982 event, the equatorial surface current changes need not be so easily described. In these model runs, both local and remote forcing exist west of 120°W.

To verify that anomalous advection is the dominant mechanism causing SST change, experiments were performed with 0.1 and 0.05 N m^{-2} wind stress anomaly patches imposed on identical initial conditions. Since the same initial conditions were used, linear theory predicts that the wave front propagation speed for a particular mode will be the same in each experiment. Fig. 8 shows equatorial time-longitude plots of SST and anomalous surface current u' for the experiments. Note that the speed of propagation of the model's first baroclinic mode wavefront ($c_\omega \approx 1.8$ m s^{-1}) is clearly seen in both plots of u' (Figs. 7b and d) and that the acceleration of u' is rapid (~30 days to maximum u'), as predicted by linear theory for eastward wind patch motion of $c_f \approx 1.2$ m s^{-1}. As also would be expected from linear theory, doubling the anomalous stress doubles the maximum anomalous surface current; the fields of u' differ by a factor of 2 in the two experiments, but are similar in shape (Figs. 7b and d). Linear theoretical notions are quite useful, even for relatively strongly forced flows on a very nonlinear basic state.

The SST equatorial sections (Figs. 7a and c) show the front at ~140°W in the initial condition (Fig. 6) beginning to move eastward ~20 days after the onset of the anomalous winds in each experiment, but mov-

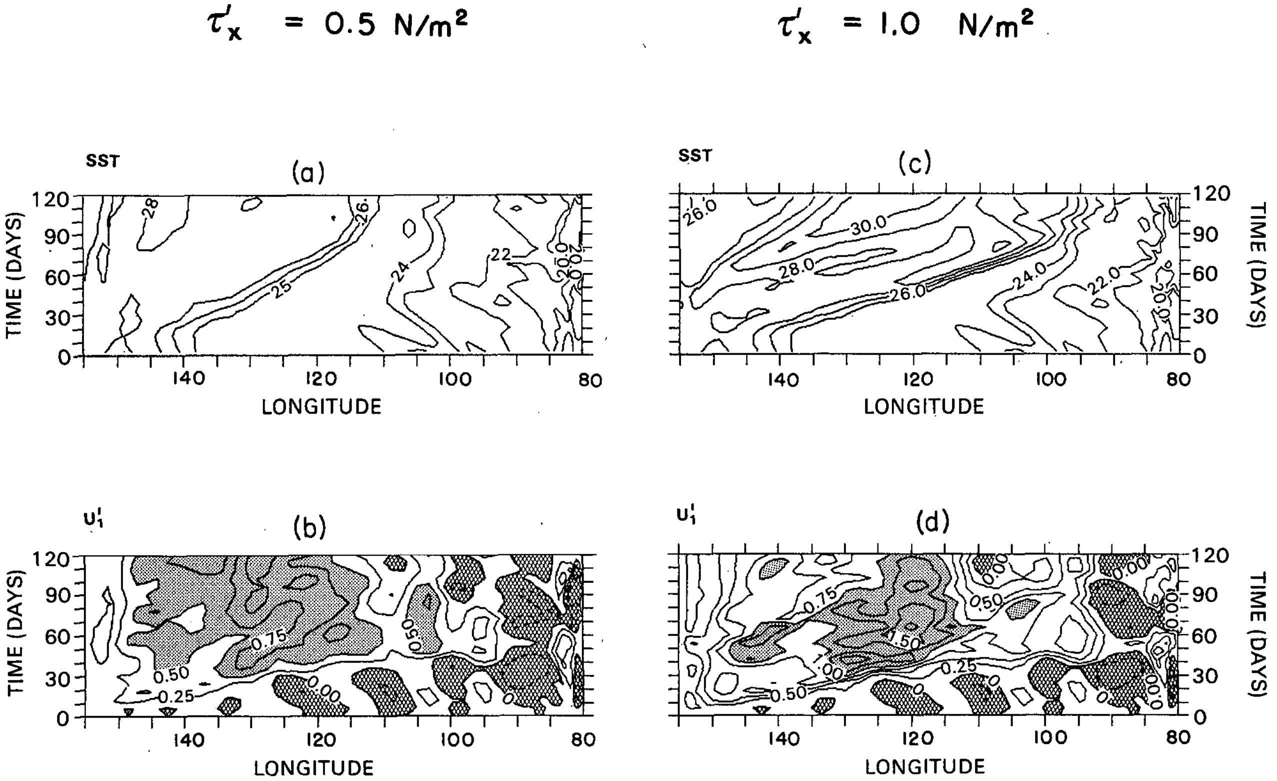


FIG. 8. Equatorial time-longitude sections of the model anomalous surface current u', and of SST for two anomalous westerly wind patch experiments using $\tau'_x = 0.05$ N m^{-2} (a and b), and $\tau'_x = 0.1$ N m^{-2} (c and d). Regions where u' exceeded 0.5 m/s^{-1} are stippled on the left, and regions where u' exceeded 1.0 m s^{-1} are stippled on the right. Negative u' regions are cross-hatched. See text for discussion.

ing at about twice the speed in the 0.1 N m^{-2} case ($\sim$1.2 m s^{-1}) than in the 0.05 N m^{-2} case ($\sim$0.6 m s^{-1}). These latter speeds are quite similar to those found for u' in the appropriate cases. The anomalous advection mechanism is clearly central in the evolution of equatorial SST; SST changes begin as the wavefront passes (the same time in each case) and proceed at rates that differ by a factor of 2 (corresponding to the different u' speeds). Vertical mixing and advective processes are allowed by the model surface-layer physics, but anomalous zonal advection appears to be the dominant SST change process.

All the preceding model discussions have focused on equatorial SST changes. The meridional extent of the SST warming produced by the anomalous advection also can be examined in the numerical model results. Fig. 9 is a plot of the SST change 120 days after the onset of the 0.1 N m^{-2} winds. It is clear that the extent of off-equatorial warming is quite comparable to that seen in the SST data.

The same model has been used to study the onset of warming in "normal" El Niño years. Schopf and Harrison (1983) and Schopf (1983) examined the model response when the zonal SST gradient along the equator was small. If there is an appropriate remote westerly wind perturbation, the anomalous advection mechanism acts, as predicted, to produce the initial warming in the east, where the temperature gradient first becomes significant and non-orthogonal to the wave-induced current.

5. Discussion

The anomalous surface currents forced by remote westerly wind stress anomalies can, through anomalous advection of the existing SST field, produce surface warming patterns like those observed in the initial months of both composite-type and 1982-type El Niño events. The anomalous advection mechanism thus provides a single simple explanation for the two very different warming patterns, in terms of the seasonal changes in the gradient of SST along the equator and the South American coast, and the surface current changes predicted by linear theory to occur after Kelvin wave front passage.

Confirmation of the importance of this mechanism requires sufficiently accurate surface current and SST data to estimate the anomalous advective changes to better than 0.5°C per month. The data available for the 1982 event indicate that the anomalous currents hypothesized in the simple model calculation in Section 4 are plausible, and support the view that the advective process was important between July and October 1982. By October 1982 the changes in local forcing had become substantial over much of the region of surface warming, and the processes responsible for further SST changes had undoubtedly become more complex.

There is considerable evidence to support an idealizing of the initial wind stress anomaly of 1982 as an abruptly appearing and eastward expanding patch of westerly stress, as assumed in the model studies described here. However, the character of the wind changes along the equator that preceed other El Niño events remains an area of active research. Documentation of precursive wind changes contained in the marine observation data set has been somewhat uncertain, as is discussed by Luther and Harrison (1984). But the later, mid- to late (northern) summer large zonal wind changes are clear even in the marine deck (e.g., Rasmusson and Carpenter, 1982). Luther *et al.* (1983) have shown, based on observations from atolls in the central and western Pacific, that substantial anomalies, in the form of westerly bursts of less than one month duration, occur one to four months prior to South American coastal warming in nine of the ten post-1950 El Niño events. Further work is required to determine the specific character of the current changes

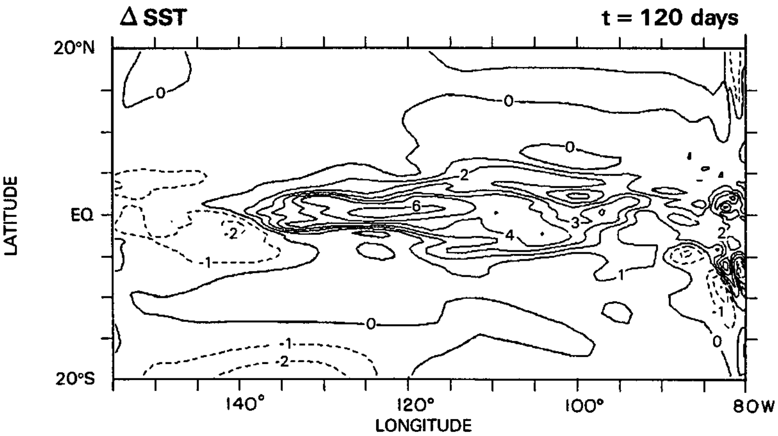


FIG. 9. Change in SST 120 days after the initial onset of a 0.1 N m^{-2} anomalous westerly stress. Note that the meridional scale of warming is comparable to that observed in Fig. 2.

induced by such bursts, and of the warming that the induced currents will create.

Although we have focused here on the initial surface warming in El Niño events, the anomalous advection mechanism is possibly important also in the massive late summer warming in composite-type El Niño events. As Philander (1981) has pointed out, the large westerly wind anomalies that occur in the central Pacific in mid-year of such events should cause anomalous eastward surface currents. Because of the strong summer zonal temperature gradient along the equator, anomalous advection will produce, very much as it did in the 1982 warming, broad equatorial warming into the later half of the year.

From this perspective the composite El Niño SST warming cycle could be produced by two anomalous advection episodes; an initial warming along the eastern boundary beginning around March which spreads slowly west along the equator, followed by a stronger warming that begins in the central Pacific and spreads rapidly eastward as a response to the summer collapse of the trade winds in the central Pacific. This view is not necessarily inconsistent with the suggestion of westward propagation of anomalously warm SST in the three-month-average composite maps of Rasmusson and Carpenter (1982) (Fig. 1), because the advective warming could occur so quickly that it is simply obscured by that sort of analysis.

To summarize, we have offered a simple mechanism for the initial SST changes of all types of El Niño event, using physically complete thermodynamics and hydrodynamics. We have not addressed either the origin of the wind changes necessary to drive the behavior discussed, or the nature of the coupled dynamics of the later stages of El Niño events. Much more work needs to be done on these problems before the El Niño–Southern Oscillation cycle can be understood.

APPENDIX

Current Accelerations From Linear Kelvin Waves Forced By Eastward-Expanding Winds

Here we consider briefly an aspect of the oceanic responses to a wind anomaly that spreads eastward with time, namely the effect of the eastward expansion on the acceleration of currents behind a Kelvin wavefront propagating east of the wind anomaly. It is convenient for our purposes to ignore the existence of boundaries, since the anomalous currents of interest are accelerated and do most of their work on the temperature field before any reflected Rossby waves would enter the region of interest. The solution consists of a set of eastward-propagating Kelvin waves in this region.

Suppose that the wind is of unit magnitude, is first seen at $x = -L$, and spreads eastward with speed c_f, arriving at $x = 0$ at time $t = 0$. The stress anomaly then occupies a region in space–time as shown in Fig. A1, on which the relevant Kelvin wave characteristics are indicated. The forced wave equation for positive x is

$$\frac{\partial u}{\partial t} + c_w \frac{\partial u}{\partial x} = F, \tag{A1}$$

where F is the wind forcing projected onto the wave mode appropriate to the free wave speed c_w; u is that portion of the total velocity field associated with the Kelvin wave and is the quantity of interest to us.

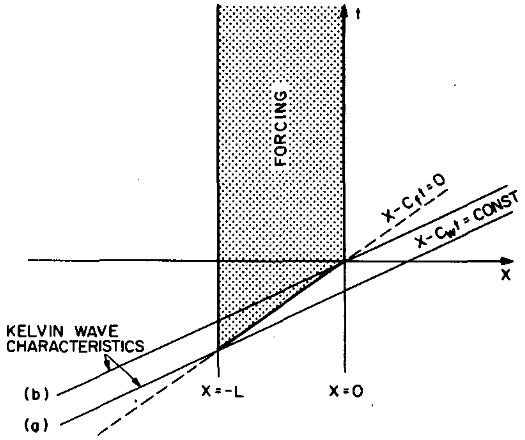


FIG. A1. Time–longitude domain of the spreading wind field, and Kelvin wave characteristics. Characteristic (a) is the first to encounter the wind, and characteristic (b) is the first to encounter the full wind anomaly.

Solutions are found by integrating along the characteristics of (A1). To determine the time to reach maximum speed, it is only necessary to identify the two characteristics which are a) the first to encounter any forcing, and b) the first to cross all the forcing. In the case shown in Fig. A1, these two characteristics are those which pass through $x = -L$ at $t = -L/c_f$ and through $x = 0$ at $t = 0$, and are labeled (a) and (b). The time taken for the flow to accelerate to full

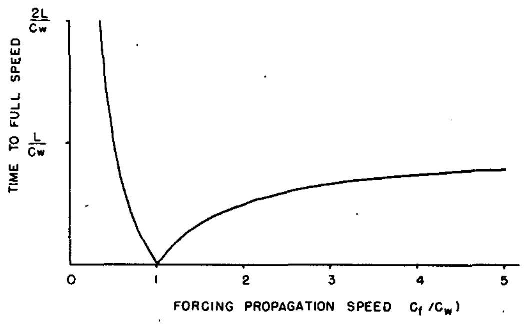


FIG. A2. Time interval required for Kelvin-wave-induced flow to reach full speed east of the forcing region ($x \geq 0$) as a function of the speed at which the wind spreads eastward, normalized by the wave propagation speed c_f/c_w. For $c_f < c_w$, the acceleration precedes the arrival of the winds at $x = 0$; for $c_f > c_w$, the acceleration follows.

speed as seen by an observer at a fixed location east of the wind anomaly is given by

$$\Delta t = L|c_f - c_w|/c_f c_w. \tag{A2}$$

Note that if $c_f = c_w$, the two criteria are met by a single characteristic, and the acceleration to full speed is instantaneous. The dependence of the acceleration time on the spreading rate of the wind is shown in Fig. A2.

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