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EL NIÑO

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INTRODUCTION

> In the year 1891, Señor Dr. Luis Carranza, President of the Lima Geographical Society, contributed a small article to the Bulletin of that Society, calling attention to the fact that a counter-current flowing from north to south had been observed between the ports of Paita and Pacasmayo.
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> The Paita sailors, who frequently navigate along the coast in small craft, either to the north or to the south of that port, name this counter-current the current of "El Niño" (the Child Jesus), because it has been observed to appear immediately after Christmas.
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> As this counter-current has been noticed on different occasions, and its appearance along the Peruvian coast has been concurrent with heavy rain in latitudes where it seldom, if ever, rains to any great extent, I wish, on the present occasion, to call the attention of the distinguished geographers here assembled to this phenomenon, which exercises, undoubtedly, a very great influence over the climatic conditions of that part of the world.

These remarks are taken from an 1895 address to the Sixth International Geographical Congress by Señor Federico Alfonso Pezet of the Lima Geographical Society (Pezet 1896). The El Niño countercurrent was apparently first reported by the Frenchman Lartigue in 1822, but the Peruvian climate anomalies that are a part of the larger pattern we now refer to as El Niño are documented at least as far back as 1726 (Quinn et al 1978).

Carranza's article and Pezet's talk were prompted by the "tremendous rains" associated with the El Niño of 1891, probably the strongest in the past 100 years—until superseded by the El Niño of 1982/83, the El Niño preceding the present article. Concerning 1891, Pezet goes on to note that

> it was then seen that, whereas nearly every summer here and there there is a trace of the current along the coast, in that year it was so visible, and its effects were so palpable by the fact that large dead alligators and trunks of trees were borne down to Pacasmayo from the north, and that the whole temperature of that portion of Peru suffered such a change owing to the hot current which bathed the coast.

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The connection between El Niño and climate is not restricted merely to the region directly touched by the El Niño current; rather, it is a *global* pattern of anomalies referred to as the Southern Oscillation. Major El Niño–Southern Oscillation (ENSO) events, such as those of 1891 or 1982, have profound global ecological, social, and economic consequences (e.g. Barber & Chavez 1983, Canby 1984, Glantz 1984). ENSO is also of scientific interest as the best-defined, most prominent signal in year-to-year climate variability. As such, it is widely perceived as an entrée to a broader understanding of the atmosphere and ocean as a coupled climate system.

The seminal figure in delineating the Southern Oscillation was Sir Gilbert Walker, the Director-General of Observatories in India. Walker assumed his post in 1904, shortly after the famine resulting from the monsoon failure of 1899 (an El Niño year). He set out to predict the monsoon fluctuations, an activity begun by his predecessors after the disastrous monsoon of 1877 (also an El Niño year). Walker was aware of work indicating a swing of sea-level pressure from South America to the India-Australia region and back, with a period of several years (cf Rasmusson 1985).

Over the next 30 years Walker added correlates from all over the globe to this primary manifestation of the Southern Oscillation; among these were rainfall in the central equatorial Pacific and in India, and temperatures in southeastern Africa, southwestern Canada, and the southeastern United States (Walker 1924, Walker & Bliss 1932). No conceptual framework supported the patterns he found; Walker's methods were strictly empirical. Together with the short duration of the records then available, this made it easier for others to dismiss his findings as mere artifacts.

By the 1960s interest in the Southern Oscillation began to revive (cf Rasmusson 1985), and Walker's correlations were found to hold when reexamined with decades of new data (see especially Horel & Wallace 1981). Although both El Niño and the Southern Oscillation had been known at the turn of the century, it was only now that the connection between them was finally recognized, principally through the work of Bjerknes (1966, 1969, 1972). Figure 1 shows how closely these two are related.

Bjerknes did more than just point out the empirical relation between the two; he also proposed an explanation that depends on a two-way coupling between the atmosphere and ocean. His ideas were motivated by observations of large-scale anomalies in the atmosphere and tropical Pacific Ocean during 1957–58, the International Geophysical Year.

As it happened, a major El Niño occurred in those years. (Coincidentally, they were also the last two years of Sir Gilbert Walker's life.) It is implausible that a local coastal warming could cause global changes in the atmosphere, but the 1957 data showed that the rise in sea-surface

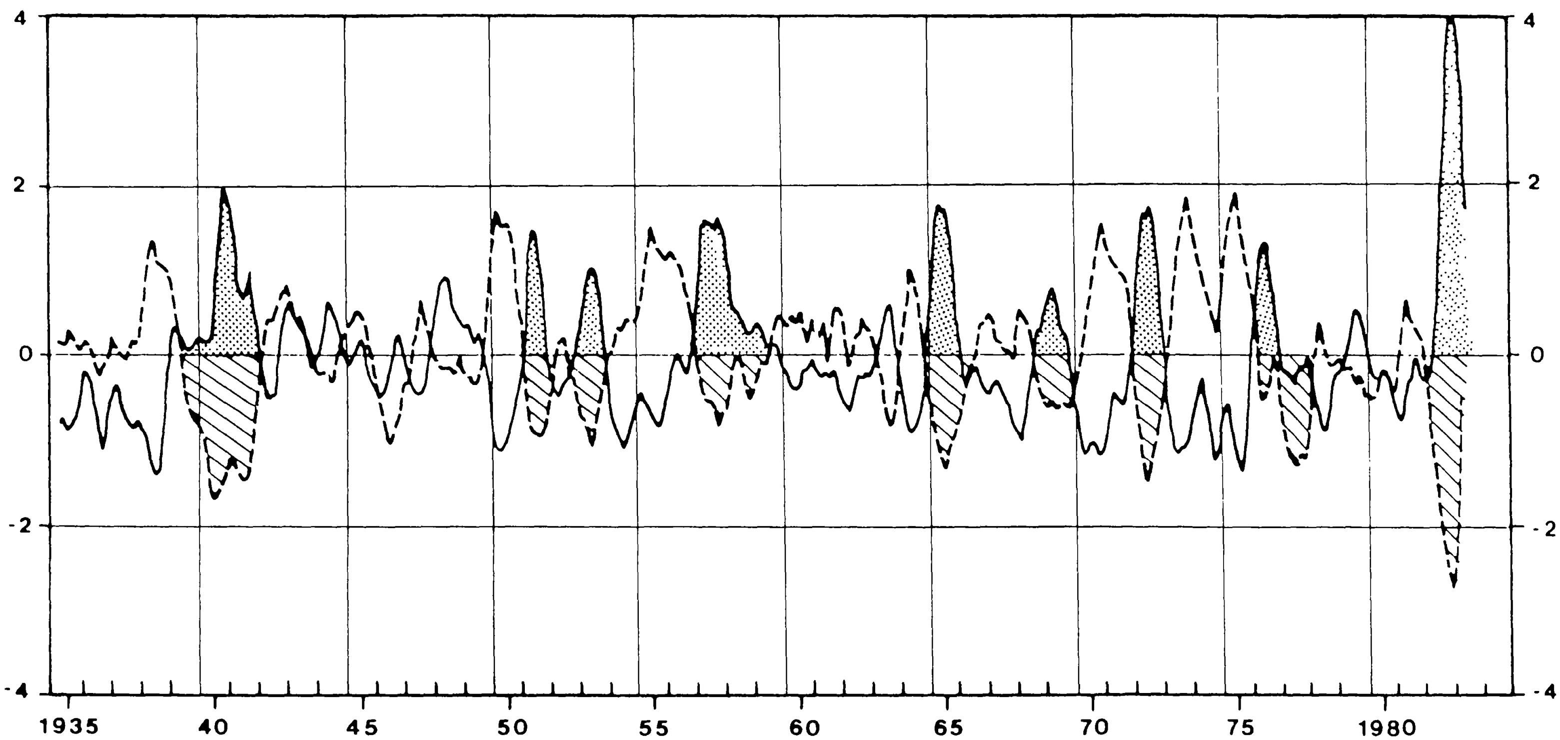

Figure 1 The solid line gives sea-surface temperature anomalies at Puerto Chicama, Peru, an index of El Niño. The dashed line is the difference in sea-level pressure between Darwin, Australia, and Tahiti, an index of the Southern Oscillation. Both are normalized by their long-term standard deviations. Major El Niño events are shaded (from Rasmusson 1985).

temperature (SST) extended along the equator from the South American coast to the date line (cf Figure 2). Bjerknes suggested that this feature was common to all El Niño events; he was correct, and the term "El Niño" is now often used to denote the basin-scale oceanic changes. In his account of the connection between the ocean and atmosphere, the coastal events constituting the narrow definition of El Niño are incidental to the important oceanic change: the warming of the tropical Pacific over a quarter of the circumference of the Earth.

Bjerknes suggested a tropical coupling between El Niño and the Southern Oscillation; he also hypothesized a link between tropical Pacific SST and midlatitude circulation anomalies. This teleconnection idea is consistent with the global nature of Walker's Southern Oscillation pattern. It is a subject of intense interest among theoreticians, observationalists, and

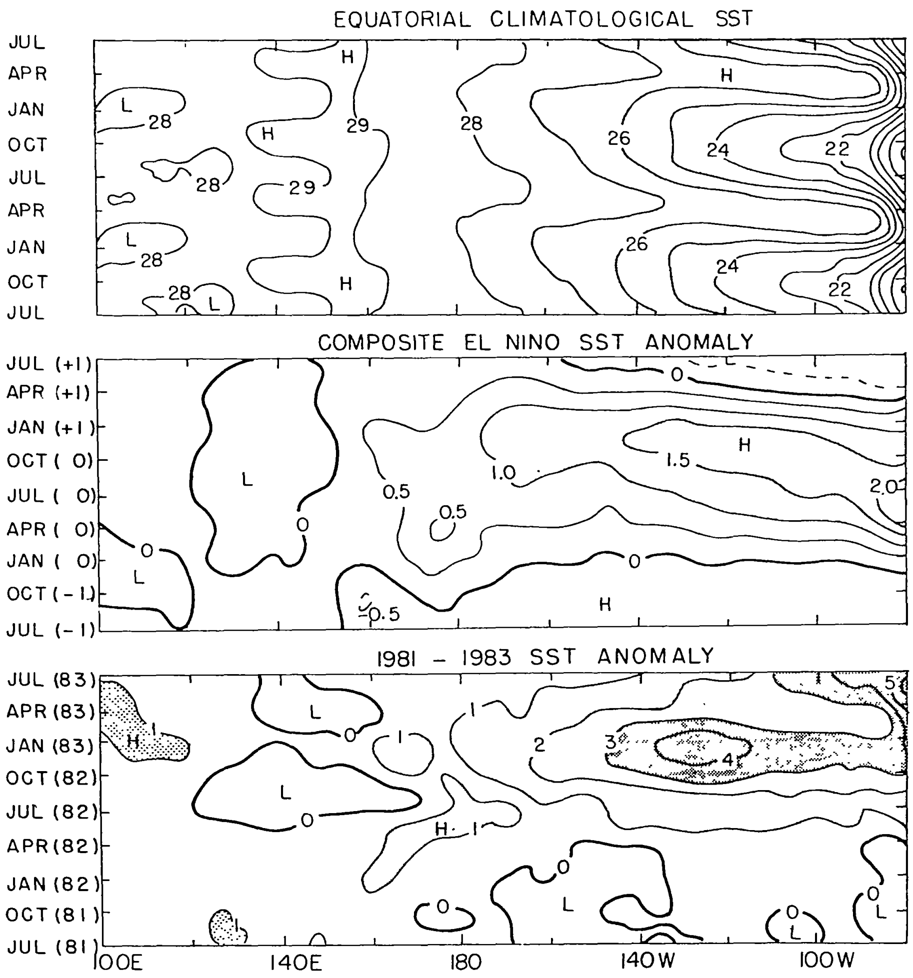

Figure 2 Time-longitude sections of sea-surface temperature (SST). The sections follow the equator to 95°W and then follow the climatological cold axis to its intersection with the South American coast at 85°S. (*top*) Mean climatology. (*middle*) Composite El Niño anomalies. The El Niño year is year 0. (*bottom*) Anomalies from 1981 to 1983. Note the larger contour interval.

long-range forecasters, but it is beyond the scope of this article (see Rasmusson & Wallace 1983, and references therein). The tropical coupling is central to our theme, for we regard El Niño and the Southern Oscillation as the oceanic and atmospheric components of a single phenomenon, referred to as ENSO.

The Bjerknes Hypothesis

Bjerknes (see especially the 1969 paper, from which we quote freely) begins his account by pointing out that the eastern equatorial Pacific is unusually cold among low-latitude oceans. He attributes this to equatorial upwelling and horizontal advection of cold waters driven by the easterly trade winds prevailing along the equator. Since the western Pacific is very warm, there is a large SST gradient along the equator in the Pacific [cf Figure 2 (*top*)]. As a result there is a direct thermal circulation in the atmosphere along the equator: The relatively cold, dry air above the cold waters of the eastern equatorial Pacific flows westward along the surface toward the warm western Pacific. "There, after having been heated and supplied with moisture from the warm waters, the equatorial air can take part in large-scale, moist-adiabatic ascent" (Bjerknes 1969). Some of the ascending air joins the poleward flow at upper levels associated with the Hadley circulation, and some returns to the east to sink over the eastern Pacific. There is a zonal surface pressure gradient associated with this equatorial circulation cell (high in the east and low in the west).

Bjerknes named this the "Walker Circulation" because he felt that fluctuations in this circulation initiated pulses in Walker's Southern Oscillation. It can have such global consequences because "it operates a large tapping of potential energy by combining the large-scale rise of moist air and descent of colder dry air" (Bjerknes 1969).

The Walker Circulation is the link between eastern Pacific SST anomalies and the Southern Oscillation. As Bjerknes (1969) states:

> A change toward a steeper pressure slope at the base of the Walker Circulation is associated with an increase in the equatorial easterly winds and hence also with an increase in the upwelling and a sharpening of the contrast of surface temperature between the eastern and western equatorial Pacific. This chain reaction shows that an intensifying Walker Circulation also provides for an increase of the east-west temperature contrast that is the cause of the Walker Circulation in the first place. Trends of increase in the Walker Circulation and corresponding trends in the Southern Oscillation probably operate in that way. On the other hand, a case can also be made for a trend of decreasing speed of the Walker Circulation, as follows. A decrease of the equatorial easterlies weakens the equatorial upwelling, thereby the eastern equatorial Pacific becomes warmer and supplies heat also to the atmosphere above it. This lessens the east-west temperature contrast within the Walker Circulation and makes that circulation slow down.
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> There is thus ample reason for a never-ending succession of alternating trends by air-

sea interaction in the equatorial belt, but just how the turnabout between trends takes place is not yet quite clear.

Bjerknes' elegant scenario, in which both the tropical ocean and atmosphere are active participants, has been the principal stimulus for subsequent research on ENSO. The framework he proposed still serves as the underpinning for the more complete structure that has been built since. An enhanced observational picture has been constructed, and Bjerknes' "admittedly somewhat tenuous reasoning" about causal connection has been buttressed by a more solid theoretical foundation.

The greatest advances since Bjerknes' day have been on the oceanographic side of the problem. Although the oceanographic component of his scenario is not very specific, he did recognize that the variations in SST during El Niño are related to ocean dynamics and not to changes in surface heat flux. The key to these dynamics was to switch attention from SST to sea-level variations. The work of Wyrtki (1975, 1979) in collecting and interpreting sea-level data from a network of tide gauges in the tropical Pacific is the basis of our present understanding of the oceanography of El Niño.

Our goal in the remainder of this article is to provide the background for a coupled model of ENSO with strong emphasis on the oceanography (i.e. on El Niño). We begin with a highly selective review of the observations of the normal annual cycle in the Pacific before moving on to observations of the evolution of a typical El Niño event. The theory for the oceanography of El Niño follows. After briefly considering the influence of SST anomalies on the tropical atmosphere, we present results from a numerical model for the coupled system able to generate El Niño events. A discussion of the implications for the real ENSO cycle concludes this review.

CLIMATOLOGY OF THE TROPICAL PACIFIC

Where the lower-level winds converge in the tropics, there is upward motion, condensation, and release of latent heat. Such regions provide much of the thermal driving for the atmospheric circulation, both tropical and extratropical. By far the most powerful of these is the Indonesian Low over the "maritime continent" between the Indian and Pacific Oceans; it is the western terminus of the easterly trade winds that constitute the lower branch of the Walker Circulation. Extending southeastward from this zone into the Southwest Pacific is the South Pacific Convergence Zone; a second band of convergence, the Intertropical Convergence Zone, is generally found north of the equator and extends eastward from the central Pacific to the American coast.

As noted above, equatorial Pacific SST is warm in the west and cold in the east [Figure 2 (*top*)]. This surface picture reflects the distribution of oceanic heat content. Almost everywhere in the ocean the surface waters are well mixed, primarily by wind stirring. Along the equator in the Pacific this surface mixed layer typically exceeds 100 m in depth, becoming shallower to the east until it almost disappears at the South American coast. The depth of the thermocline, the thin layer of high temperature gradient separating the warm waters of the upper ocean from the cold abyssal waters, has a similar zonal variation. Sea level is also higher in the west. The western tropical Pacific is the largest pool of very warm water in the world ocean. It is maintained by the oceanwide trade winds, which drive currents westward along the equator under the tropical sun.

Figure 2 shows that there is very little temperature variation—annual or interannual—west of the date line, where the warm pool lies. The annual variation is largely in the east, roughly in the region bounded to the east and west by the South American coast and longitude 140°W and to the north and south by latitudes 3°N and 15°S. The interannual variability associated with El Niño is also largest in this region (Figures 2, 3). As noted by Bjerknes (and others) this area is the coldest in the low-latitude oceans. Heat exchange with the atmosphere is not the cause: The surface heat flux in this

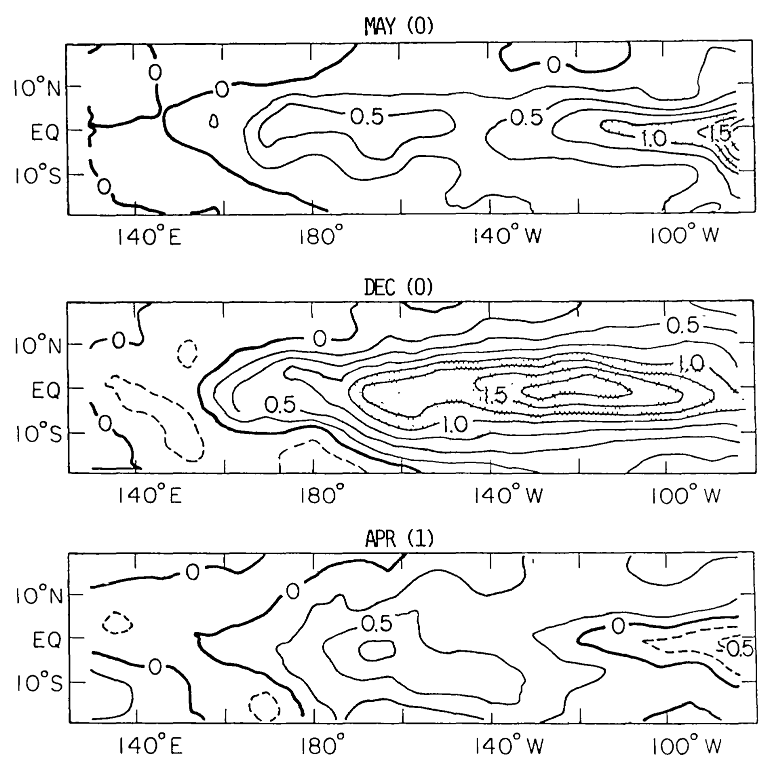

Figure 3 Sea-surface temperature anomalies (°C) for the composite El Niño for May and December of the El Niño year and April of the following year.

region is in excess of 50 W m^{-2} into the ocean, enough to increase the temperature of a 50-m-thick surface mixed layer by 1°C in less than a month. Most of the surface flow into this cold tongue is the relatively cold water brought in from the south in the Peru Current. There is a net inflow of colder water, since the outflow (westward in the South Equatorial Current and poleward to the north and south) is warmer, having been heated by the Sun.

Coastal and equatorial upwelling are other sources for the cold SST in this area. Winds along the South American coast are southerly, and the Coriolis effect turns the surface currents offshore. The waters leaving the coast are replaced by colder waters from below. Similarly, easterlies induce equatorial upwelling because the Coriolis effect turns the waters poleward in both hemispheres, making the surface flow divergent at the equator. Since the thermocline in the eastern Pacific is so close to the surface, the waters brought up to the surface mixed layer by both forms of upwelling are unusually cold. Two recent estimates (Wyrtki 1981, Bryden & Brady 1985) indicate that while the horizontal divergence of heat in the surface layer is not negligible, the flux of cold water from below associated with upwelling is the dominant process maintaining the cold tongue.

Beginning late in the boreal fall there is an annual warming of the usually cold tongue in the eastern equatorial Pacific [Figure 2 (*top*)]. SST variations are a consequence of basin-wide equatorial ocean dynamics, not of changes in surface heat flux. As the Sun retreats south, the Intertropical Convergence Zone migrates equatorward and the southeast trade winds relax, which reduces coastal and equatorial upwelling and slows the flow in the Peru and South Equatorial Currents. All these effects combine to reduce the flux of cold water into the surface layer, and since the surface heating rate is maintained, the surface waters warm.

These local factors are aided by remote influences. The warm waters to the west are advected eastward as a consequence both of the weakening of the easterlies in the western and central Pacific that occurs during the fall and winter and of the seasonal transition of the Asian monsoon (cf Cane 1983). A related oceanic response is a deepening of the thermocline in the east, so that water upwelled to the surface is warmer than before.

THE COMPOSITE EL NIÑO

As background for our discussion of the mechanisms governing the ENSO cycle, it is useful to describe the "composite" El Niño event. It is based on data from the 1950s to the 1970s from a number of sources [especially Rasmusson & Carpenter (1982) and Wyrtki (1975, 1979)]. It is possible to composite data from many past events because El Niño tends to be locked to the annual cycle [cf Figure 2 (*top*, *middle*), Figure 4].

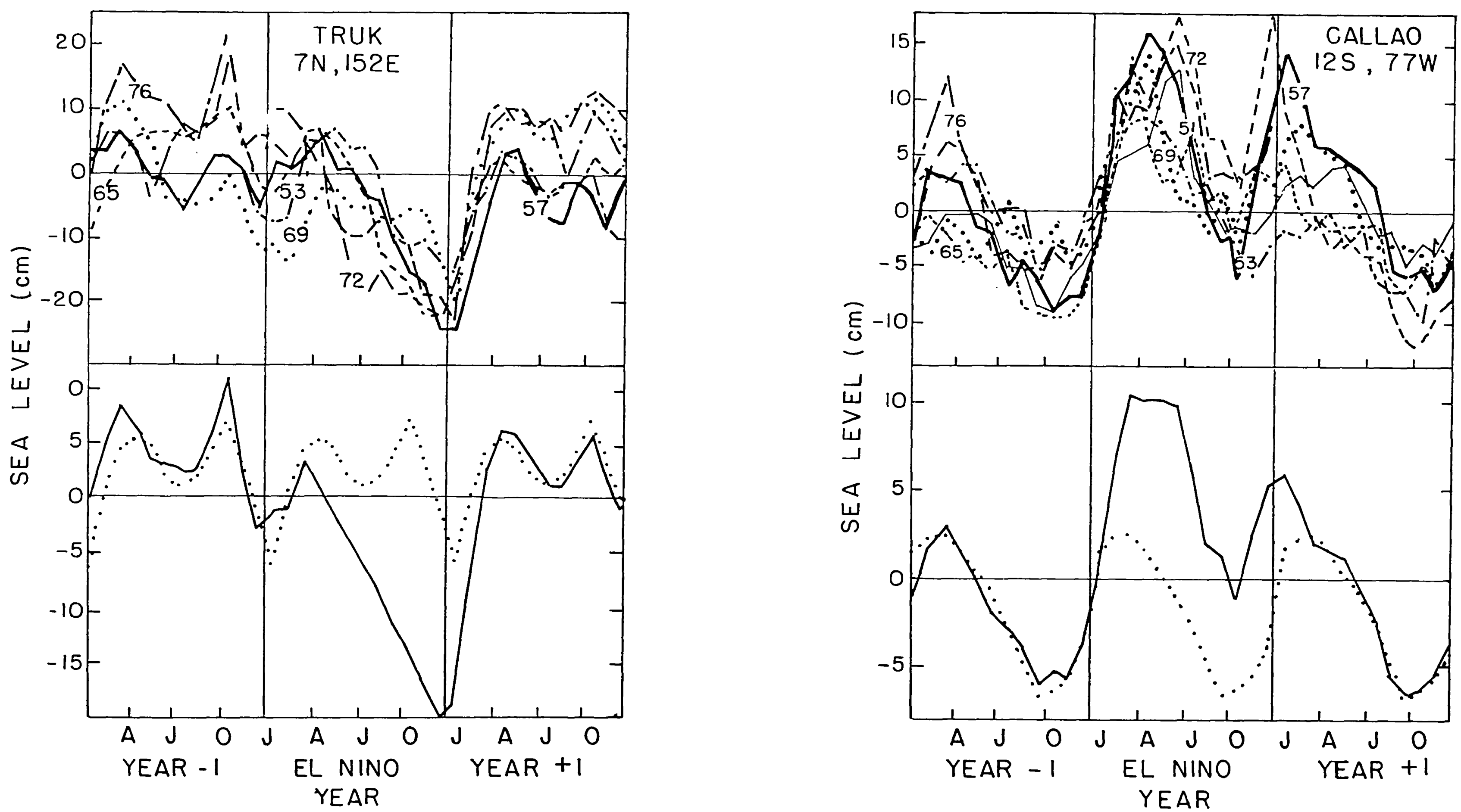

Figure 4 El Niño signatures: sea level at Truk and Callao for indicated El Niño events (top panels), for the composite El Niño (bottom panels, continuous line), and for the annual mean in non–El Niño years, 1953 to 1976 (bottom panels, dotted line). At Truk, note the similarity among El Niño events and their collective difference from the semiannual cycle of non–El Niño years. In the eastern Pacific (e.g. Callao), El Niño events typically appear as an enhancement of the annual cycle (after Meyers 1982).

Prelude

Typically, there are stronger than average easterlies in the western equatorial Pacific preceding an El Niño event, especially a strong event. These winds move water westward, and consequently sea level is higher than normal in the west and lower in the east. Equatorial SST is slightly warm in the west and somewhat cold east of 160°E.

Onset

In the fall preceding El Niño, the warm anomaly in the South Pacific develops a northward extension across the equator in the vicinity of the date line. This is associated with a northeast shift of the South Pacific Convergence Zone, which brings it closer to the equator than normal. The easterlies west of the date line have started to diminish, and the sea-level slope along the equator has begun to relax. There are positive precipitation anomalies west of the date line (e.g. Nauru and Ocean Islands), but no discernible pattern to the convergence anomalies.

Event

The anomalous warming off the coast of South America begins in January or February and increases until June (Figure 3). For the first several months it is difficult to distinguish it from the normal warming that occurs every winter [Figure 2 (*top*)]. At the same time, the sea level rises in a narrow region along the South American coast (see Callao in Figure 4) and the thermocline deepens. There is strong southward flow at the coast (the El Niño Current mentioned by Pezet). There is also evidence for a sea-level rise north of the equator, at least as far north as San Diego (Enfield & Allen 1980). The SST anomaly at the equator in the vicinity of the date line persists (and perhaps expands) throughout this period (Figure 2). At this time there are westerly wind anomalies along the equator from 110°W to 170°E, with the maximum near the date line. The Intertropical Convergence Zone has shifted equatorward in the east, so there is enhanced convergence and precipitation all along the equator from Peru to 175°E.

During the next half year, the warm anomaly spreads northwestward and then westward along the equator at a speed of about 1 m s^{-1}. By late fall the eastern anomaly has merged with the one in the central Pacific: Warm water now girdles a quarter of the Earth (Figures 2, 3). At this time, SST at the coast is only slightly anomalous, although the thermocline is still substantially deeper than normal there.

The large drop in sea level at Truk shown in Figure 4 is characteristic of the western Pacific. Thus there is a redistribution of mass from west to east during an event; in the 1976 El Niño this occurred at an average rate of 27×10^6 m^3 s^{-1}, about half the strength of the westward-flowing South Equatorial Current (Wyrtki 1979).

Mature Phase

Something more or less like the normal annual warming takes place at the coast beginning in December of the El Niño year. After reaching a peak, SST drops off very sharply, and by the end of the normal warm season in March-April it is slightly colder than normal (Figure 3). Sea level follows a similar pattern (Figure 4); note how quickly the sea level at Truk returns to normal. The positive SST anomaly farther to the west remains through the early part of the year, disappearing from east to west [Figure 2 (*middle*)]. During this time the winds relax to their normal pattern, and the westward sea-level slope is reestablished. During the second half of the year, the system overshoots its mean state: The trade winds are stronger than normal at the equator, as are the easterlies in the far western Pacific; sea-level slope is greater than normal; and eastern equatorial SST is below normal.

Discussion

This description of the composite event omits features judged to be extraneous to the question of how El Niño events are created and evolve. For example, events outside the tropical Pacific have been neglected. [Cane & Sarachik (1983) point out some possibly significant omissions.]

In Bjerknes' scheme, SST changes can induce wind changes, and conversely, wind changes can produce SST changes. The question has often been raised, which is the prime mover setting off the ENSO event—the atmosphere or the ocean? Our description is true to the data in its inability to sort out lag-lead relationships; to within the temporal resolution of the observations, many of the critical changes in the atmosphere and ocean are simultaneous.

Although SST anomalies, a surface expression of deeper changes, are conspicuous only in the east, El Niño is a basin-wide change in the equatorial Pacific that involves a substantial east-to-west redistribution of upper-ocean waters. If only the eastern Pacific Ocean were considered, it might seem proper to characterize El Niño as an enhancement of the usual annual cycle. On the other hand, El Niño in the western part of the Pacific Ocean is markedly different from the normal cycle (e.g. Figure 4). El Niño events are not just the tail of the distribution of annual events; the distribution is bimodal, with El Niño and non–El Niño years being distinctly different (Meyers 1982).

The atmospheric changes may be succinctly characterized by saying that the convergence zone normally centered over the maritime continent migrates into the central equatorial Pacific. Concomitantly, rainfall increases in the central Pacific and decreases in the Australasian region. Winds now converge toward the central Pacific, which results in a net eastward anomaly in the surface winds along the equator. The Intertropical Convergence Zone in the eastern Pacific is unusually far south, bringing rain to normally arid parts of the eastern Pacific all the way to Peru.

A glance at Figure 1 makes it obvious that the interval between events also varies a great deal. Over the historical record going back to 1841, it is most often 3 or 4 years but can be as little as 2 or as many as 7 years (Quinn et al 1978). Moreover, El Niño events are not alike. They can differ in timing, amplitude, duration, and pattern. Among all the departures from the composite norm, none is more deviant than the most recent, the El Niño of 1982/83 (Cane 1983, Rasmusson & Wallace 1983, Barber & Chavez 1983, Gill & Rasmusson 1983). Even this event adheres to the composite pattern in many respects (see Cane 1983, Rasmusson & Wallace 1983, Barnett 1984). However, its timing is certainly highly unusual [cf Figure 3 (*middle*, *bottom*)], and Figure 1 shows how out of scale its amplitude is.

THE OCEANIC RESPONSE

In the past decade, the observed oceanic changes during El Niño have been successfully modeled, provided the atmospheric changes are specified. The central idea is that the El Niño signal is largely a linear dynamical response to variations in the surface wind stress.

Sea Level

Bjerknes had pointed out that during El Niño the ocean had to be responding dynamically rather than to changes in the surface heat flux, but this notion was first developed to a specific theory by Wyrtki (especially 1975, 1979). He collected and charted sea-level data, showing that the changes during El Niño were basin-wide. SST variations are evident only in the eastern part of the ocean, and even if one recognizes that changes in SST are dynamically caused, it is a far more complex response than that of sea level and therefore harder to decipher. Wyrtki also showed that the initial changes in the wind were in the central and western Pacific, far from the locale of the SST changes. Finally, he suggested that the signal could propagate eastward from the area of the wind change to the South American coast through the equatorial waveguide in the form of equatorial Kelvin waves. A number of theoretical calculations embodying this idea followed Wyrtki's (1975) paper (e.g. McCreary 1976, Hurlburt et al 1976), but Busalacchi & O'Brien (1981) and Busalacchi et al (1983) were the first to demonstrate a causal relation between actual wind changes and sea-level response during El Niño. (These two papers are henceforth referred to as BOB.) A linear shallow-water model was driven by nearly two decades (1961–78) of monthly surface wind stress fields, and the model thermocline anomalies showed a significant correlation with sea-level observations.

The relevant linear theory is summarized here. [Fuller accounts are given in BOB and in Cane (1984). Moore & Philander (1977) contains an introduction to equatorial wave theory.] The ocean's circulation may be analyzed into a sum of vertically standing normal modes whose structure depends on the mean density stratification. The external, or barotropic, mode makes a negligible contribution to the El Niño signal (Cane 1984). There are an infinite number of internal, or baroclinic, modes, which may be ordered by their vertical wavelength. All satisfy the same formal equations, but the response of each is different because the length and time scales governing each are different, as is the strength of the coupling to the surface wind stress.

For each mode this response may be analyzed into a sum of free and forced waves. For the time and space scales relevant to El Niño, only two types of wave motions are of possible importance: long Rossby waves and equatorial Kelvin waves. The latter are strongly trapped to the equator and owe their existence to the vanishing of the Coriolis force there. Except within a few degrees of the equator, the geostrophic balance between Coriolis and pressure gradient forces dominates the dynamics of the ocean. This balance is characteristic of Rossby waves and strongly constrains their amplitudes and propagation speeds. The Kelvin wave is the fastest of low-frequency ocean motions: The gravest (first) baroclinic mode Kelvin wave can cross the Pacific in less than 3 months. The most equatorially confined Rossby wave is three times slower, and Rossby wave speed decreases as the square of the latitude.

Long Rossby waves propagate energy only to the west, while Kelvin waves travel only eastward. When a Kelvin wave hits the eastern boundary, its reflection is made up of an infinite sum of Rossby waves. Because of their latitudinal dependence, the reflected signal narrows with latitude, finally becoming coastally trapped. Thus the eastern boundary is an extension of the equatorial waveguide, but a leaky one: The faster low-latitude Rossby waves carry most of the mass and energy brought east by the Kelvin wave back toward the west.

The special properties of equatorial waves mentioned above are essential to the El Niño phenomenon. Only at low latitudes can low-frequency waves cross the ocean in times matched to the seasonal variations in the winds. A given change in the wind generates a stronger response at the equator than at higher latitudes, and equatorial waves are less susceptible to the destructive influences of friction and mean currents. A considerable body of observational evidence has accumulated to show that a signal much like the theoretically conceived Kelvin wave does indeed cross the breadth of the Pacific at speeds of almost 3 m s^{-1}.

In pre–El Niño conditions the prevailing easterlies, whether or not stronger than normal, tend to pile up warm water at the western side of the Pacific. A relaxation of the winds along the equator in the central or western Pacific excites packets of Kelvin waves, which cross the ocean to the South American coast. Their effect is to raise sea level in the east.

In principle, the coastal changes could depend on the local setup in response to longshore winds. In fact, as shown by Wyrtki (1975; see also Enfield 1981), there is almost no change in the coastal winds during El Niño. Hence, changes in currents and in all aspects of the thermal structure at the coast, including sea-level displacement and thermocline depth, depend solely on the amplitude of the incident Kelvin waves (Cane 1984).

This amplitude is determined by its initial value at the western end of the Pacific plus the amount added by wind forcing as it propagates along the equator. Model calculations show the latter to be the principal influence (BOB, Cane 1984). Furthermore, all that matters is the zonal wind stress within a Kelvin wave width of the equator—a few hundred kilometers. Figure 5 shows this forcing for the gravest baroclinic mode, based on the composite winds of Rasmusson & Carpenter (1982). The dashed lines show the path of a Kelvin wave through the longitude-time plane. For the composite El Niño, the primary cause of the rise in sea level at the beginning of the El Niño year is the change from easterly to westerly anomalies in the vicinity of the date line. For the four major events encompassed in the BOB calculations, the locale and nature of this initial wind signal varied: Sometimes it was east of the date line and sometimes west; sometimes it was more of a slackening of anomalously strong easterlies, and sometimes an actual westerly anomaly. The second peak late in the year is a response to the massive collapse of the trade winds that begins in the summer (Figure 5), a feature common to all events.

The most quantitative comparison of linear theory with El Niño sea-level changes to date is Busalacchi & Cane's (1985) study of the 1982/83 event. They found excellent agreement in the eastern Pacific (i.e. toward the end of the equatorial-coastal waveguide), with correlations between model and data above 0.9. A test of a different sort is provided by an ocean general circulation model simulation of the 1982/83 event (Philander & Seigel 1985). This model includes as complete an account of ocean physics as is presently possible, and the mechanisms described above are clearly operative.

Perhaps it is surprising that the linear dynamical theory works as well as it does. The dynamics governing currents along the equator (e.g. the

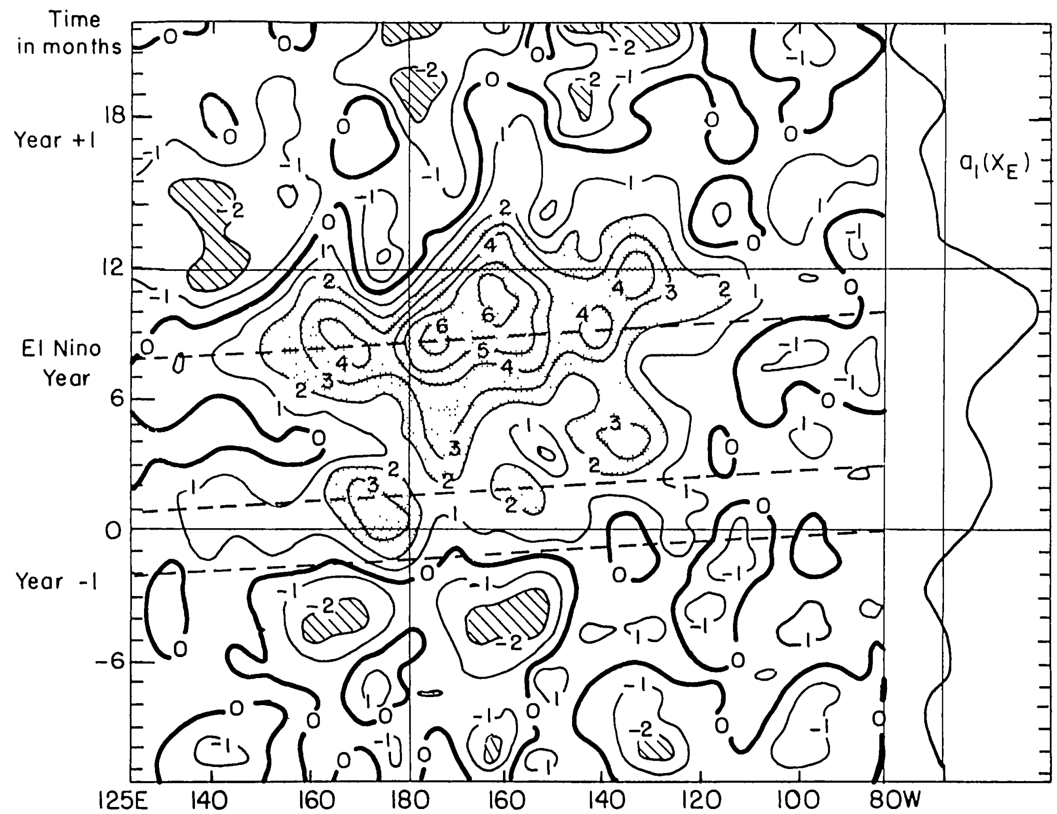

Figure 5 Forcing for the gravest baroclinic Kelvin wave, based on the composite El Niño wind anomaly field. Dashed lines indicate the path of a Kelvin wave. The curve on the right gives the Kelvin wave amplitude at the eastern boundary (from Cane 1984).

equatorial undercurrent) are highly nonlinear and viscous. However, numerical experiments with nonlinear models (Cane 1979, Philander 1979) indicate that variations in such essentially integral quantities as sea level and dynamic topography are well predicted by linear dynamics. [On the other hand, Cane (1984) suggests some important discrepancies in a linear calculation, and Philander & Seigel (1985) describe other mass redistribution mechanisms present in their general circulation model simulation.]

SEA-SURFACE TEMPERATURE

Despite their central role in ocean-atmosphere interaction, there have been few heat budget or modeling studies of El Niño SST anomalies (but see Barnett 1977). Although there may be local exceptions, the preponderant evidence is that surface heating does not contribute to the El Niño warming (Bjerknes 1969, 1972, Ramage & Hori 1981, Weare 1983). The data indicate an inverse relation between SST and heat flux into the ocean because of increased evaporation. This is the expected sense if SST anomalies are to lead to the heating that drives the atmospheric circulation during ENSO. If it is assumed that anomalous surface flux into the ocean depends only on local SST anomalies, then, as with sea level, the influence of the atmosphere reduces to the anomalous surface wind stress.

Based on this idea, Zebiak & Cane (1985) constructed a simple perturbation model for SST anomalies, with mean temperature structure and surface currents specified on the basis of climatological data. The dynamics of the model begin with the linear reduced-gravity model that is so successful in simulating thermocline depth anomalies and surface pressure changes during El Niño events. Such models produce only depth-averaged baroclinic currents, but the surface current is usually dominated by the frictional (Ekman) component. Therefore, a shallow frictional layer of constant depth is added to simulate the surface intensification of wind-driven currents in the real ocean. The dynamics of this layer are also kept linear, but only by using Rayleigh friction to stand in for nonlinear influences at the equator [see Zebiak & Cane (1985) for a discussion]. Upwelling velocity is computed as the divergence of the surface-layer transport. Inclusion of this surface layer allows a strong response to local winds; models that omit it understate upwelling effects as a consequence.

In contrast to the dynamics, the evolution equation for perturbation SST is complete and nonlinear, including three-dimensional temperature advection by both mean and anomalous currents. The temperature of upwelled water is parameterized as a function of the total thermocline depth, varying most rapidly when the thermocline is near the surface. Since the mean thermocline is shallower in the east, the model is more sensitive to depth changes there, in accord with observations. The only significant simplification in this equation is that the surface heat flux is taken to be linearly proportional to the SST anomaly. This Newtonian cooling formulation is the simplest embodiment of the inverse relation discussed above.

The Zebiak & Cane (1985) model was forced with the composite wind anomalies; results are shown in Figures 6 and 7. The first of these figures indicates the extent of the model's ability to reproduce the time evolution averaged over key regions. The second shows the anomaly patterns at key times and should be compared with Figure 3. Given the model's simplicity, the results are encouraging, especially in view of the large uncertainties in the forcing and verification data. Evaluation of the contribution of the various terms in the SST equation leads to the conclusion that all make a significant contribution at some time or place. Mean upwelling (i.e. warming of upwelled water due to a deepening of the thermocline) is the strongest influence at the South American coast (NINO1). In the central Pacific (NINO4), horizontal advection dominates because the reduction in the upwelling strength is offset by a rise in the thermocline. In between, in

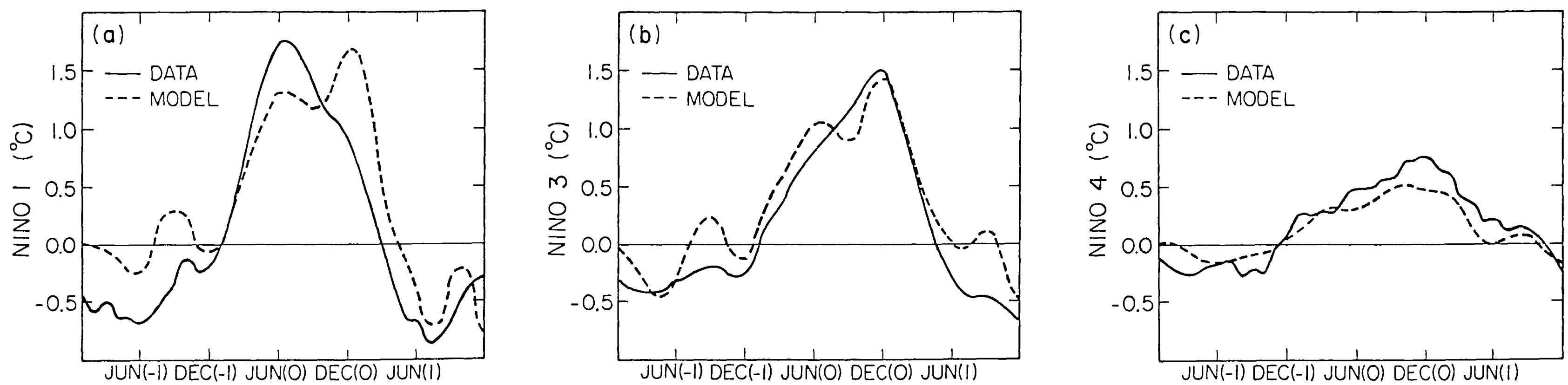

Figure 6 SST anomaly indices from the model (dashed lines) and composite data (solid lines) over the 3-year simulation period. NINO1 is the average in the region 5–10°S, 80–90°W. NINO3 : 5°N–5°S, 90–150°W. NINO4 : 5°N–5°S, 150°W–160°E (from Zebiak & Cane 1985).

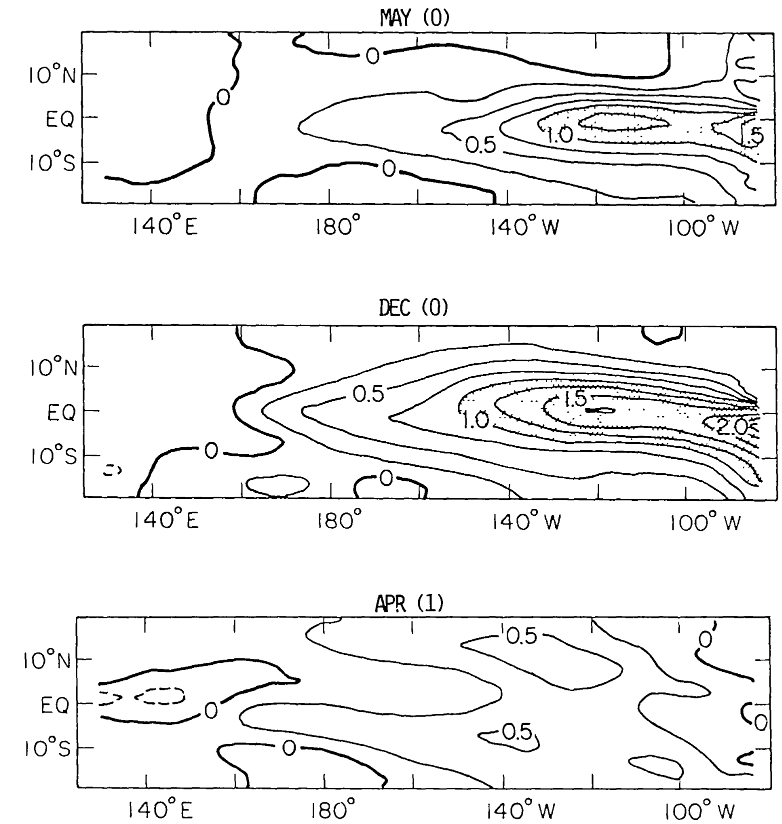

Figure 7 Model SST anomaly fields for composite wind forcing. Shown are May and December of the El Niño year, and April of the year after El Niño (from Zebiak & Cane 1985). Compare with Figure 3.

the eastern equatorial Pacific (NINO3), all the dynamical terms make a substantial contribution to the warming.

The discussion of SST has focused here on the equatorial waveguide. Meridional currents are important in spreading the anomalies off the equator and away from the coast (e.g. Leetmaa 1983, Zebiak & Cane 1985). The North Equatorial Countercurrent strengthens during El Niño, transporting more warm water eastward north of the equator (Wyrtki 1975). In the powerful 1982/83 event, some of this warm water may even have spilled across the equator (Philander & Seigel 1985).

TROPICAL ATMOSPHERIC RESPONSE DURING ENSO

We have seen that the ocean state can be accounted for if the wind stress is specified. Similarly, if SST anomalies characteristic of El Niño are given, then the principal changes in the tropical circulation may be calculated. This has been amply demonstrated by simulations with atmospheric general circulation models. [Shukla & Wallace (1983) contains a thoughtful review of general circulation model studies up to that time.] The most convincing is the set of 15-year integrations reported by Lau & Oort (1985) and Lau (1985). Runs made with observed tropical Pacific anomalies for the years 1961 to 1976 were contrasted with runs with climatological SSTs. The former simulated the ENSO signal, the latter did not.

The outstanding change observed during an ENSO event is the migration of the zone of convergence normally found in Australasia to the central Pacific. The general circulation models simulate this, and Bjerknes' ideas on the variations of the Walker Circulation explain the changes. Beyond that, observations show that the tropical anomalies have a simple vertical structure with a universal form, namely, a reversal of polarity between the lower and upper troposphere (e.g. regions of low-level convergence lie below regions of upper-level divergence). Linear dynamical models with a single degree of freedom in the vertical have proven remarkably adept at reproducing the horizontal structure of the atmosphere (Matsuno 1966, Gill 1980), but the physical interpretation of these models is uncertain [on this issue, see especially Geisler & Stevens (1982) and Zebiak (1982)].

In their purest form, these are models for the dynamical response to heating, not to SST variations (cf Shukla & Wallace 1983), and they give the most impressive results when the heating is specified (e.g. Gill & Rasmusson 1983). Anomalous heating need not be closely related to SST anomalies. First, the data show that the maximum convergence, and hence the maximum heating, tends to be near the SST maximum. Thus, the maximum heating *anomaly* need not be where the maximum SST *anomaly* is. Second, heating is determined less by local evaporation (a function of local SST) than by the convergence of moisture in the boundary layer. Thus the heating depends on the circulation and does so with a potentially positive feedback: Stronger moisture convergence gives more heating; more heating gives more convergence. General circulation models include parameterizations of all the physical processes involved in this complex chain, while the simple models usually do not. There are exceptions; for example, Webster (1981) and Zebiak (1985) include convergence feedbacks. Zebiak's is a model for the perturbations about the climatological state, which takes explicit account of the effect of mean convergence and total SST. The resulting model is capable of reproducing most of the principal features of the surface wind field over the tropical Pacific during an El Niño event.

COUPLED MODEL RESULTS

The atmospheric and oceanic responses during El Niño have been considered separately, but it has not yet been demonstrated that the mechanisms discussed above are enough to account for the evolution of the coupled system. Furthermore, investigation of the coupled system is essential to understanding the initiation and termination of events, the turnabout between El Niño and non–El Niño states that puzzled Bjerknes.

In the past decade there have been numerous restatements, modifications, elaborations, and enhancements of the Bjerknes hypothesis, all with the goal of providing a scenario for the complete ENSO cycle. The more interesting descriptive ones include Julian & Chervin (1978), Wyrtki (1981), and Philander (1983). Based on Bjerknes' ideas, McWilliams & Gent (1978) developed a nonlinear model with only five degrees of freedom. The model's most El Niño–like oscillations were rapidly damped. A number of simplified linear or nearly linear dynamical coupled models are reviewed in McCreary (1985). All exhibit long-period regular oscillations and/or growth of unstable modes. The characterization of the essential air-sea interaction as an instability (Philander 1983) taps a rich hydrodynamical literature; we return to this point below.

The results described here are more realistic than those obtained previously. They derive from the ocean-atmosphere interaction model constructed by coupling the tropical atmosphere model of Zebiak (1985) to the upper-ocean model of Zebiak & Cane (1985). The most significant differences from earlier coupled models are the attention to mean climatological fields and the explicit inclusion of an ocean mixed layer. The atmospheric heating is strongly influenced by the mean convergence pattern; SST can be changed by advection of mean temperature fields and by the advection of anomalies by mean currents and upwelling. Inclusion of surface-layer dynamics allows a mode of response that is local and rapid, granting upwelling its full measure of influence.

A numerical experiment with the coupled model was initiated with an imposed 2 m s^{-1} westerly wind anomaly of 4 months duration beginning in December of the year designated -1. There was no external forcing thereafter: Aside from the model physics, evolution of anomalies in SST, winds, etc, depends only on this initial condition and on the monthly mean climatological fields specified in the component ocean and atmosphere models. Furthermore, because of the damping in the model, the initial conditions are largely forgotten within a decade.

A 90-year time series of model SST anomalies averaged over the eastern equatorial Pacific is shown in Figure 8. There are peaks of varying amplitude occurring at irregular intervals but typically 3 to 4 years apart.

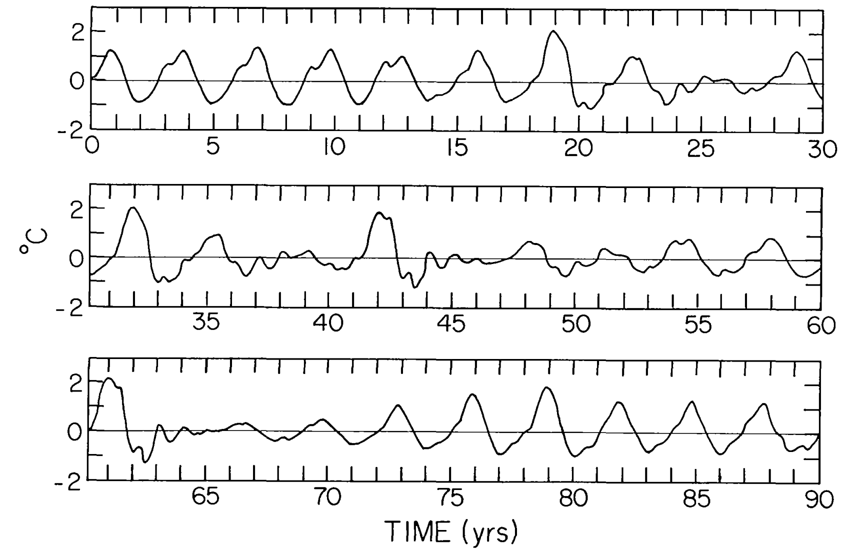

Figure 8 SST anomalies averaged over the eastern equatorial Pacific (the region NINO3—see Figure 6) for 90 years of coupled model integration.

They tend to be phase locked to the annual cycle, with major events reaching maximum amplitude at the end of the calendar year and decaying rapidly thereafter. All of these features are characteristic of observed El Niño events, as described earlier. The amplitudes of model events are similar to observed ones, although the model did not produce anything as extraordinary as the 1982/83 event. Note that the mean anomaly is close to zero (i.e. the model climatology is correct). Although it is a perturbation model, it is a nonlinear one, so this is not guaranteed. The model is somewhat more regular than nature; the high-frequency fluctuations present only in the real atmosphere and ocean may account for the broader natural spectrum.

Figure 9 depicts the evolution of SST during the El Niño event of model

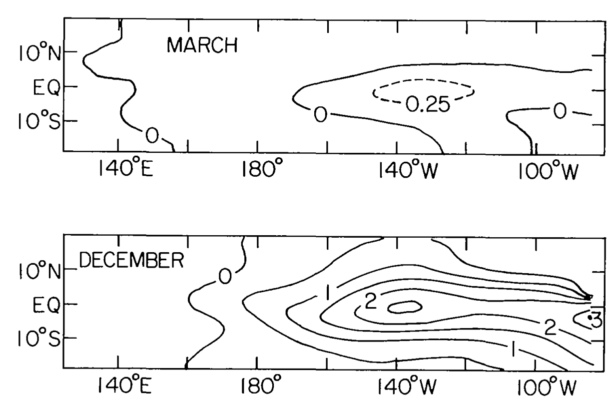

Figure 9 Coupled model SST anomalies for March and December during the model El Niño event in model year 31. (Note that the contour interval is 0.25°C for March and 0.5°C for December.) Compare with Figures 3 and 7.

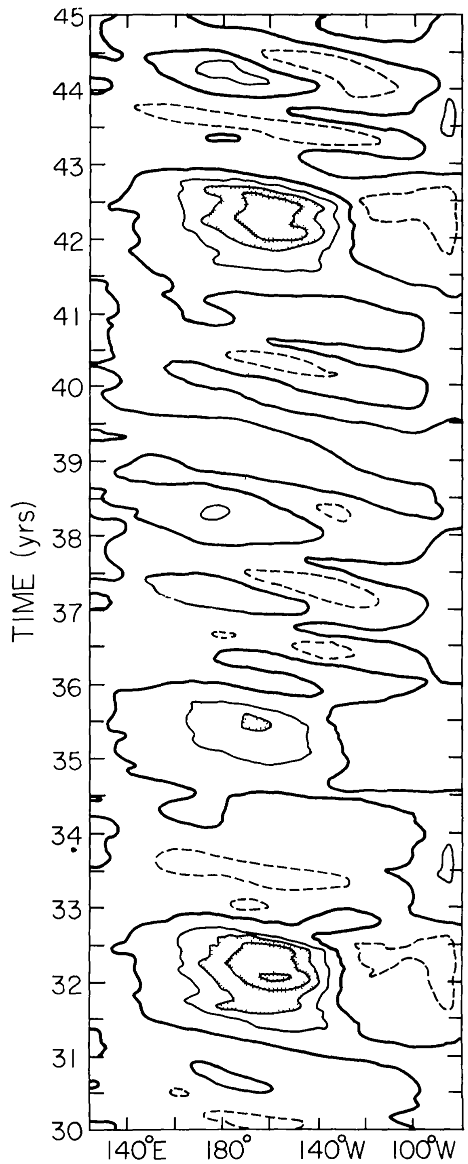

Figure 10 Time-longitude sections for model years 30–45 of the coupled model integration showing the forcing for the gravest mode oceanic Kelvin wave, a measure of zonal wind anomalies along the equator (cf Figure 5).

year 31. In December of the preceding year there was no discernible anomaly; by March of year 31 there is a small but systematic warming in the eastern Pacific; by December the anomaly extends to the date line, with a maximum at about 135°W. The model patterns and amplitudes are fairly realistic (cf Figure 3) except near the South American coast, where the model's coarse resolution precludes an accurate simulation of coastal upwelling processes.

Figure 10 shows the evolution of zonal wind along the equator. The prominent feature is the band of westerly anomalies in the central Pacific. The spatial and temporal patterns are realistic until the year following the event (year 32). The model westerly anomalies persist several months longer than is typical of El Niño events. The same is true for SST and other fields and is characteristic of model events. A possible cause is the model's inability to produce the easterly anomalies in the far western Pacific, which appear during the termination phase of observed events. As is the case even when observed SST anomalies are specified, the model winds are poorest in the Asian monsoon region and in the far eastern Pacific. As with observed events, El Niño anomalies disappear quite rapidly, to be replaced by cold SST in the eastern Pacific and stronger-than-normal easterlies along the equator.

In summary, a coupled ocean-atmosphere model incorporating the physical processes discussed in the preceding sections proved able to reproduce the spatial and temporal evolution of El Niño events. Moreover, without external forcing it was able to terminate these events and generate new ones in a never-ending ENSO cycle.

CONCLUSION

The coupled model results presented in the previous section have a number of implications for the real ENSO cycle. Since there is a leap from a model to reality, these are best regarded as hypotheses about the nature of the ENSO cycle. Nothing of what is suggested here is in conflict with observations, but alternative interpretations of the data are possible.

ENSO is an oscillation internal to the coupled ocean-atmosphere system. All of the interactions essential to creating and maintaining this cycle take place within the tropical Pacific region: No extratropical or extra-Pacific influences are required to account for the initiation or termination of El Niño events. The interactions required are deterministic: Random fluctuations in the atmosphere or ocean are not needed to initiate events or to account for the aperiodicity of ENSO.

Warm events result from a positive feedback between anomalies in the atmosphere and ocean. Warmer-than-normal SST in the east leads to increased atmospheric heating in the central Pacific. The anomalous inflow into this heating region includes westerly surface winds along the equator. The associated surface wind stress changes reduce upwelling, drive eastward currents, and deepen the thermocline in the east. The first two of these responses depend primarily on surface-layer dynamics, while the last involves the upper ocean down to the thermocline. All reinforce the warm anomaly.

Thus, the model calculations support Bjerknes' "chain reaction" hypothesis for the growth of ENSO anomalies. However, the hypothesis does not explain why there is a switch to an El Niño state (i.e. why the anomalies start). If this is explained by assuming that the coupled system is unstable, then the fact that El Niño does not occur all the time must be accounted for.

The answer must be that there is a necessary condition for the instability of the coupled system, which is not met every year: From time to time the normal seasonal cycle combines with the interannual variations to precondition it for an El Niño. In the real climate system the atmosphere has little year-to-year memory compared with the ocean. In the model the atmosphere has no memory at all: It is completely determined by the present state of the ocean. The necessary condition must reside in the ocean. The thermal damping time of the ocean surface mixed layer is only a few months, so its memory is short compared with ENSO time scales. Inspections of model SST fields before events show no discernible precursor pattern. The same may be said of the many diagnostic studies of the real SST data. In the model this leaves only the upper-layer depth (i.e. the oceanic heat content) as the possible locale for the necessary condition; this leads naturally to the hypothesis that the same is true for the real system. Preliminary analysis of model results suggests that the appropriate condition is that the heat content of the Pacific within the equatorial waveguide (5°S to 5°N) be above its average value. This applies to the zonal integral across the basin, and it is likely that further analysis will lead to refinements of this criterion. [On the basis of sea-level measurements, Wyrtki (1985) has recently proposed a similar criterion involving a broader meridional expanse of ocean.] The condition is physically plausible: Even given an initial westerly wind anomaly, the chain reaction will sputter if not enough warm water is readily available to maintain the warming of the eastern ocean.

If conditions are favorable, an event may be triggered by a variety of initial perturbations. As in other instability problems, the necessary and sufficient conditions for instability are a more crucial issue than the precise nature of the growing normal mode. From this point of view, one would expect great differences in the initial stages of El Niño from event to event. This is as observed. In nature the most readily available favorable perturbations are the bursts of westerly wind that occur with great frequency in the western equatorial Pacific (e.g. Luther & Harrison 1984). However, other fluctuations, such as intrusions of midlatitude westerlies, may also serve as triggers. The model does not simulate the westerly bursts and generally understates the variability of the atmosphere over the western Pacific. As a result, more of the model events begin in the central Pacific. (Note that the model wind anomalies lack the eastward propagation often observed in real events; compare Figure 10 with Figure 5.)

The variations of the atmosphere and ocean over their annual cycle strongly influence the susceptibility of the coupled system to instability. Conditions in the northern summer and fall are most favorable, so once begun, ENSO anomalies are best able to grow to large amplitude during these seasons. In the following spring, the normal seasonal changes (reductions in trade winds, upwelling, and zonal temperature gradient) weaken the coupling between the atmosphere and ocean sufficiently so that the warm event can no longer be sustained. With the coupling strength reduced the warm state of the ocean overbalances the wind, and the ocean retreats toward its normal, non–El Niño state. Modulation by the seasonal cycle is not the only way to generate oscillations (e.g. the models reviewed in McCreary 1985), but it appears to be the principal cause in nature. For example, a calculation with perpetual May conditions (Zebiak 1984) also gives long-period oscillations, but its evolution and amplitude are quite unrealistic.

As the system relaxes, it overshoots its mean state, resulting in the cold eastern Pacific SST and stronger-than-normal equatorial easterlies characteristic of the year following an El Niño event (cf Figures 2, 3, 5). Sea level slopes upward to the west more steeply than normal, while the overall heat content of the equatorial ocean is lower than normal: The El Niño event results in a heat loss from the equatorial Pacific. This is in part a loss of heat to the atmosphere, which provides the substantial anomalous atmospheric heating needed to power the global changes associated with the Southern Oscillation. However, the ocean's thermal capacity is very great, and this diabatic loss is much smaller than the dynamical export of heat through the ocean to higher latitudes.

Over the years following an event, the equatorial Pacific heat reservoir is refilled until the ocean is once again prepared for an El Niño event. It is not obvious that this must happen, that the coupled system cannot remain in a colder equilibrium with strong easterlies and a large zonal temperature contrast. A possible explanation lies in the nature of linear equatorial ocean dynamics (Cane & Sarachik 1981): The response to an equatorially confined easterly wind anomaly includes a positive zonally integrated heat anomaly in low latitudes. Thus, the strong easterlies that go with the enhanced zonal SST gradient following El Niño necessarily restore the condition needed for the next event.

In both the model and nature, ENSO has the character of a relaxation oscillation of the coupled system: The slow buildup to the necessary condition for instability during the cold phase leads to a rapid warming during the event itself; an even more rapid change to cold conditions follows. In both model and nature the ENSO cycle is aperiodic. The fact that the model system is deterministic supports the idea that the aperiodicity of the natural system also results from the deterministic physics discussed above and not from extraneous random fluctuations. This idea should not be surprising: There is an extensive literature documenting chaotic behavior in far simpler deterministic dynamical systems (e.g. Guckenheimer & Holmes 1983). In such systems, behavior can change in complicated ways as parameters are varied, so it is not likely to prove a simple task to delineate the parameter dependencies important for ENSO.

Results on the predictability of dynamical systems indicate that it will be impossible to predict ahead several events, so it is fortunate that only the next El Niño is of paramount practical interest. Even for the next one, there may be circumstances where the coupled system is so close to a bifurcation point that unobservable differences decide between its occurrence or nonoccurrence. This does not rule out forecasting procedures with useful (if imperfect) skill, and it has already been shown that the 1982/83 El Niño could have been forecast several months ahead by statistical methods if appropriate data had been available in real time (Barnett 1984).

Pezet had only Peru in mind when he asserted that the El Niño question is important, "not only from the oceanographic point of view, but also from the climatic," and therefore "calls for the serious attention of the men of science of the whole world." Some 70 years later, Bjerknes established a link between El Niño and the Southern Oscillation pattern of global climate effects. Advances since then have motivated the creation in 1985 of an international program, TOGA (Tropical Ocean Global Atmosphere), to study the question. At the time of this program's birth, it appears that a satisfactory theory for the ENSO cycle is within reach and that successful prediction of El Niño will follow within the decade.

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