EL NIÑO, PAST AND PRESENT

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Abstract. El Niño events—anomalous warmings of the tropical Pacific with associated climatic and economic impacts around the globe—have occurred at several-year intervals since before written records began with the logs of Francisco Pizarro in 1525. In this review, the history of El Niño research is traced from its beginnings through the key innovations of Bjerknes and Wyrtki to the unusual 1982-1983 event. Recent research is then reviewed, with detailed discussions of two important processes: instability growth and vacillation between climate states. Throughout the paper there are adjunct discussions of extraregional teleconnections, ecological impacts, and research on El Niño in the ancient record. The final section discusses the present paradigm for vacillations between El Niño and non-El Niño states and speculates on the possibly chaotic nature of El Niño. El Niño and its atmospheric counterpart, the Southern Oscillation, appear to occur as an internal cycle of positive and negative feedbacks within the coupled ocean-atmosphere climate system of the tropical Pacific, although hypotheses based on external forcing also exist. All events are preceded by westerly wind anomalies on the equator near the date line. Baroclinic equatorial Kelvin waves are generated, propagating eastward toward South America where they depress the thermocline and raise sea level, while the deep, upper ocean reservoir of warm water in the western Pacific is depleted. Sea surface temperature (SST) anomalies in the cool eastern Pacific occur primarily because the normal source of cold water is depressed below the reach of mixing and upwelling processes. In the central equatorial Pacific, eastward advection by anomalous zonal flows is the principal mechanism. Nonlinear heat transfer to the lower atmosphere creates a positive ocean-atmosphere feedback resulting in the unstable growth of anomalies along the equator. Much of the present research aims at determining how the ocean-atmosphere system vacillates between the El Niño and non-El Niño states. Coupled models suggest that a longer time scale, negative-feedback process produces the transitions: at the apex of an El Niño development an anomalous atmospheric convection above the areas of maximum SST produces areas of reduced upper layer thickness in the off-equatorial ocean, which slowly propagate westward to the western boundary as Rossby waves and back to the central equatorial Pacific as upwelling Kelvin waves, reestablishing the normal cooling process. A similar negative feedback of opposite sign completes the second half of an oscillation, returning again to the El Niño state. However, the notion that El Niño-Southern Oscillation variability results only from an internal feedback process is still highly contentious, and a number of external forcing mechanisms have been proposed.

INTRODUCTION

On the most superficial level at which it is understood, El Niño needs no introduction. It is one of those scientific topics of which even the average layman is aware, because the interannual climatic anomalies associated with the El Niño phenomenon are known to have an impact on everyday life (Figure 1). The many treatments of the subject escalate in complexity from newspaper articles through the layman-oriented pictorial narrative of *Canby* [1984] and the general review of *Enfield* [1987*a*] (aimed at a general science audience) to a number of more specialized reviews that concentrate on specific aspects such as the 1982-1983 El Niño [*Cane*, 1983; *Rasmusson and Wallace*, 1983; *Barber and Chavez*, 1983] and modeling studies [*McCreary*, 1985; *Cane*, 1986]. Those who already know something of the subject, but wish to know a great deal more, could profitably start with this review. The review covers nearly all important aspects of El Niño research to some extent, giving the reader critical leads to

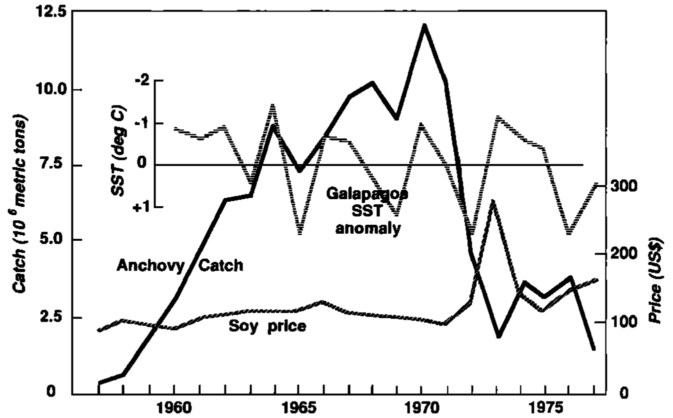

Figure 1. The annual Galapagos sea surface temperature (SST) anomalies, the Peru anchovy catch, and the cost of soybean meal, illustrating the economic impact of the 1972-1973 El Niño on world markets. SST anomaly scale is inverted, with upward swings indicating enhanced upwelling and cooler conditions. The switch to less anchovy meal and more soy meal was permanent, motivating large-scale clearings of Amazon forest and North American wetlands for agriculture. (After *Barber* [1988].)

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further, more in-depth sources. It attempts to convey that understanding through several mechanisms: a historical tour of developments leading up to the extraordinary event of 1982-1983; the review and discussion of El Niño research that has taken place since then; and the generous use of figures and references to key research papers. While the emphasis is on physical oceanographic aspects, I have tried to include discussions and key references within the other subdisciplines represented in El Niño research.

HISTORICAL OVERVIEW

Origins

The tropical marine conditions imposed by El Niño are an intermittent feature of the Peru coast that stand in contrast to the remarkably cool conditions that otherwise prevail at these low latitudes. Alexander von Humboldt attributed this coolness to water of Antarctic origin carried northward by the coastal current off Chile and Peru. We now know, of course, that northward blowing (southerly) winds along the South American coast combine with the Earth rotation to transport coastal surface water offshore, thus inducing a nearshore upwelling of colder subsurface water as the primary cooling agent. Although this mechanism was not understood before the pioneering work of Ekman in 1902, it was de Tessan in 1844 who first suggested that the Peru (or Humboldt) Current is cooled by upwelling. Although confusion on the point continued well into the twentieth century, the reasons for the coolness of the Peru Current were certainly well understood two decades later [*Gunther*, 1936; *Murphy*, 1936, p. 95].

As for El Niño, the following excerpt from *Quinn* [1987] is germane:

> Originally, El Niño referred to the warm current that sets southward each year along the coast of southern Ecuador and northern Peru during the southern hemisphere summer when the southeast trade winds are weakest. It was named El Niño ("the Child") by devout inhabitants of this region in reference to the "Christ Child" since it ordinarily sets in shortly after Christmas.

This annually occurring, southward setting ocean flow, traditionally called "la corriente del Niño" by coastal inhabitants, heralds the onset of occasional light summer rains over the adjacent Sechura desert and Andean highlands, from which the farmers of the region receive runoff for the irrigation of their crops. (See note 1, in the notes section at the end of the paper.) It also dictates the seasonal change in fishing arts, a retooling from the schooling fishes of the cool, nutrient-rich upwelling environment of winter to the foraging predator species of the less productive equatorial water mass carried south by the current.

At varying intervals of 2-10 years the current is extraordinarily strong (in excess of a knot (0.5 m/s)) and carries anomalously warm and fresh surface water inshore of its normal range and hundreds of kilometers farther south, together with a great deal of debris and unusual tropical fauna [*Murphy*, 1926; *Lobell*, 1942]. Peruvian scientists use the term "el fenómeno del Niño" in reference to the prolonged and unusual warming of coastal waters that accompanies the anomalous current. Although sea and air temperatures typically begin to decrease from their annual maximums by late March or April, they frequently remain anomalous for a year or more. There is usually a hiatus of near-normal temperatures that typically occurs between June and September, followed by renewed anomalous warming in December-January and a return to normal temperatures in January-March of the second year [*Rasmusson and Carpenter*, 1982]. Scientists both within and outside Peru now reserve the term "El Niño" to signify the more unusual events, i.e., those associated with geographically extensive sea surface temperature (SST) anomalies of a standard deviation or more for extended periods of many months to more than a year [*Scientific Committee on Oceanographic Research (SCOR), Working Group* 55, 1983]. For this paper I adopt the modern usage.

The most comprehensive compilation of El Niño events is the history by *Quinn et al.* [1987], who revise the earlier work of *Quinn et al.* [1978] and *Hamilton and Garcia* [1986], while extending the list to the early Spanish conquest, when written records began. They classify El Niños as weak (W), moderate (M), strong (S), or very strong (VS) depending on the intensity and duration of environmental anomalies and/or their social and economic impact. (See note 2.) Events of all intensities occurred most frequently at intervals of 3-4 years, but the S events seldom occurred less than 6-7 years apart, while eight VS events occurred at intervals in excess of 20 years. (See note 3.) Some of the source information must make for fascinating perusal, indeed. The first documented El Niño (though not by that name) was in 1525-1526; the evidence appears in the campaign logs of Francisco Pizarro. *Murphy* [1926] was aware of this when he wrote

> . . . it has been suggested that the march which Pizarro made through Piura, while on his triumphal journey toward Cuzco, was possible only because he chanced upon the desert shores during one of the rare "años de abundancia", or years of abundant water and vegetation.

The historical importance of El Niño lies in the social and economic upheavals it has caused. Prior to 1972 the adverse effects of the phenomenon were recognized only in South America, especially Peru: greatly reduced harvests of fish and guano that restrict foreign exchange; damage to agriculture and transportation by coastal flooding and erosion; rain-induced plagues of insects that devour crops;

and the spread of disease. Following the 1972-1973 El Niño it was further realized that the fisheries impacts in South America can reverberate seriously through the world markets for food commodities (Figure 1). One gets an excellent sense for the evolution of environmental anomalies and their consequences in the account of the strong 1972-1973 El Niño by *Caviedes* [1975]. The present significance of El Niño is even wider, however, because it is now recognized as part of a global syndrome of climatic anomalies that are peridoically felt in many regions of the world [*Caviedes*, 1982; *Philander and Rasmusson*, 1985; *Rasmusson and Arkin*, 1985; *Ropelewski and Halpert*, 1987].

The Ocean-Atmosphere System

The Southern Oscillation The atmospheric counterpart to the El Niño is the Southern Oscillation (SO). *Walker* [1923] and *Walker and Bliss* [1932] recognized the SO as a coherent variation of barometric pressures at interannual intervals that is related to weather phenomena on a global scale, particularly in the tropics and subtropics. The low surface atmospheric pressure in regions dominated by tropical convection (ascending air) and rainfall, such as Indonesia, is inversely correlated with the high pressure in regions typified by subsidence (descending air) and dry conditions, such as the southeast (SE) Pacific (Figure 2). Air is continually transferred at low levels, through the zonal trade wind circulations, from the subsidence regions to the convective regions. The air returns at upper tropospheric levels, completing a series of zonal cells around the globe that compose the Walker Circulation [*Bjerknes*, 1969; *Flohn and Fleer*, 1975]. In the "high phase" of the SO, the SE Pacific high pressure is higher than normal while the Indonesian trough (low pressure) is lower than normal. The increased pressure gradient between the two regions drives stronger Pacific trade winds and thus creates a greater mass exchange in the dominant Indo-Pacific Walker cell. During the low phase the pressure seesaw is reversed and the trades are weaker than normal.

The state of the SO pressure system is characterized by the Southern Oscillation Index (SOI), usually defined as the anomaly of pressure difference between Papeete (Tahiti) and Darwin (Australia). (See note 4.) Meteorologists were unaware of the relation between the Southern Oscillation and El Niño until *Berlage* [1957] noted a strong correlation between time series of the SOI and SSTs in Peru (Figure 3), thus adding another regional climatic phenomenon to those previously found by Walker. It was Bjerknes, however, who proposed a plausible physical mechanism for linking the oceanic and atmospheric phenomena.

Bjerknes: On the Connection of the SO to El Niño Initially, *Bjerknes* [1961] tried to explain El Niño as an occasional exaggeration of the seasonal countercurrent that intermittently flows south along the northern Peru coast during the austral summer. As had others before him [*Murphy*, 1926; *Schott*, 1931; *Lobell*, 1942], he argued that El Niño is caused by a local cessation of the upwelling-favorable winds along the Peru coast and by the north-south ocean density gradients within the El Niño region itself. However, from observations fortuitously taken during the strong 1957-1958 El Niño, oceanographers became aware of widespread oceanographic anomalies along the equator as far west as the date line [*Sette and Isaacs*, 1960]. This later led *Bjerknes* [1966*a*] to point out that the regional El Niño is closely related to a Pacific-wide response of the equatorial ocean to weakened trade winds on a much larger scale.

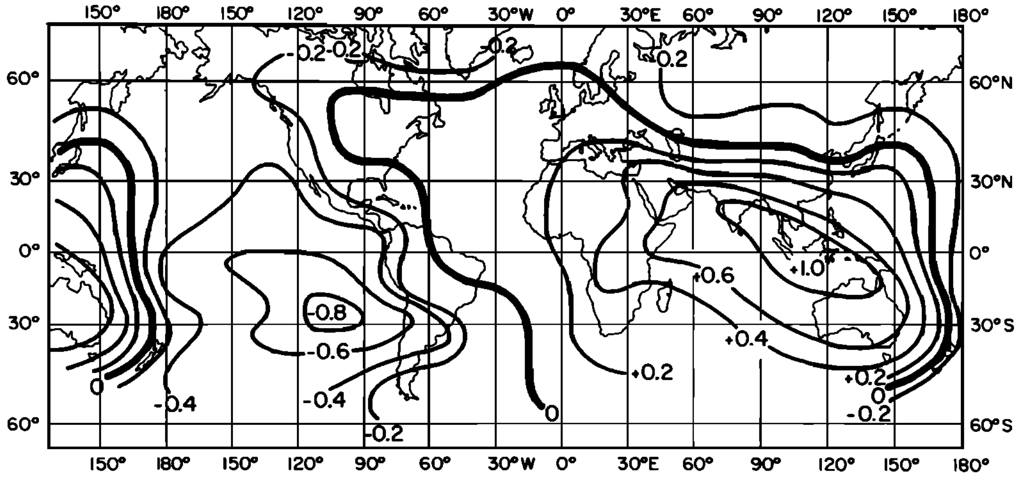


Figure 2. The global distribution of the correlation coefficient between the barometric pressure variations at Djakarta, Indonesia, and those elsewhere. The negative correlation between the eastern and western hemispheres, with centers over Indonesia and the southeast subtropical Pacific, characterizes the pressure seesaw associated with the Southern Oscillation, an interannual fluctuation in the strength of the Walker Circulation. (After *Berlage* [1957].)

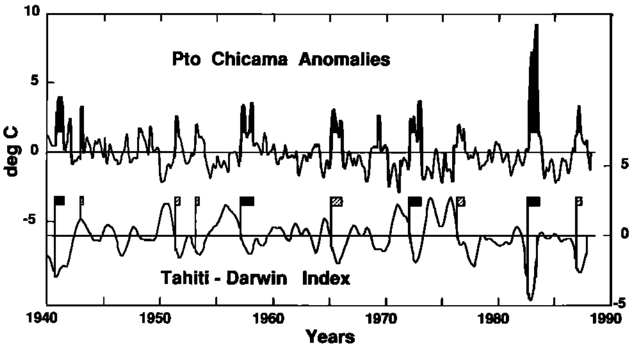


Figure 3. Time series of SST anomalies at Puerto Chicama, Peru (smoothed with a 3-month running mean), and the Southern Oscillation Index (smoothed with an 11-month recursive filter). SST anomalies above one standard deviation are shaded in black. Small flags attached to the SOI curve signal the beginning (staff) and duration (flag) of the SST shading for each El Niño event. Solid (hatched) flags refer to S and VS (W and M) events from the compilation of *Quinn et al.* [1987].

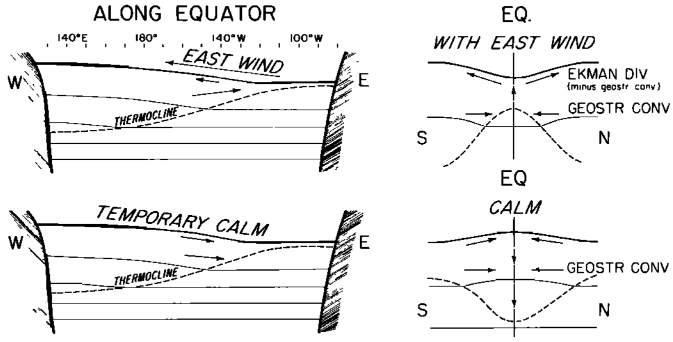


Figure 4. (Left) Schematics of isotherms (solid contours), thermocline (dashed line), and upper ocean currents (arrows) in a vertical section along the equator in the Pacific Ocean under conditions of normal (above, positive SOI) and abnormal (below, negative SOI) trade winds. (Right) Schematics of the transverse circulation patterns in a north-south section across the equator, with the thermocline and a nearby interior pressure surface shown by dashed and solid lines, respectively. At the top (normal situation), westward wind stress carries surface water westward and forces a surface "Ekman" transport poleward into either hemisphere; sea level and temperatures are low at the equator because of upwelling, and a convergence at depth compensates for the Ekman divergence at the surface. At the bottom (El Niño), western Pacific waters flow back to the east, and Ekman divergence and upwelling cease as the winds relax; the convergence continues throughout the upper ocean, however, raising sea level and depressing the thermocline. (From *Bjerknes* [1966*a*].)

Bjerknes began with a fundamental tenet of oceanography (Figure 4): that the tropical ocean can be thought of (to a first approximation) as consisting of a layer of warm water (low density) overlying a much deeper layer of cold water (high density). The interface between the layers where the temperature (density) decreases (increases) rapidly downward is the thermocline (pycnocline). Under the normal action of the westward blowing (i.e., "easterly") trade winds, a system of westward surface currents accumulates much of the upper layer water in the western Pacific, with a deep thermocline (150-200 m), leaving only a shallow layer and thermocline in the east (30-50 m). As Ekman had argued, the easterly winds, combined with the Earth's rotation, cause a steady movement of water away from the equator (Ekman transport) into both hemispheres, creating a horizontal divergence of surface water that in turn induces an equatorial upwelling of water from a few tens of meters below. Upwelling produces an elongated east-west tongue of cool surface water in the central and eastern equatorial ocean, where the winds are strong and colder water is brought up from beneath the shallow thermocline. The cooling does not occur in the western Pacific where the winds are weaker and the thermocline is deep (150-200 m). The ocean circulation that accompanies this normal state is termed "baroclinic," meaning that it arises from the east-west and north-south gradients in the upper layer thickness (ULT) and is associated with vertical variations in the currents.

When the easterly trade winds decrease, the forces that maintain the zonally asymmetric thermocline and the upwelled cold tongue disappear, and upper layer warm water moves equatorward and eastward, resulting in a readjustment, or "relaxation," of the ocean system away from the normal state. The redistribution of ULT that accompanies the wind changes is closely associated with the corresponding alteration of the current system. This, the Bjerknes scenario, captures the essential character of the transient ocean response we have observed extensively since his time: a deceleration of the normally westward equatorial surface currents accompanied by cessation of equatorial upwelling, accumulation of warm upper layer water in the equatorial zone, and consequent large-scale warming (Figure 4).

Bjerknes [1966*b*] also recognized that an interaction between the ocean and the atmosphere was necessary to explain the long time scale of SO swings, which belies the known volatility of atmospheric processes alone. He therefore proposed that an unusually warm equatorial ocean over a large zonal extent would create anomalous zonal and meridional SST gradients over large space scales, and that these gradients would provide an enhanced input of thermal energy to the direct atmospheric circulations, especially the meridional circulation of the atmospheric "Hadley cells" in that quadrant of the globe (*Barnett* [1981*a*, *b*] later demonstrated this association statistically). This would in turn increase the poleward flux of angular momentum to the winter hemisphere jet streams through a more efficient meridional circulation, finally strengthening the mid-latitude westerlies and affecting weather patterns downstream (to the east) of the disturbance. This became the basis for the notion of "teleconnections," by which El Niño warming can project climatic anomalies to remote regions of the globe. Public and scientific awareness of the atmospheric teleconnections proposed by Bjerknes was increased because of marked weather abnormalities that occurred in North America during the 1976-1977 winter: an exaggerated circulation pattern brought a severe drought to the U.S. west coast while the east coast suffered the numbing effects of repeated snowstorms and record cold [*Namias*, 1978]. Additional analyses of observations and atmospheric model results confirmed the teleconnection principle and showed that the mid-latitude westerlies are indeed energized during El Niño, especially over the eastern Pacific and North America [*Flohn and Fleer*, 1975; *Julian and Chervin*, 1978].

Evolution of Modern Concepts Two pervasive notions in the 1960s and early 1970s were that El Niño comes and goes through transitions between quasi-steady equilibrium states [*Bjerknes*, 1966*b*, 1969] and that the trades relax uniformly both along the equator and down the Peru coast, i.e., that the coastal El Niño is a local response to a weakening of the coastal winds [*Bjerknes*, 1961, 1966*a*; *Wooster and Guillen*, 1974]. These concepts were questioned by *Wyrtki* [1975], who examined Pacific-wide observations of sea level and ship winds. He found that sea level first falls in the western Pacific after being unusually high prior to the event; within a month or two the sea level along the South American coast rises by comparable amounts along with contemporaneous rises in coastal SST. Although the trade winds in the central and western Pacific weaken or reverse at the onset of anomalous conditions as Bjerknes had contended, there is little wind change in the eastern equatorial Pacific or in the upwelling-favorable southerly winds along the Peru coast. (See note 5.) The coastal El Niño was somehow a lagged response to remote wind forcing in the far equatorial Pacific, rather than a locally produced warming due to the cessation of coastal upwelling under reduced (or reversed) alongshore winds. Wyrtki proposed that when the trade winds aperiodically weaken along the equator, the unbalanced eastward pressure gradient in the upper ocean drives some of the upper layer water (previously stored in the western Pacific) toward South America in a wavelike fashion. This causes the thermocline to deepen and sea level to rise along the Peru coast (as observed) and accounts for the west-to-east lag in sea level changes. In the process, the warm water reservoir in the western Pacific is "drained," causing the thermocline there to rise and sea level to fall.

Concurrently with and immediately following Wyrtki's work, numerical modelers showed how the ocean response worked. The first models imposed a sudden, uniform decrease of easterly winds over an idealized tropical ocean basin and allowed the ocean to readjust (relax) from its initial state. In these models the wind anomaly excites equatorial Kelvin waves that propagate eastward from the western ocean boundary, plus Rossby waves that emanate westward from the eastern boundary into the ocean interior [*White and McCreary*, 1974; *Godfrey*, 1975; *Hurlburt et al.*, 1976; *McCreary*, 1976]. Later models [e.g., *O'Brien et al.*, 1981] allowed the wind to decrease only in the western basin, more in agreement with observations. The principal difference in the ocean response with nonuniform wind forcing is in the Rossby waves, which first emanate westward from the eastern end of the anomalous wind patch, rather than from the eastern ocean boundary, thus causing a shoaling of the thermocline in the western Pacific. Subsequently, other sets of Rossby waves reflect off the South American coast following the arrivals of the Kelvin waves there.

The nature of the Kelvin and Rossby wave responses are illustrated in Figure 5. The baroclinic Kelvin wave is a

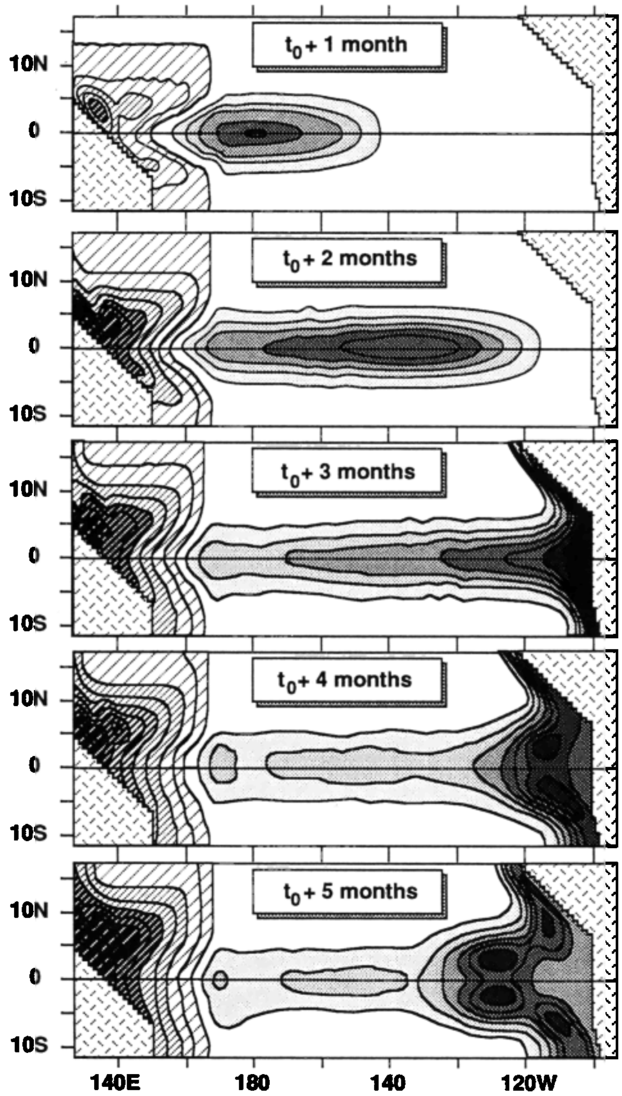


Figure 5. Upper layer thickness anomaly for the tropical Pacific at five successive monthly intervals following the onset of a westerly wind anomaly in the western Pacific at time t_0, from a linear reduced gravity model simulation by *O'Brien et al.* [1981]. Contours with stippled (hatched) shading indicate a depression (shoaling) of the model pycnocline. Contours are given at 5-m intervals starting with ± 2.5 m (the zero contour is suppressed).

transient response that is otherwise similar to the quasi-steady Bjerknes relaxation because it is associated with a rise in sea level (trapped to the equator), plus an anomalous thermocline deepening and eastward flow of upper layer water as it passes a particular location along the equator. The disturbance is said to be "trapped" to the equator because the Earth rotation has the effect of confining the water motions to the near-equatorial zone. After about 2-3 months, the Kelvin waves reach the coast of South America, where part of the incident energy continues poleward into either hemisphere as coastally trapped Kelvin waves (deepened thermocline and sea level rise).

The Rossby waves were not discussed by Wyrtki. The thermocline shoaling in the western Pacific (Figure 5) is entirely due to the Rossby waves initially excited by the anomalous winds. These Rossby waves constitute the mechanism by which the western Pacific is depleted of upper layer water. Another set of Rossby waves occurs as a low-latitude reflection of the incident Kelvin wave energy at the eastern end of the equatorial waveguide. They are evident after 4 months as closed-contour, anticyclonic eddies drifting to the west from South America at one third of the incident Kelvin wave speed, with a deeper thermocline at their center.

The role of the reflected Rossby waves is to broaden the resulting baroclinic coastal disturbance in the offshore direction. As the coastally trapped Kelvin waves carry part of the incident energy rapidly poleward, Rossby waves continually emanate westward from the coast in their wake, at ever increasing latitude (not distinguishable individually in Figure 5). Because the Rossby response becomes slower and smaller in scale with increasing latitude (successively higher meridional modes), the coastal broadening is fastest and greatest near the equator and tapers off rapidly toward the poles.

In the wind-forced models the successive excitation and propagation of Kelvin and Rossby waves across the basin provide a mechanism for the time-dependent adjustment of the ocean circulation to a new equilibrium state after the impulsive change in the winds. Naturally, when the wind regime returns to normal, the ocean again readjusts through a transient response back to the non-El Niño condition. In reality, however, the entire El Niño cycle involves interactions between the ocean and the atmosphere (to be discussed later) that prevent a steady El Niño state from ever being established. This is never seen in the early models, which calculate the ocean response to prescribed wind fields and do not allow for such interactions.

Following the work by *Wyrtki* [1975], additional results quickly emerged. Earlier, *Wyrtki* [1974] had used meridional sea level differences between Pacific islands to show that the westward equatorial currents were weakened and the eastward North Equatorial Countercurrent (NECC, located in a broad zonal band between 5°N and 10°N) was strengthened during El Niño years. The numerical study of *McCreary* [1976] confirmed this and further demonstrated that wind weakening within only a few degrees of the equator was sufficient to produce an El Niño-like response. *Barnett* [1977] was able to confirm the wave theory statistically from a large suite of basin-wide observations. *Enfield* [1981] pieced together a series of north-south hydrographic sections off Ecuador during the 1971-1973 El Niño cycle that clearly demonstrated the thermocline deepening off South America (Figure 6). He also argued that the depressed thermocline along the coast leads directly to the observed Peru SST anomalies, because the water upwelled under the influence of unabated coastal winds is warmer than normal. In agreement with theory [*Moore and Philander*, 1977; *Cane and Sarachik*, 1977], *Hurlburt et al.* [1976] showed numerically that the equatorial disturbance continues poleward into both hemispheres (along the west coast of the Americas) as coastally trapped Kelvin waves, producing reversals of the normally equatorward boundary currents. Then, a 25-year time series of coastal sea levels from Valparaiso (Chile) to Yakutat (Alaska) showed that equatorial anomalies indeed propagated poleward at Kelvin wave speeds as far as northern California [*Enfield and Allen*, 1980; *Chelton and Davis*, 1982].

Further progress was also made in understanding teleconnections [*Rasmusson and Wallace*, 1983]. *Horel and Wallace* [1981] showed that one particular modal distribution in the northern hemisphere pressure fields, the Pacific North American (PNA) pattern, is coherent with indices of the El Niño warming in the equatorial Pacific (Figure 7). *Van Loon and Madden* [1981] found SO correlates in surface temperature and pressure fields at temperate latitudes of both hemispheres, while *Van Loon and Rogers* [1981] saw midtropospheric patterns of teleconnections to the extratropics in the form of enhanced subtropical jet streams and an increased (poleward) eddy transfer of sensible heat through extratropical weather systems. Stationary Rossby wave propagation on a sphere was the mechanism proposed to explain the observed teleconnections [*Hoskins and Karoly*, 1981; *Webster*, 1981]. The teleconnections were most evident during the winter season for the respective hemisphere. Central Chile, for example, has experienced devastating rainstorms in June-July of El Niño years, and correlations between the SOI and rainfall in Valparaiso and Santiago bear this out [*Quinn and Neal*, 1983].

By the start of the 1980s, the wave theory of El Niño was firmly entrenched and had been embellished with a number of observational and theoretical details. However, this process was—and still is today—interpreted somewhat differently by oceanographers and meteorologists. As seen by oceanographers, the oceanic events are initiated

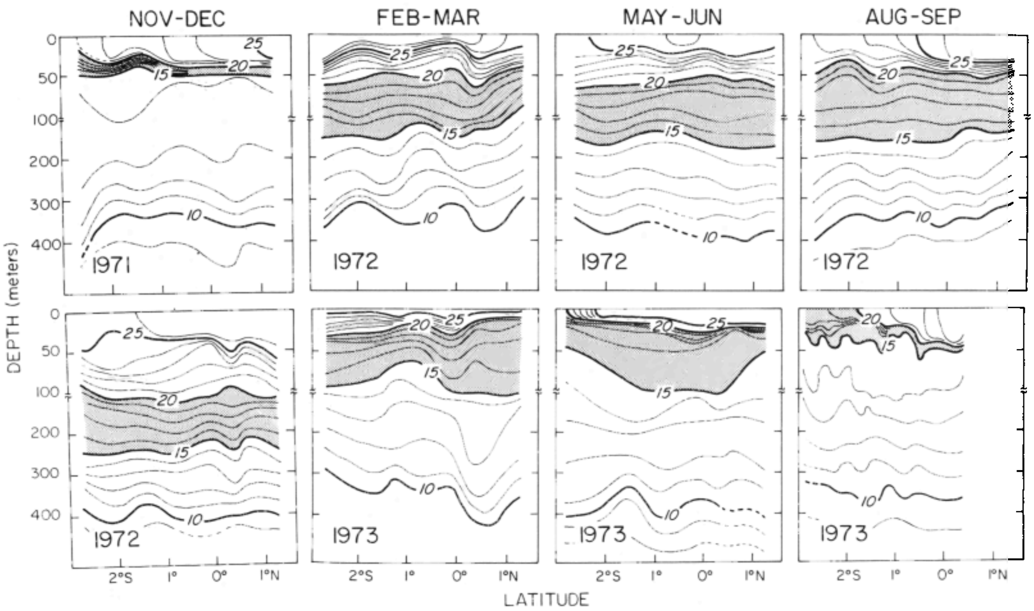


Figure 6. Eight successive ocean temperature (degrees Celsius) sections across the equator off Ecuador (82.5°W) at 3-month intervals before, during, and after the 1972-1973 El Niño. The first (top) and second (bottom) years of the sequence begin in November-December (left) and end in August-September (right). (Reprinted from *Enfield* [1981] by permission of John Wiley.)

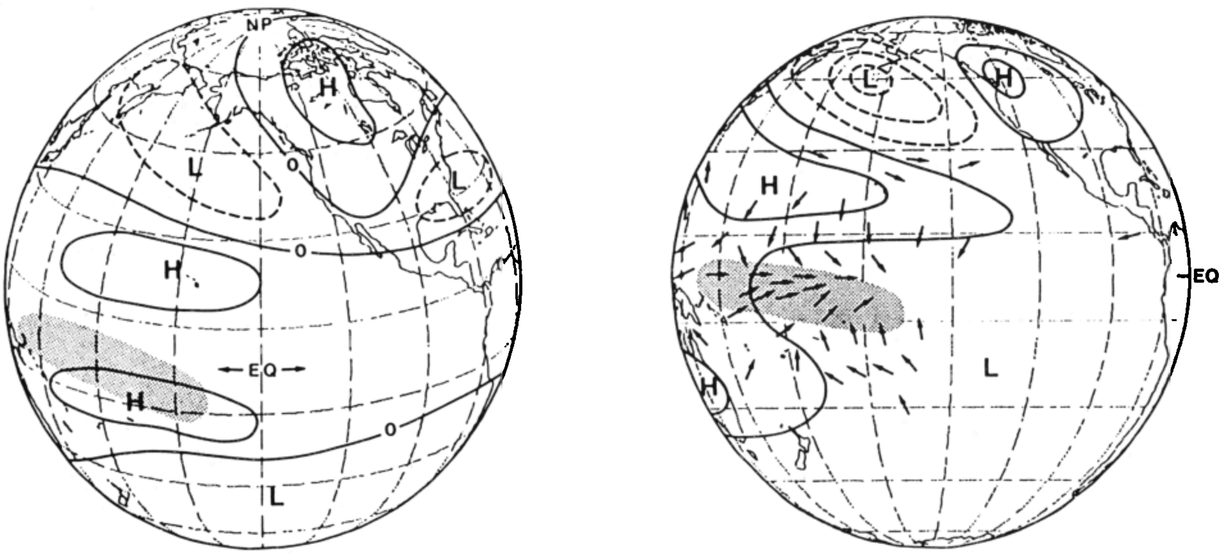
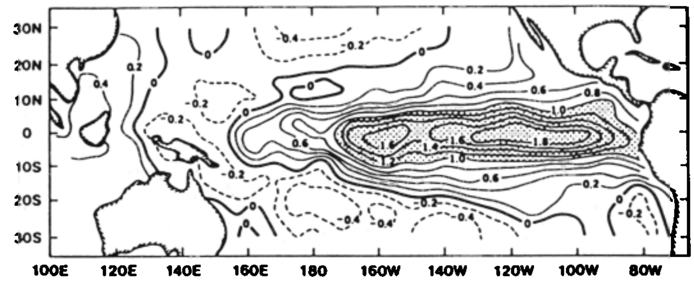


Figure 7. An illustration of the distributions of key properties involved in the teleconnection process during a typical El Niño-Southern Oscillation event. (Left) Upper troposphere anomalies of geopotential height for the northern hemisphere winter. (Right) Contours of surface barometric pressure, with surface wind anomalies (arrows) in the tropics. (Bottom) Distribution of anomalous sea surface temperature (degrees Celsius). (From *Rasmusson* [1984].)



by weakened trade winds associated with a decreasing SOI, while to meteorologists the reason for sustained downturns in the SOI (and associated large-scale weakening in the trade winds) is the alteration of equatorial SST patterns that occur during the El Niño/Southern Oscillation. Both statements are true, because the process involves continuous interactions between the ocean and the atmosphere. As equatorial warming progresses, the atmospheric circulation changes to accommodate new SST distributions, bringing about the anomalous advection of moisture to areas of high SST. The moisture rises to upper tropospheric levels, condenses, and releases latent heat, thus creating a "draft" effect that powers large-scale convection anomalies. As the highly altered wind field develops, more Kelvin waves are generated, continuing the ocean processes that result in anomalous increases in SST. The end result of the interactive process is that the SOI and SST anomalies are observed to reach their peak phases roughly simultaneously. Regardless of how the process was viewed at the close of the 1970s, the physical outlines for an El Niño-Southern Oscillation (ENSO) system had been established that provided a new framework for research on interannual climatic fluctuations. (See note 6.)

The Canonical ENSO

Conventional wisdom during the late 1970s held that El Niño is synchronized with the seasons: a typical episode would begin early in the year, go through anomalous peaks in the boreal spring and following winter, and terminate after 10-15 months of unusually high temperatures along the South American coast. Moreover, *Wyrtki* [1975] had observed that sustained periods of stronger SE trades (or high SOI) precede the El Niño (Figure 3) and argued that they served to "build up" the pool of accumulated warm water in the western Pacific prior to the El Niño collapse.

The perception that El Niño cycles develop in seasonally synchronized states motivated *Rasmusson and Carpenter* [1982] to analyze a pan-Pacific data set of SST, winds, and precipitation from the perspective of a canonical event. They combined the data for the 3 years before, during, and following each of six El Niño episodes that occurred between 1951 and 1973. In the "antecedent" phase (September of the year prior to El Niño), the winds in the western equatorial Pacific are stronger than normal, and eastern Pacific SSTs at low latitudes are low. In the "onset" phase (December) an anomalous westerly component develops in the zonal winds near the date line, while SSTs along the coast of Ecuador and north-central Peru are near normal. (See note 7.). In April of the El Niño year, following the initial ocean relaxation (propagation of Kelvin waves eastward), the "peak" phase of the canonical event features strong, positive anomalies along the Peru-Ecuador coast, extending to somewhat lower values along the equator from the Galapagos (90°W) to the Line Islands (155°-160°W). A "transition" phase (September) comprises the ubiquitous hiatus in Peru SST departures combined with well-developed westerly wind anomalies that extend from New Guinea to the Line Islands, and strong SST anomalies along the equator from the Galapagos to the date line. This condition continues through the "mature" phase (January), immediately before a rapid descent of coastal SST anomalies to below normal values in May of the year following El Niño, completing the sequence.

The western and eastern canonical sequences of sea level anomalies are well represented by the 3-year El Niño composites for sea level at Truk Island (7°N, 152°E) and Callao, Peru, respectively, compared with the composites for non-El Niño years (Figure 8). There is a single large fall in sea level at Truk while the western Pacific is "drained" of upper layer water (advected eastward). Meanwhile, the sea level at Callao rises to successive anomalous peaks that occur as enhancements to the mean annual maximum, the result of the massively depressed thermocline in the eastern Pacific. During non-El Niño years the average behavior at Truk is semiannual, while during ENSO periods there is only one (annual) extremum of much larger amplitude. Thus the tropical Pacific behaves like a bimodal system in which El Niño occurs as an internal "switch" from one modal state to another [*Meyers*, 1982]

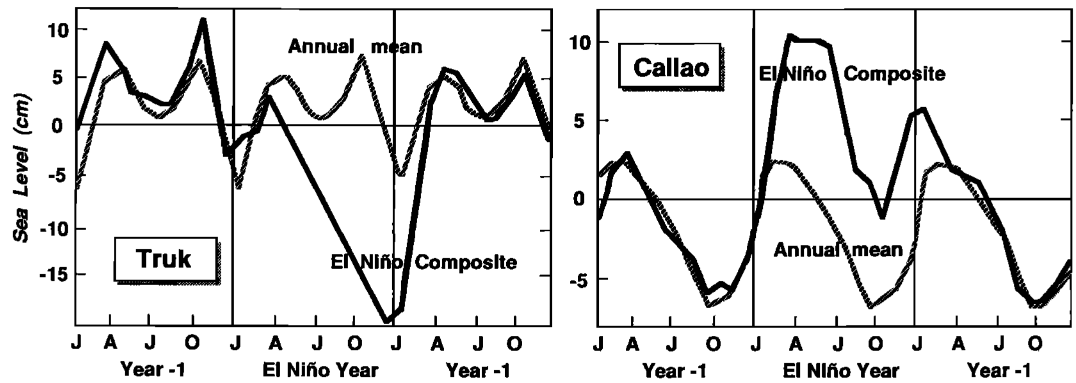


Figure 8. El Niño and non-El Niño signatures in the sea level at Truk Island and Callao, Peru. The El Niño sequence is constructed from 30-year composites centered on the six El Niño events of *Rasmusson and Carpenter* [1982], and the non-El Niño sequence is a repeating semiannual cycle averaged from normal years. (After *Cane* [1983].)

The El Niño of 1982-1983

The canonical ENSO provides a model of the commonalities that occur during El Niño and has served as a phase-oriented guideline to subsequent investigators seeking to understand the mechanisms by which the anomalies evolve. By mid-1982, many scientists felt they had sufficient understanding of the ENSO process to predict an El Niño with several months advance notice [e.g., *Barnett*, 1981*a*]. Oceanographers, in particular, felt reasonably confident that a period of enhanced trades and high SOI were a prerequisite for a major ENSO development. Another expectation for the start of an ENSO cycle was the onset of noteworthy SST anomalies along the Peru coast, prior to signs of equatorial warming (i.e., the sequence expected from the canonical ENSO described by *Rasmusson and Carpenter* [1982]).

As if to chide scientists for their presumptuosness, Nature confounded the newly gained insights only a few months after the *Rasmusson and Carpenter* [1982] paper was published. Following weak and unimpressive SST anomalies off Peru early in the year, and lacking a clear antecedent strengthening of the trade winds, experts meeting in the boreal fall of 1982 discounted the importance of a mild climatic oscillation that had been observed in the Indo-Pacific region during the preceding spring and summer (which had led to speculation that another El Niño was under way). By the end of the year the scientific community was in shock: SSTs at Puerto Chicama had catapulted from below normal in September to 2°C, 5°C, and 7°C above average over the following 3 months. By the boreal summer of 1983 the strongest El Niño in at least a century came to a close. (See note 8.) In direct contradiction to the canonical model, the timing of the SST anomalies was offset by a half-year off South America, having been preceded by SST anomalies near the date line.

Along the Equator A considerable body of scientific literature documents the 1982-1983 El Niño, including reviews by *Gill and Rasmusson* [1983], *Philander and Rasmusson* [1985], and *Cane* [1983]. Following the collapse of the western equatorial Pacific easterlies in July-August of 1982, a series of first and second vertical mode Kelvin waves propagated to the South American coast, effecting the advection of warm upper layer water eastward from its normal locations and causing sharp increases in coastal sea level and SST during the fall and early winter [*Lukas et al.*, 1984; *Busalacchi and Cane*, 1985]. These events took place in spite of the fact that the wind in the eastern Pacific remained normal from August through December [*Halpern*, 1987].

By early November the westward flowing South Equatorial Current (SEC) had disappeared along the equator near 95°W and was replaced by an eastward transport of surface water, such that SSTs east of there were above 25°C and the equatorial thermocline (20°C isotherm) was depressed by 50-100 m below normal depths [*Mangum et al.*, 1986]. By the end of 1982 the normal east-west sea level slope that drives the Equatorial Undercurrent (EUC) had been eliminated by the redistribution of mass and heat [*Firing et al.*, 1983; *Wyrtki*, 1984]. The EUC began to weaken at 110°W in late October, and equatorial SSTs reached their first peak in mid-December; the coastal SSTs entered a hiatus in January and February 1983, and the EUC virtually disappeared at the 110°W and 95°W equatorial moorings [*Halpern*, 1987]. The west-to-east progression of the EUC disappearance was considered significant by *McCreary and Lukas* [1986], and they show that this could have resulted at least partially because the patch of anomalous winds migrated eastward in the same direction as the Kelvin waves it generated.

The development of large-scale convection in the tropics tends to occur over water whose SST is greater than about 27°-28°C [*Graham and Barnett*, 1987], a normal condition in Indonesia but not east of the date line. Hence, although the locations and timing of SST anomalies may vary between ENSO episodes, the region of highest absolute SSTs invariably expands eastward along the equator from the normally warm western Pacific. The situation in 1982-1983 was no different. As anomalous atmospheric convective activity migrated eastward in pursuit of the highest absolute surface temperatures, the winds in the eastern equatorial Pacific began to collapse in early 1983 (Figure 9). Although the sense of the west-to-east progression was typical, the intensity of the wind collapse in the east was unprecedented. This was probably due to the unusual timing of the ocean-atmosphere interactions, which in the canonical ENSO occur during the austral winter when eastern Pacific SSTs are lowest (hence absolute SSTs do not reach critical values, in spite of large anomalies). In early 1983, however, eastern Pacific SSTs were near the peak of their annual cycle, and by May the anomalies had pushed them above 30°C.

As the wind collapse went to completion, the equatorial circulation again relaxed in the eastern Pacific, but this time because of local rather than remote forcing, the coastal sea level hit a second peak centered near April-June. By May 1983 the zonal pressure gradient between 95°W and 100°W had reversed, and the EUC was replaced by a westward jet at 75 m [*Hayes et al.*, 1987]. Other notable anomalies included a strong peak in the eastward flow of the NECC and the appearance of very low (rain-induced) surface salinities in the central Pacific [*Kessler and Taft*, 1987].

Off South America Two peak anomalies of 60 cm in monthly sea level occurred in Ecuador and Peru in December-January and April-June 1983, along with SST anomalies of nearly 10°C (Figures 3 and 9). The high sea level stands, along with long-period swell from extraordi-

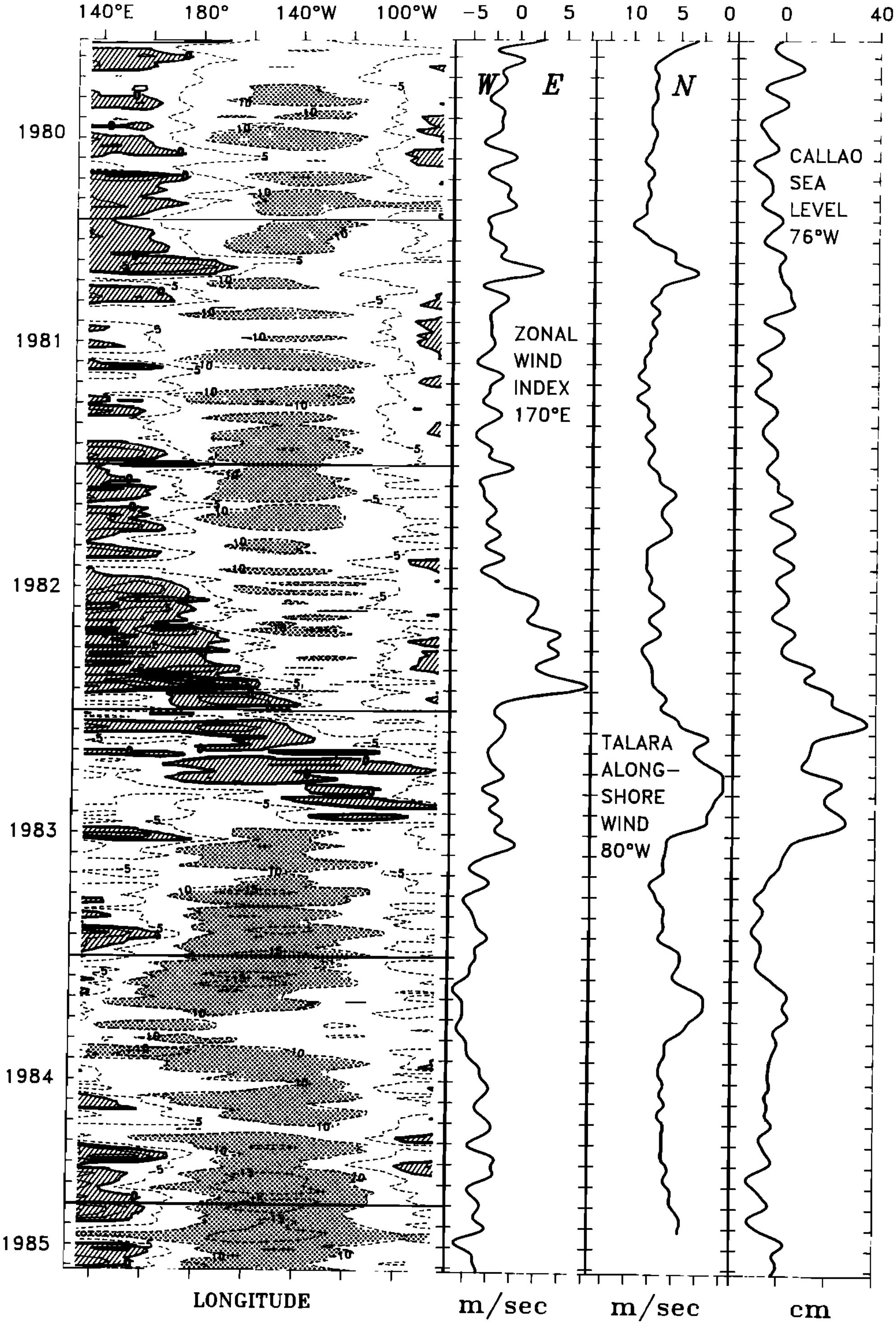


Figure 9. Four panels showing (from left to right, time increasing downward) contours of low-level (850 mbar) zonal wind velocity along the equator; the zonal surface wind near the equator and 170°E in the western Pacific (islands); the northward component of the wind at Talara, Peru (increasing to left); and filtered sea level at Callao, Peru (12°S). The contour interval (left panel) is 5 m/s; stippled shading indicates westward winds in excess of 10 m/s, and hatching indicates eastward winds. (From *Enfield* [1987*b*].)

nary North Pacific storms, caused extensive wave damage and shore erosion in Ecuador and Peru from 2°S to 5°S. The eastern equatorial collapse of the wind field affected the coast of Ecuador and extended down to Talara, Peru (Figure 9), but not much farther south [*Horel and Cornejo-Garrido*, 1986]. Although isotherms were depressed to anomalous depths, the winds continued to be upwelling favorable over most of the Peru coast, and the upwarping of isothermal surfaces characteristic of upwelling was usually present [*Huyer et al.*, 1987]. This

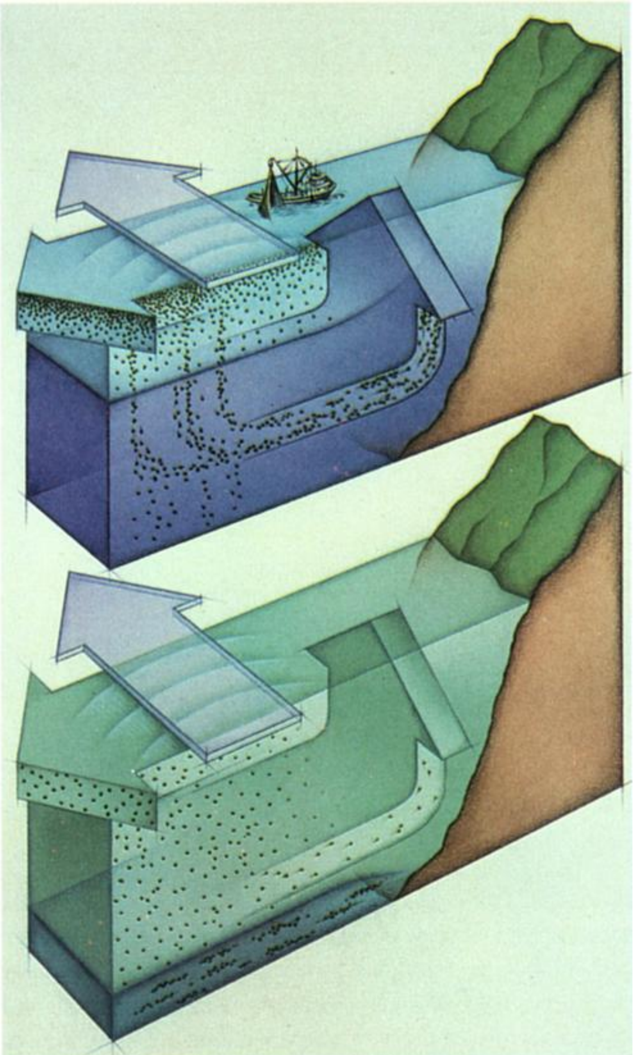


Plate 1. Schematic illustration of upwelling characteristics along the coast of Peru during (top) normal and (bottom) El Niño conditions. A thermocline and nutricline separate the warm, nutrient-deficient upper layer (light color) from the cool, enriched lower layer below (dark color). (Artwork by A. Carroll based on original drawing by R. T. Barber, copyright National Geographic Society [*Canby*, 1984].)

confirms previous indications that subsurface temperature anomalies are brought to the surface near shore through the continued process of upwelling (Plate 1).

There was extensive damage to the marine ecology along the South American coast in 1983 [*Arntz et al.*, 1985; *Instituto de Fomento Pesquero*, 1985]. The overall coastal ocean productivity was greatly reduced because water was upwelled from the nutrient-depleted upper layer water that overlaid the depressed thermocline [*Barber and Chavez*, 1983; *Huyer et al.*, 1987]. Ironically, however, not all of the fisheries impacts were disastrous, with certain commercial species, most notably shrimps but also dolphin fish, scallops, octopus, and many others, appearing in unusually large numbers [*Arntz*, 1984]. High temperatures and low concentrations of traditional plankton varieties decimated the commercially important pelagic (midwater) fish stocks, such as anchovies and sardines, while bottom dwellers like shrimp and scallops fared well because of an enriched oxygen supply. Other demersal (near-bottom) species such as hake were redistributed by the envirionmental changes. Mortality of the normally abundant guano birds and marine mammals was widespread because their normal food supply of schooling fishes was greatly reduced and/or made unavailable to them. Since the hungry adults abandoned their nests and broods in large numbers in search of scarce food, their populations were subsequently slow to recover after environmental conditions returned to normal in 1984. A well-documented microcosm of the bird mortalities occurred near the equator on Christmas Island, halfway across the Pacific [*Schreiber and Schreiber*, 1984].

By far the most extensive damage to the South American coast came in the form of rainfall during the first 5 months of 1983. Unheard of amounts of rain fell on coastal Ecuador and Peru, north of Lambayeque (6°41′S). The meteorological characteristics of the desert rainfall (mostly nocturnal convective storms) have been extensively researched by *Horel and Cornejo-Garrido* [1986] and *Goldberg et al.* [1987]. The resulting flash floods roared through the desert gullies, ripping out roads and bridges and damaging the pipelines that transport crude oil to ports of embarkation. Talara, a port built in a canyon cut through the surrounding "tablazo" (plateau), was inundated with mud that took more than a year to remove. Talara and other isolated communities had to be resupplied by helicopter until road links could be reestablished. Vast regions of the Sechura Desert were revegetated by the rainfall, and large shallow lakes appeared, often burying major highways, some remaining for almost 2 years (Plate 2). Agriculture, highly dependent on a well-controlled system of irrigation, was ravaged by untimely water damage, a lack of transportation facilities and—not the least—by infestations of voracious insects spawned by the rogue vegetation.

The teleconnections of weather phenomena to more remote regions may have begun as early as June-July 1982, when central Chile suffered the effects of record rainfall and flooding resulting from an intensified southern hemisphere winter jet stream [*Quinn and Neal*, 1983]. This may have been a contemporaneous manifestation of the same climatic fluctuation that initiated the wind collapse in the western equatorial Pacific. By December 1982 the sea surface temperatures along the equator had risen to 4°-6°C above normal and were pumping energy into the subtropical jet stream of the northern hemisphere [*Rasmusson*, 1984]. Frequent storms moved south of their normal tracks and battered the California coast with high surf. The coastal erosion was all the more catastrophic for coastal communities because mean sea level had risen

Plate 2. During the 1982-1983 El Niño, record rains fell over coastal Ecuador and the northernmost desert region of Peru. This scene depicts a portion of the Sechura Desert in November 1983, about 5 months after the rains subsided and a shallow lake had dried up, parching the soil. Many vestiges remain of the copious vegetation that spontaneously emerged from the deluge. (Photograph by H. Soldi.)

about 30 cm above normal levels [*Komar and Enfield*, 1987]. The offshore circulation of the normally southward California Current was reversed, and hundreds of marine species were carried far north of their normal ranges [*Wooster and Fluharty*, 1985]. Some fisheries prospered, but others collapsed; of these, a few had not yet recovered several years later. The list also includes a record drought in Australia, South Pacific hurricanes as far east as Tahiti, unusual winter rainfall in the southern United States and northern Caribbean, etc. [*Canby*, 1984]. Certainly, the global weather disturbances were remarkable during 1982-1983, confirming the basic hypothesis of Bjerknes, although the effects were more spectacular than those usually seen. However, in certain regions, such as the west coast of the United States, the pattern of oceanic anomalies and the climatic phenomena produced by the teleconnections turned out to be radically different from those observed on previous occasions, e.g., 1976-1977 [*Namias and Cayan*, 1984].

CURRENT RESEARCH

The unprecedented El Niño of 1982-1983 unleashed a wave of research activity in observational analysis and modeling. Scientific interest was awakened by the very strength of the event, its baffling differences vis-à-vis the composite model, the fact that valuable observations had been taken along the equator and near the South American coast, and the availability of more sophisticated modeling schemes and basin-wide data sets with which to systematically probe the underlying processes. Moreover, the global occurrence of associated weather anomalies motivated significant increases in research funding for observations and modeling, under the aegis of the newly formed decadal program, Tropical Ocean-Global Atmosphere (TOGA).

By the end of 1983 there was agreement on the general outline of the ocean-atmosphere interactions that typically accompany an ENSO episode, although many details remained unclear, such as the relative importance of various processes and the reasons for the unusual evolution of the 1982-1983 event. These concepts also coincide with our current but more complete understanding. Shortly before the ENSO onset, the SSTs in the Western Pacific tend to be slightly warmer than normal. The western Pacific winds then become less easterly or even westerly, usually after an extended period in which the easterly trades are well developed. The wind anomalies, not strong at first, force eastward propagating Kelvin waves in the equatorial ocean waveguide that arrive at the eastern boundary about 2 months later. The first positive SST anomalies are usually generated in the eastern equatorial Pacific and off Peru by the interaction of a deepened thermocline with continued upwelling-favorable winds. Somewhat later, within about 10° latitude of the equator, a weakened or reversed SEC and accelerated EUC and NECC advect warm water eastward along the equator.

This gives the appearance, in the canonical case, that the SST anomalies are migrating westward from the coast out into the central equatorial Pacific. However, in terms of absolute surface temperatures, the SST anomalies correspond to an eastward expansion of the western equatorial warm pool, accompanied by an eastward migration of the atmospheric convection activity associated with the initial anomalous westerly winds (Figure 10). Kelvin waves are again excited (farther east, in the central Pacific) as the ocean relxation continues. As the zone of maximum SST pushes eastward, the atmospheric heating also expands, and so on in an unstable, positive-feedback process.

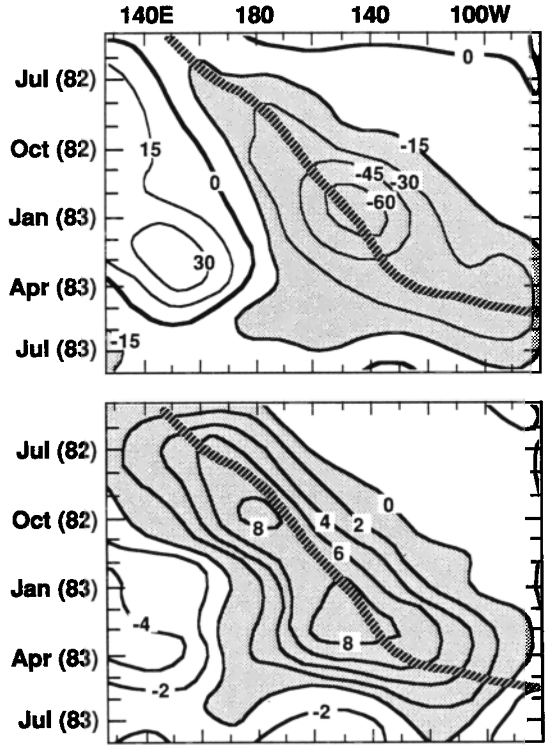


Figure 10. Longitude-time plots during 1982-1983 of (top) monthly mean values of anomalous convection (indicated by outgoing long-wave radiation from cloud tops, in watts per square meter) and (bottom) westerly wind anomaly, 5°N to 5°S (in meters per second). The heavy striped line traces the time-longitude path of maximum convection. (After *Gill and Rasmusson* [1983].)

In addition to details regarding the processes, several important pieces were still missing from the puzzle in 1983: How does the initial, small anomaly progress to the critical point where unstable interaction takes over? How is the instability process stopped and the El Niño terminated? And, how is the overall ENSO cycle repeated?

Wave Processes

Results from observations and modeling quickly began to confirm and to clarify the role of equatorial waves in the ocean response. Equatorial moorings at 152°W and 110°W and a tide gauge at the Galapagos detected the first documented Kelvin wave [*Knox and Halpern*, 1982]. It was also seen to occur as an annual (boreal) spring event in successive non-El Niño years, following wind changes in the western Pacific [*Halpern et al.*, 1983]. *Lukas et al.* [1984] studied the correlation structures in sea level between tide gauges of Pacific islands during the 1982-1983 El Niño. They found evidence of the first two vertical modes in the Kelvin waves, as well as indications of the low-latitude Rossby waves reflecting off the eastern boundary. They also showed that the superposition of the various wave modes (of differing speeds and directions) gave sea level in the mid-Pacific a much different character from that at the South coast.

A series of model simulations forced by realistic winds demonstrated the usefulness of the simplest model formulations and successfully tested the hypothesis that sea level variations during El Niño occur as a response to wind changes farther west, transmitted by equatorial Kelvin waves. *Busalacchi et al.* [1983] successfully verified a linear ocean model in a hindcast of interannual pycnocline variations for 1961-1978, forcing the model ocean with reprocessed ship wind data developed by *Goldenberg and O'Brien* [1981]. Kelvin waves produced differing responses in coastal sea level during the various El Niño episodes, depending on the zonal location and timing of the associated wind changes to the west (Figure 11). The lowest meridional mode Rossby waves reflected off the eastern boundary were shown to be a significant part of the variability in the low-latitude central Pacific. However, the wind anomaly also directly forces Rossby waves in the western Pacific (Figure 5) that are even more important, since they effect the large sea level drops (thermocline rises) there, e.g., at Truk Island (Figures 8 and 11).

Cane [1984] used an El Niño composite of real winds to force a simulation of the canonical event. Only the first two vertical modes make significant contributions to the sea level response (as observed by *Lukas et al.* [1984]), and the model reproduces the double-peak structure of sea level anomalies at the South American coast. The first (boreal spring) peak results from the weaker western Pacific wind anomalies that initiate the event, while the second peak (at year's end) is a response to the massive collapse of the central Pacific trade winds that occurs in the boreal summer. The simulation of the 1982-1983 El Niño by *Busalacchi and Cane* [1985] also compared well to sea level observations and confirmed that both the first and the second baroclinic modes were important in the response.

The El Niño response to wind forcing is a complex mixture of equatorial waves of various types. Those that clearly play an active and fundamental role in the ocean readjustment process are low-mode, low-frequency Kelvin

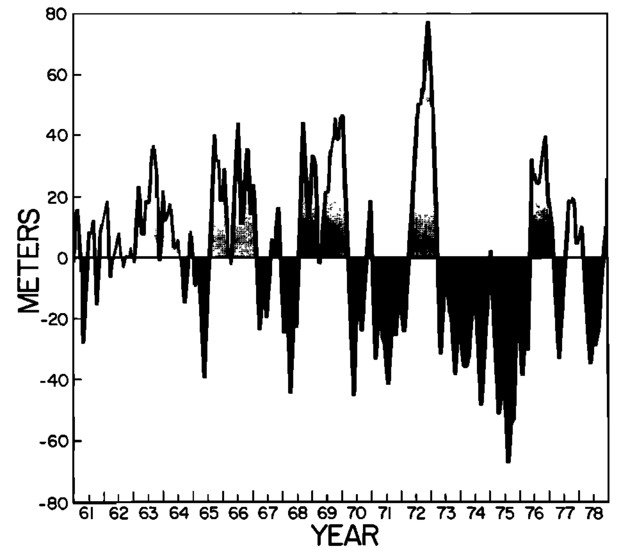
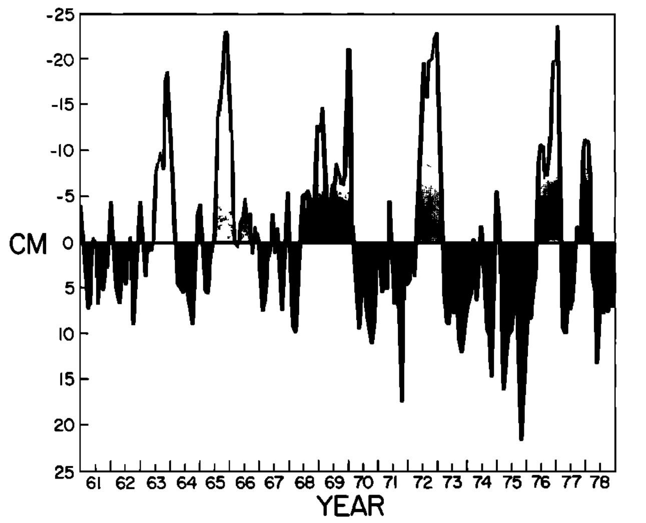


Figure 11. (Top) Monthly time series (1961-1978) of observed sea level at Truk Island (7°N, 152°E). (Bottom) Model pycnocline height anomaly at a location corresponding to Truk Island. (After *Busalacchi et al.* [1983].)



and Rossby waves. Careful examination of sea level records from the 1982-1983 El Niño reveals that the sustained periods of high sea level were composed of other waves as well, which were interannually modulated and whose role in the relaxation process is unclear. Fluctuations of 40- to 60-day periods are quite evident in Peru sea level records (e.g., Figure 9) and were shown by *Enfield* [1987*b*] to be Kelvin waves forced in the western equatorial Pacific by the so-called "intraseasonal oscillation" of similar period that has been extensively studied by meteorologists and atmospheric modelers since their serendipitous discovery by *Madden and Julian* [1971]. The sea level oscillation is modulated interannually and had larger than average amplitude during the 1972-1973 and 1982-1983 El Niños. Although this may have been fortuitous, there are independent reasons to believe the oscillation may play a critical role in the early stages of El Niño episodes [*Lau and Chan*, 1988]. There is no universal agreement on this point, however. It may be that the oscillation is only effective as a trigger if it intensifies at the proper location, when the ocean is in a proper configuration. Or, it may be that the oscillation is decoupled from the ENSO sequence and merely modulates the observed anomalies.

Other high-frequency fluctuations, though seemingly innocuous in the context of El Niño, may play a significant role in the heat flux variations that govern SST anomalies. *Halpern et al.* [1988] present extensive evidence, from 7 years of data, for 20-day oscillations in the meridional currents at five equatorial mooring sites between the Galapagos and the Line islands. The oscillations appear to be associated with the westward propagating, cusp-shaped waves discovered in satellite thermal (infrared) imagery by *Legeckis* [1977]. These instability waves are believed to be generated by large meridional current shears between high-energy zonal currents (SEC and NECC) near the equator [*Philander et al.*, 1985]. As the SEC relaxed during the 1982-1983 El Niño, the instability waves disappeared. Very large amounts of heat are mixed laterally into the equatorial zone by the instability waves [*Hansen and Paul*, 1984]. This process was parameterized in the climatological study by *Enfield* [1986], who found it to be seasonally important in the east-central Pacific, along with zonal and meridional advection and vertical diffusion (but opposite in sign). Research is currently being planned to determine the possible importance that the disappearance of instability waves may have on oceanic heat balance variations during ENSO cycles.

Surface Thermal Response

The matter of how anomalous SST patterns evolve during El Niño is a fundamental piece of the ENSO puzzle. They are thought to be primarily a function of how heat gets moved around by upper layer ocean processes. The climatological study of the equatorial Pacific heat balance by *Wyrtki* [1981] shows that meridional Ekman transports and upwelling are normally about twice as important as the westward advection of cool water (from South America) for the removal of heat gained through the sea surface in the equatorial cold tongue. The importance of mean and seasonal upwelling induced by zonal wind stress also appeared in the climatological studies of *Bryden and Brady* [1985] and *Enfield* [1986]. In the latter analysis it is argued that horizontal and vertical mixing processes are also important in the central and eastern Pacific, respectively. Unfortunately, studies of this type have large errors due to the bulk thermodynamic methods used and have not been extended to the interannual time scale because of the scarcity of subsurface observations.

There seems to be a fairly general agreement that net heat gains to the equatorial ocean from the atmosphere do not play a major role in the unstable growth of ENSO episodes. Increases of SST due to anomalous ocean processes cause an increased rate of evaporative heat loss that far outweighs any anomalous heat gains from solar radiation, while increased cloudiness associated with anomalous convection reduces the incoming solar radiation over large areas. While pointing out this inverse relation between SST anomalies and net surface heat flux, *Weare* [1983] also shows that some of the large heat gain found during a non-El Niño (cold) phase persists into the onset phase of the subsequent El Niño episode and thus may be a factor during the period in which El Niño is triggered, particularly in the western Pacific. *Leetma*'s [1983] study shows that surface heating is probably a factor during El Niño in the eastern Pacific, but mainly outside the confines of the equatorial and coastal waveguides.

Although it has not been possible to sort out from observations which of the normal oceanic processes are altered most critically during El Niño, it is clear that their most important net effect is to alter the tropical ocean heat content. *Wyrtki* [1985] has inferred from sea level observations that upper layer water stored in the western Pacific prior to El Niño is transferred eastward during the subsequent ENSO development and is then depleted by renewed meridional (Ekman) transports away from the equator as the El Niño comes to an end (Figure 12). The importance of such adiabatic changes in heat content (produced mainly by meridional advection) aslo emerges in the linear ocean model of *Pares-Sierra et al.* [1985], who find that the interannual variations rival both the seasonal changes and the mean. *Philander and Hurlin* [1988] use a nonlinear oceanic general circulation model to realistically simulate the heat transports during the 1982-1983 El Niño. They confirm that large amounts of heat are removed from the equatorial zone by meridional advection during the later stages of the episode.

The question of how the adiabatic volume changes in the upper ocean are related to the evolution of anomalies cannot be addressed by the linear dynamics of the simple

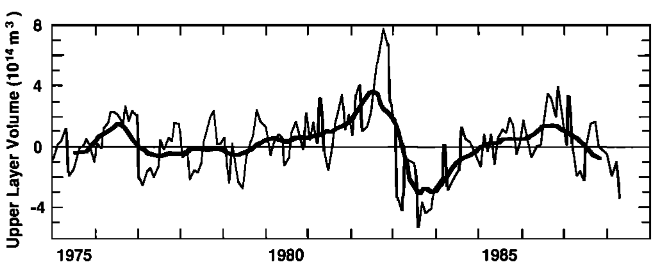


Figure 12. Upper layer volume in the tropical Pacific between 15°N and 15°S relative to its mean value of about 70×10^{14} m^3. The annual cycle is not removed. Note the large rise in upper ocean volume leading to a peak in mid-1982, followed by a rapid fall to low values at the end of 1983. (Redrawn from a figure provided by K. Wyrtki.)

linear ocean models. Ocean nonlinearities are thought to be important in the dynamics of the equatorial mixed layers and currents, especially the EUC, and hence also in the production of SST anomalies. The Kelvin waves produced by linear models depress the thermocline but leave SST unchanged, whereas the Kelvin wave fronts in nonlinear models interact with the zonal flows and mixed layer to cause surface warming [*Philander*, 1981]. In addition, the simplest reduced-gravity models lack any vertical mixing of cold water into the surface mixed layer from below the thermocline (also a nonlinear process). Vertical mixing is normally important in the eastern and east-central Pacific but is presumably suspended as adiabatic depression of the thermocline takes place in association with downwelling Kelvin waves, or, as occurred in 1983, the easterlies (and upwelling) collapse in the eastern ocean.

Starting in 1983 a series of numerical studies were devised to test various ideas about how SST anomalies are generated in the course of El Niño events. In all cases the wind forcing was specified, and nonlinearities were included in the model formulations as they affected temperature. *Schopf and Harrison* [1983] used the nonlinear ocean model of *Schopf and Cane* [1983] with a themodynamical surface layer to study the evolution of SST anomalies. They showed that anomalous thermocline depression associated with Kelvin waves reproduces essential features of SST changes along the South onset of El Niño events, provided the model ocean has been previously cooled by upwelling-favorable winds. As previously suggested by observations, it is the upwelling of anomalous water in the altered thermal profile that produces the coastal warming. However, the broad warming along the equator does not develop in later stages of the model simulation, contrary to the composite description by *Rasmusson and Carpenter* [1982] based on observations. The same model produces more realistic, persistent, and large-scale SST anomalies when the model atmosphere is made reactive and allowed to equilibrate to the changing ocean surface [*Schopf*, 1983]. In this case, Rossby wave reflections from the eastern boundary play a more critical role in the westward spread of SST anomalies along the equator than do the Kelvin waves, and the first baroclinic wave mode appears more important than the second.

One of the more baffling aspects of the 1982-1983 El Niño was the reverse order of the SST anomalies (compared with the canonical model), which occurred first in the equatorial region and later at the coast. *Harrison and Schopf* [1984] used the *Schopf* [1983] model to show that this was related to the unusual timing of the El Niño onset in 1982. Kelvin waves force SST anomalies any time of year along the Peru coast as a result of the invariant upwelling and shallow thermocline there. However, along the equator, where SST anomalies result mainly from the zonal advection associated with equatorial waves, anomalous warming is most marked during the May-November period when the zonal SST gradient is initially strong. In the canonical situation the onset of anomalous advection occurs around January-February when the SST gradient along the equator is nearly absent; hence the SST response occurs first at the coast and later farther west. The 1982 event was initiated in August-September when the equatorial cold tongue was well developed; SST anomalies appeared there almost immediately and then somewhat later at the coast following further propagation of the Kelvin pulses.

Zebiak and Cane [1987] modeled the SST problem with linear reduced-gravity dynamics plus a thermodynamic mixed layer with a nonlinear heating mechanism. Wind-driven surface jets and Ekman transports are accommodated by a shallow friction layer that allows for strong local forcing and realistic upwelling effects, and the temperature of upwelled water is made a function of thermocline depth. Once again, the model shows that upwelling of the depressed thermal structure is the source of warming off the coast of South America. Zonal advection dominates warming in the central Pacific, where reduced upwelling is offset by a rise in the thermocline. In the eastern equatorial Pacific, where the winds remain substantially unaltered during most El Niño episodes, both mechanisms are at work.

Philander and Seigel [1985] use a nonlinear, tropical ocean general circulation model to hindcast the 1982-1983 El Niño. The model spins up to a stable seasonal behavior under the influence of a specified climatological annual wind cycle; this provides a realistic initial state as real wind data begin to drive a 2-year simulation starting in January 1982. After an initial transient that is somewhat unrealistic (owing to the sudden shift from climatological to real winds), the simulation from about mid-1982 through the end of 1983 bears a remarkable resemblance to observations made by ships and moorings during the El Niño. The verification is most impressive for zonal flow and isotherm displacements near thermocline depths, where both the massive subsurface warming and the disappearance of the EUC are reproduced. The weakest aspect of the simulation is the evolution of SST, which requires improvements in the mixed layer formulation and would probably benefit from more accurate wind field data.

Ocean-Atmosphere Feedback

The effect of idealized diabatic (turbulent, convective) heating of the tropical atmosphere through latent heat release was investigated analytically by *Gill* [1980], with results similar to those from earlier work by *Webster* [1972]. The convection is associated with a zonally asymmetric surface wind convergence: easterly wind anomalies occur east of the heating center (produced by atmospheric Kelvin waves), and a cross-equatorial pairing of cyclonic vortices develops west of the heat source, with westerly and equatorward wind anomalies (Rossby wave response). This physics appeared in the atmospheric numerical model response of *Julian and Chervin* [1978], which produced circulation anomalies and teleconnections similar to those proposed by *Bjerknes* [1966*b*]. Paired cyclonic vortices, east of their normal location over the Indonesian maritime continent, have come to be a commonly recognized feature of ENSO developments [*Keen*, 1982]. Both the anomalous easterlies east of the highest SSTs and the cyclonic winds in the West can be clearly seen in the anomalous wind distributions of *Rasmusson and Carpenter* [1982], during the mature phase of the canonical El Niño event (Figure 13).

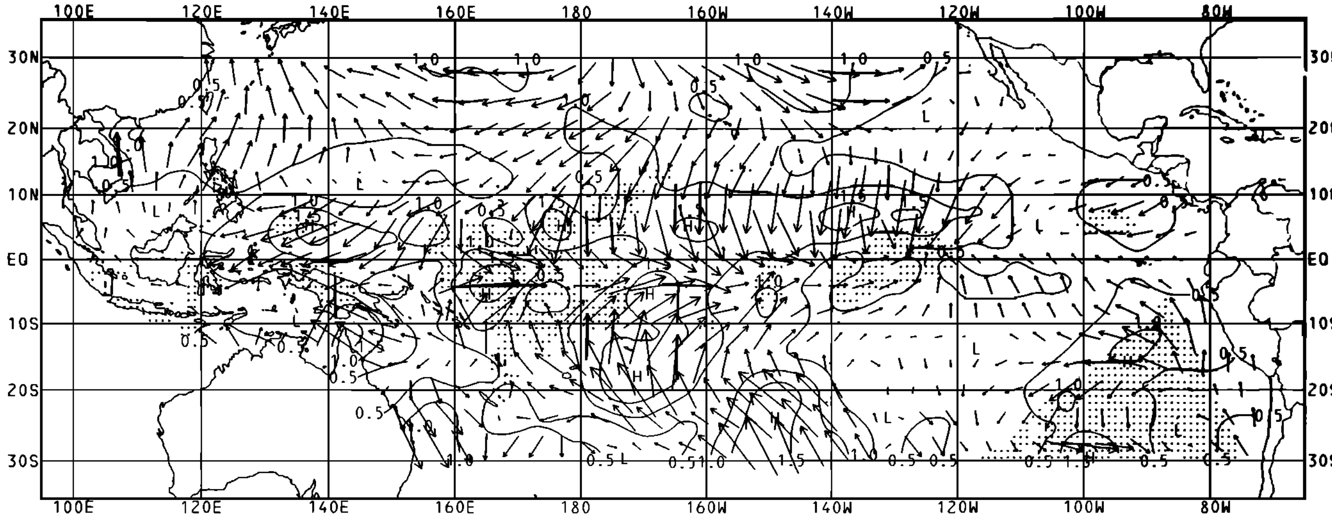


Figure 13. Composite anomaly of surface winds for the mature phase of the canonical El Niño (3-month average starting in December of the El Niño year). Isotachs (solid lines) give wind speed in meters per second, and shaded regions are data poor. (From *Rasmusson and Carpenter* [1982].)

The unstable development of air-sea interactions is related most critically to two nonlinear, thermodynamic processes: the suspension of cold-water upwelling through the depression of the eastern Pacific thermocline, and the lateral convergence of atmospheric moisture by anomalous convection. The first process has been mentioned several times. Sea surface temperatures rise in response to the suppression of normal ocean cooling processes, causing the area covered by water of 27°-28°C or more to expand eastward along the equator. Such SSTs are required in order for the thermodynamic profiles in the tropical marine atmosphere to achieve the unstable configuration needed for deep convection [*Graham and Barnett*, 1987]. As anomalous convection develops eastward of its normal locations over Indonesia and the western Pacific, additional moisture converges on the convective centers at low levels, feeding more latent heat to be released in the upper troposphere. In fact, meteorologists believe that most of the latent heat released in deep-convective processes is due to the horizontal convergence of moisture from surrounding areas and not directly from local evaporation [*Webster*, 1981]. These thermodynamic processes, oceanic and atmospheric, are interactive, each having an enhancing effect on the other.

The SST-convection linkage and the additive effect of the nonlinear processes explain the observation that anomalous convection migrates eastward in conjunction with the 29°C SST isotherm during El Niño [*Barnett*, 1981*a*; *Gill and Rasmusson*, 1983]. These temperatures are usually found considerably west of the regions where SST is normally coldest (and SST anomalies are therefore largest during ENSO). Hence the center of anomalous convection typically lies west of the maximum SST anomalies. When SST reaches values near 30°C, the evaporative heat loss from the ocean surface is as large as the gain from incoming solar radiation on a cloudless day. Since any additional heat gained is immediately lost through evaporation, temperatures in excess of 30°-31°C are seldom found in open-ocean regions [*Newell*, 1979]. More important, this effect places a natural limit on the unstable growth of SST anomalies.

The ENSO Oscillator

McCreary [1985] and *Cane* [1986] reviewed coupled (ocean-atmosphere) numerical models that have had varying success at producing unstable growth of SST anomalies, eastward migration of convection centers, and oscillatory interannual behavior. *Anderson and McCreary* [1985] and *Philander et al.* [1984] use a reduced-gravity ocean with active thermodynamics and a *Gill* [1980] atmosphere. Unstable growth develops as anomalous westerlies deepen the equatorial ocean mixed layer, which in turn causes intensification and eastward migration of the convective region, further mixed layer deepening, and so on. The instability undergoes rapid growth in the Anderson and McCreary model, which uses a nonlinear SST dependence for atmospheric heating. The heating is realistically capped by a maximum possible SST, so the instability does not grow indefinitely. The convective region migrates steadily eastward into the central Pacific, more slowly than observed, and vanishes near the eastern boundary. Interannual oscillations are produced, but the onsets are not realistically sudden, and the intermittency is not as irregular as observed.

The mechanism for the oscillatory behavior of the above models was first proposed by *McCreary* [1983] and is perhaps best exemplified by the models of *Zebiak and Cane* [1987] and *Schopf and Suarez* [1988]. In the *Zebiak and Cane* [1987] model, both fluids have dynamics that simulate anomalies about a zero mean state. The thermodynamic processes evolve about a mean climatological state; they are nonlinear, including low-level moisture convergence in the atmosphere in addition to direct heating by SST anomalies. (Comparing various lineralizations to the full nonlinear experiment, the authors show that realistic results cannot be obtained without nonlinear thermodynamics.) The model produces quasi-periodic vacillations that tend to be phase-locked to the annual cycle and are robust over a wide parameter range that lies within realistic limits (Figure 14). Zonally integrated, dynamically produced increases of the upper ocean heat

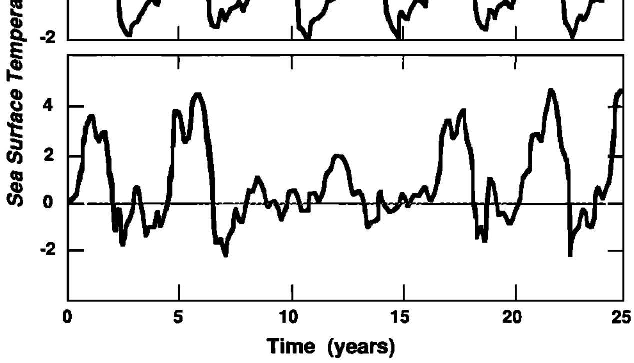


Figure 14. Twenty-five-year computer simulations of sea surface temperature in the east-central equatorial Pacific, by the coupled ocean-atmosphere model of *Zebiak and Cane* [1987]. Each case is a variant of a "standard" run using benchmark model parameters, in which one of the parameter settings has been changed. In the top panel the oceanic equivalent depth (stratification) has been decreased by 16%, in the middle panel it is decreased by 13%, and in the bottom panel the drag coefficient is increased by 20%. (After *Zebiak and Cane* [1987].)

content lead the SST increases in the central and eastern equatorial Pacific by a quarter cycle (9-12 months). The *Schopf and Suarez* [1988] model uses nonlinear dynamical equations in both fluids and a linear SST coupling. It evolves its own mean states and produces natural high-frequency variability superimposed on an irregular ENSO oscillation at 3- to 4.5-year intervals. As in the Zebiak and Cane model, the eastern and western ocean boundaries are crucial because they are needed for wave reflections, which comprise the cycling mechanism and set the underlying time scale of the oscillation.

Graham and White [1988] explain with elaborate detail how these oscillating ENSO models work. Although the various authors characterize the behavior of their models differently, they really produce oscillations in the same way: by moving upper layer water back and forth between the equator and off-equatorial region and between the central Pacific and the western boundary. They produce these mass transfers through low-mode baroclinic Kelvin and Rossby waves, which provide short and long (respectively) time delays between interactive phases in the departures from normal of three key variables: SST, zonal wind, and upper layer thickness.

Initially (the choice of where to begin the process is arbitrary), eastward propagating, downwelling Kelvin waves produce a positive-feedback, short-delay response in SST along the equator in the central and eastern Pacific, i.e., the well-accepted instability growth previously identified in models and observations. The SST departures grow to the critical value required for organized convection, at which point, moisture convergence from the surrounding regions into the instability zone begins, greatly augmenting the tropospheric latent heat release and generating stronger wind anomalies and more Kelvin waves (positive feedback).

The El Niño instability produces its own demise. The westerly equatorial wind anomalies produce an anomalous, cyclonic wind stress curl off the equator. This creates a decrease in ULT some 5°-10° away from the equator, which propagates slowly toward the western boundary in the form of low-latitude, baroclinic Rossby waves. These then reflect eastward off the western boundary as upwelling equatorial Kelvin waves (Figure 15). The arrival of the upwelling (rather than downwelling) Kelvin waves in the central and eastern Pacific completes one half of an ENSO cycle: the rising thermocline is more strongly upwelled by easterly winds, shutting off the El Niño process and causing the development of a cold phase and "anti-El Niño" conditions. The creation of the negative ULT anomaly and its slow westward propagation constitute a long-delay, negative feedback because it requires 1-2 years to complete and reverses the ocean-atmosphere state. At that point, a colder Pacific induces a stronger easterly circulation in the winds, generating an area of deeper ULT off the equator, which then begins its slow trip westward, ultimately to trigger the next El Niño.

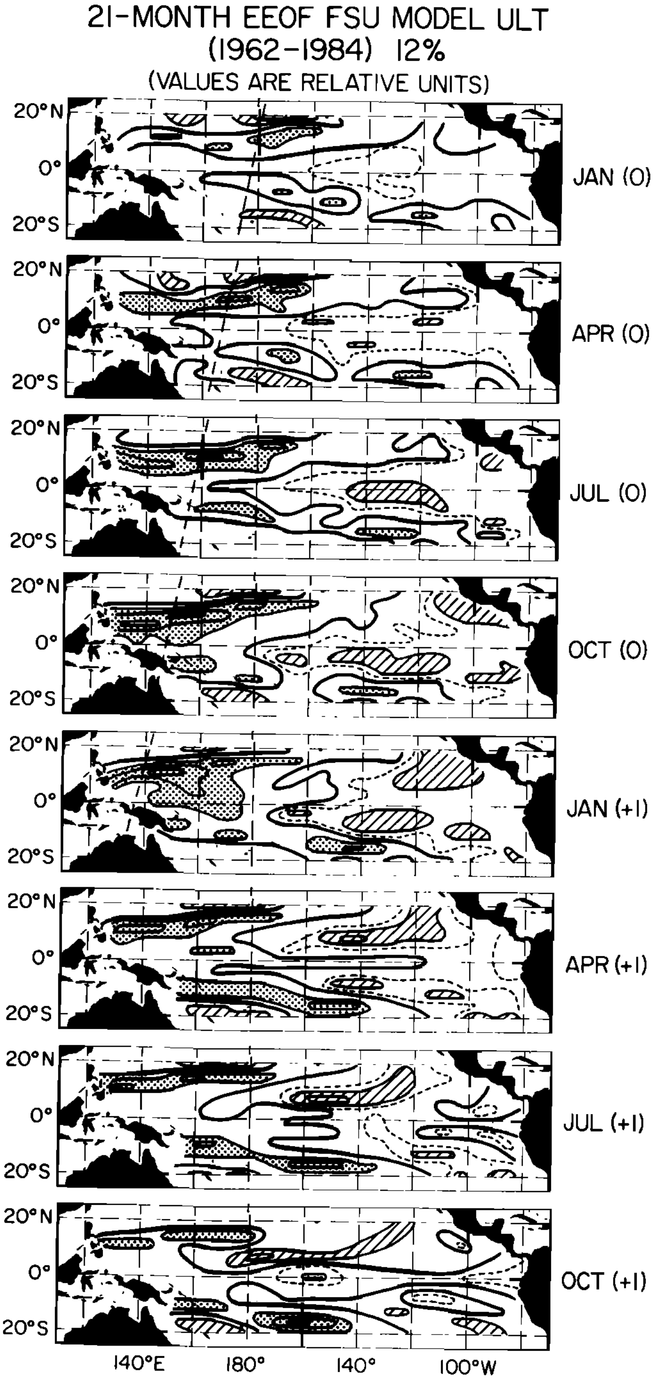


Figure 15. Maps from a 21-month extended empirical orthogonal function of upper layer thickness from the *White et al.* [1987] model for 1962-1984. The number after the month indicates the years since the onset of the El Niño event, and time advances downward. Values are relative, solid contours are spaced at 10 units, and the zero contour is the heavy line. Regions with values in excess of 10 are hatched, and those less than -10 are stippled. Dashed contours are 5 units. (From *Graham and White* [1988].)

The heat content (ULT) mechanism is plausible because it is supported by observations [*Wyrtki*, 1985; *Pazan et al.*, 1986]; it also reinforces (in principle) *Wyrtki*'s [1975] original contention that a warm-pool reservoir in the western Pacific is a necessary precondition to El Niño. A multiple-year data set of expendable bathythermograph (XBT) observations in the tropical Pacific, in conjunction with simulations using the *Busalacchi et al.* [1983] model, demonstrates that the redistribution of heat content from off the equator back to the western equatorial Pacific is accomplished by Rossby waves incident on the western ocean boundary [*Pazan et al.*, 1986; *White et al.*, 1987]. The incident mass flux is transferred equatorward and thence eastward by trapped Kelvin waves, consistent with the analysis of *Cane and Gent* [1984] for western boundaries of arbitrary geometry. While this appears to match very well with the coupled model results, there is an important discrepancy: the XBT observations show thermal structure propagation mainly in the 5°-20° latitude band, whereas the oscillation mechanism in the models appears related mainly to Rossby waves within ±10° of the equator (S. E. Zebiak, personal communication, 1988).

The success of the simple, coupled numerical models establishes a favored hypothesis to explain ENSO cycles: that they are an internal oscillation of the tropical Pacific ocean-atmosphere system. While the coupled models have certainly provided additional and important pieces of the ENSO puzzle, they have also raised new, conflicting questions that must be resolved by further research (I reserve my discussion and speculation about these important matters for the final section.)

External Forcing

The oscillator models challenge the notion that ENSO is somehow initiated by factors external to the tropical Pacific Ocean, because they can reproduce statistically realistic interannual variability entirely based on internal dynamical feedbacks. Alternate scenarios have been proposed for the external initiation and oscillation of ENSO cycles. *Barnett* [1981*b*] shows that tropical surface wind variability is coherent between the Pacific and Indian oceans, with a phase progression from the Indian monsoon region into the western Pacific. This suggests that Asian climatic variability can feed into the Pacific and provide a trigger mechanism for ENSO. Other connections to the Indian Ocean and the Asian monsoon have also been suggested [*Bye and Gordon*, 1982], as well as the effect of snow cover over Asia on global pressure fluctuations of which the Southern Oscillation is a part [*Barnett*, 1985]. In particular, *Barnett et al.* [1988*a*] have recently shown that wind stress perturbations related to Asian snowfall anomalies can produce a weak El Niño in a sophisticated ocean model, and they conclude that such external forcing may serve as a trigger for ENSO cycles.

Lau and Chan [1988] suggest that the ocean-atmosphere instability is forced stochastically by enhanced westerlies associated with the intraseasonal (40-50 day) oscillation in the western Pacific; the oscillation in turn undergoes an interannual amplitude modulation which may set the inherent time scale of ENSO. Further removed (geographically), it has been suggested that persistent influences elsewhere in the Southern Oscillation system can excite the El Niño instability [*Wright*, 1985] or that events in extratropical regions can feed back to the equatorial Pacific [*Namias*, 1976; *Reiter*, 1978].

Solid earth geophysicists are beginning to offer their own candidates for external forcing. *Walker* [1988] calls attention to a contemporaneous agreement between ENSO variability (inferred from an SOI time series) and ocean bottom strain relief episodes derived from seismic data in the region of Easter Island. He poses the possibility that seismic events may be physically connected with ENSO through ocean bottom heat inputs correlated with earth movements. *Shaw and Moore* [1988] argue from magmatic heat evidence that large submarine lava flows in the Pacific "may produce thermal anomalies large enough to perturb the cyclic processes of the ocean and could be a factor in the genesis of El Niño phenomena."

Arguments in favor of external forcing tend to compete with each other, and no single hypothesis is clearly dominant over others as a clear counterpoint to the coupled model results. However, it is quite clear that a serious divergence of opinions exist among scientists as to the importance and nature of external forcing to ENSO variability.

Teleconnections

Understandably, most of El Niño research has been concentrated in the equatorial Pacific where the core instability and ocean-atmosphere interaction takes place, and from which the energy for changes elsewhere emanate. (See note 9.) In a sense, any climatic anomaly removed from but associated with the core interaction along the equator is a "teleconnection" (i.e., a remote consequence), including the anomalies that occur along the South American coast and the droughts in Australia (regions that lie at the opposite geographic and phenomenological extremes of the Southern Oscillation).

One of the problems in determining what constitutes an ENSO teleconnection is that ENSO itself is loosely defined (nonunique) and comes in all sizes and shapes. *Deser and Wallace* [1987] have pointed out the nonuniqueness by showing that time series of the SOI and Peru coastal SST do not have a perfect 1:1 correspondence between coastal warmings and downturns in the Southern Oscillation. This can be seen in the plot of Figure 3. The strong and very strong El Niño events always involve a coupled ENSO oscillation (a strong negative correlation between events in Peru SST and the SOI). However, lesser warmings (weak or moderate El Niño) have not always been accompanied by low SOI or equatorial instability, while weak equatorial warmings have also occurred without impressive anomalies along the coast (Peruvians would not have called them "El Niño").

Similarly, the popular press has frequently picked up on suspected climate anomalies around the world that scientists are unwilling to attribute to ENSO. Worse still, even what might be called "true" teleconnections at extratropical latitudes do not recur in a consistent manner. Certainly, models and data show large-scale effects that survive long-term averaging. Examples are a strong Aleutian low (atmospheric pressure system) in the North Pacific or stronger extratropical westerly wind circulations and rainfall [*Pan and Oort*, 1983; *Ropelewski and Halpert*, 1987] (Figure 16). Related, global correlation structures between ENSO indices and global atmospheric fields have also been found [*Horel and Wallace*, 1981; *Wright et al.*, 1988]. However, the climatic details tend to differ from one event to another, resulting in a low signal-to-noise ratio. Consequently, the statistical variance explained by ENSO fluctuations is largely disappointing from the perspective of forecasters interested in predicting winter wheat crops in Oregon or water supplies for the subsequent summer in the San Joaquin Valley. The 1976-1977 El Niño was associated with drought conditions along the west coast of the United States [*Namias*, 1978], whereas the 1982-1983 event brought increased storminess [*Canby*, 1984; *Rasmusson*, 1985]. *Namias and Cayan* [1984] give many examples of such inconsistencies, pointing out that the northern hemisphere climate is the result of many competing factors, of which ENSO is only one. Even without the existence of other deterministic effects, it is easy to imagine how the timing and/or effective longitude of the equatorial convective anomalies, plus the variable state of the extratropical atmosphere at the time, could seriously alter the way in which teleconnections evolve over a given geographic region.

There is perhaps more consistency in the oceanic teleconnections to the higher latitudes of the Pacific eastern boundary and in climatic anomalies that arise in direct association with ENSO owing to the geographic shifts in convective phenomena. Examples of the latter are the severe droughts that consistently occur in Australia [*Nicholls*, 1987] and northern Brazil/Suriname [*Caviedes*, 1973], and the heavy rainfall in Ecuador and northern Peru [*Horel and Cornejo-Garrido*, 1986; *Goldberg et al.*, 1987] (Figure 17). The former occurs at least partly because the ubiquitous equatorial Kelvin waves that accompany El Niño bifurcate at the coast of Ecuador and propagate poleward into both hemispheres as coastal disturbances in sea level [*Enfield and Allen*, 1980; *Chelton and Davis*,

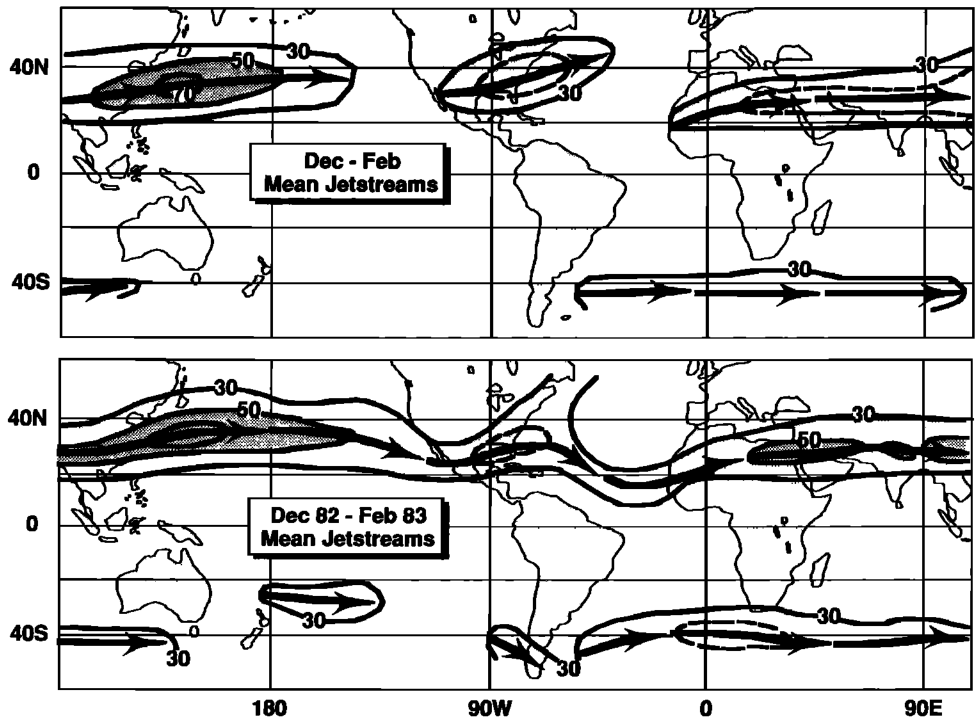


Figure 16. (Top) Typical December-February jet stream pattern and (bottom) the pattern during the period December 1982 to February 1983. Isotachs of wind speed are in meters per second. (After *Rasmusson* [1984].)

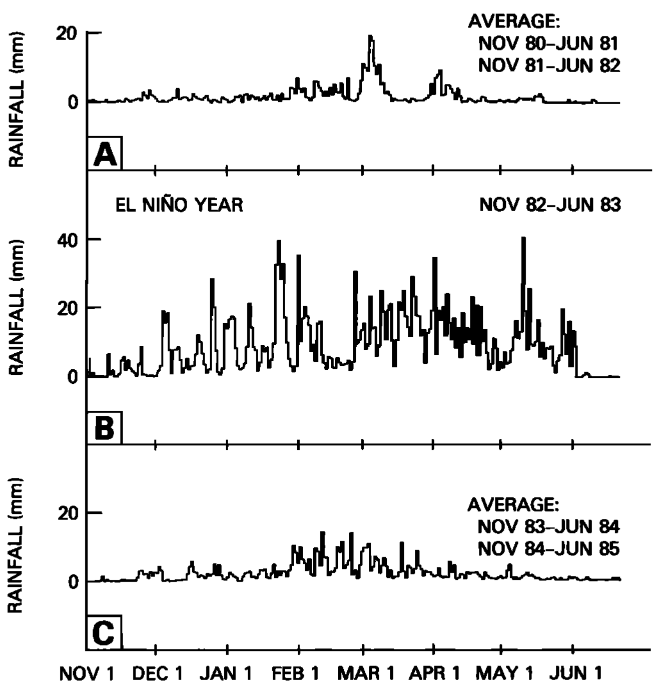


Figure 17. Daily rainfall means for November-June (millimeters) using 66 ground stations on the Sechura plateau (4°N-6°S) in northern Peru: (*a*) average of 1980-1981 and 1981-1982, (*b*) 1982-1983 (El Niño), and (*c*) average of 1983-1984 and 1984-1985. (From *Goldberg et al.* [1987].)

1982]. Northward intrusions of water masses of near-equatorial origin are the clearest cause of the interannual variability of the Gulf of California [*Baumgartner and Christensen*, 1985]. Farther north, hydrographic evidence indicates that a spindown and reversal of the California Current occurred during the strong El Niños of 1957-1958 and 1982-1983 [*Sette and Isaacs*, 1960; *Wooster and Fluharty*, 1985], prompting the coinage of expressions such as "California El Niño," and "El Niño North." In those events, thermal structure off California was altered for hundreds of kilometers offshore, along with large associated changes in the zooplanktonic assemblages [*Chelton et al.*, 1982] and other marine fauna [*Sette and Isaacs*, 1960; *Wooster and Fluharty*, 1985]. During other El Niños the effects in the California Current have been far less spectacular, suggesting that local forcing by the atmosphere may interfere with the ocean-propagated anomalies or, as in the 1982-1983 case, positively reinforce them [*Simpson*, 1984*a*, *b*; *Emery and Hamilton*, 1985; *Mysak*, 1986].

The biological consequences of El Niño are many and complex [*Barber and Chavez*, 1983]. The documented effects begin at Christmas Island in the instability region [*Schreiber and Schreiber*, 1984] and proceed eastward to the Galapagos [*Feldman et al.*, 1984]. Through the various teleconnective mechanisms they then extend northward as far as the coast of Alaska [*Wooster and Fluharty*, 1985] and southward along the Peru coast [*Arntz et al.*, 1985; *Barber et al.*, 1985] to southern Chile [*Instituto de Fomento Pesquero*, 1985]. The El Niño, more than any other phenomenon, has forced biologists to depart from their traditionally small-scale perspective to consider the existence of a virtual "ocean basin ecosystem" [*Barber*, 1988]. Although an extensive treatment of biological aspects is beyond the scope of this paper, the subject has been well reviewed by *Glynn* [1988].

Predictability of El Niño

It might be said that a de facto empirical system of El Niño prediction existed prior to the 1980s, based on phase relationships between various parameters within the ocean-atmosphere system. This included, for example, precursors such as the prior buildup of high sea level in the western Pacific [*Wyrtki*, 1975] and the observed tendency for six consecutive events to follow an approximately canonical pattern synchronized with the seasonal cycle [*Rasmusson and Carpenter*, 1982].

Thus, for example, both the western Pacific sea level and the SOI were anomalously high in early 1974, poised for an El Niño. A forecast was issued in the fall of that year and gave rise to a specially funded research cruise called El Niño Watch, in January-April, 1975. The cruise immediately documented an initial, El Niño-like warming in February-March of 1975. However, after the R/V *Moana Wave* made its port call in Callao, the second phase of the cruise found there had been a sudden return to cold conditions in April-May. The event became euphemistically known as the "aborted" El Niño of 1975. At the time, this was regarded by some as a successful prediction [*Wyrtki et al.*, 1976], but in retrospect it appears most likely that the event was a large-amplitude annual Kelvin wave of the type documented by *Halpern et al.* [1983] (K. Wyrtki, personal communication, 1988). Irregular events such as the 1975 case have occurred previously and should more properly be termed "equatorial warm events" (W. H. Quinn, personal communication, 1988). These episdoes probably involve ENSO-like interactions but lack a fully developed instability phase and do not lead to true El Niño conditions in the coastal zone off South America.

The 1975 case teaches us an important lesson: We have gained the ability to detect and to observe such ocean phenomena to the extent that our present perception of what constitutes an El Niño may be more sensitive than before. This becomes critical in evaluating the success of predictions when the observed outcome approaches the threshold of our definitions.

The failure of the empirical forecast approach was not limited to marginal episodes—it was also unable to anticipate the unusual but severe 1982-1983 El Niño. Out of the research that followed the 1982-1983 event there evolved several new approaches to predicting El Niño: a physical-statistical method [*Barnett*, 1984; *Barnett et al.*, 1988*b*], a linear dynamical numerical model driven by observed winds [*Inoue and O'Brien*, 1984], and the coupled ocean-atmosphere model of Zebiak and Cane [see *Cane*, 1986]. All are designed to take advantage of modern dynamical concepts about how ENSO developments occur.

The performances of these forecast schemes for the 1986-1987 event are reviewed by *Barnett et al.* [1988*b*]. In spite of the fact that the three methods have important, fundamental differences, all three were successful in forecasting the El Niño onset in mid-1986 with a 2- to 3-month lead time. The statistical and coupled models had almost as much success for a 9-month lead time and correctly predicted the eventual magnitude (two standard deviations of SST anomaly 1 year later). According to the authors, the success of these disparate methods "appears to be derived from the low-frequency, large-scale evolution of characteristic patterns in the atmospheric circulation." There is a fairly strong feeling in the modeling community that predictions will improve when more accurate tropical surface wind data become available for initializing the models.

El Niño in the Ancient Record (ELNAR)

Ironically, one of the most recently developed areas of El Niño research attempts to document the occurrence (or not) of El Niños during the historical and prehistorical times that predate the emergence of modern concepts following World War I. Scientists from many disciplines are applying diverse methods to extract proxy variables that indicate or correlate with past El Niño activity, e.g., ice records, coral growth, tree rings, molluscan assemblages, river deposits, and sediment cores. The primary aim of ELNAR investigators is to detect and to understand significant events in the record of year-to-year climate variations, whose quintessential manifestation is the El Niño-Southern Oscillation. This research is relevant to a question that could be quite critical to climate modelers and oceanographers striving to understand the mechanisms of ENSO and discover its origins: Is ENSO an unstable oscillation between two climatic states that can "lock" into one condition or another depending on the background climate? Or, is the phenomenon so robust as to defy the vagaries of large changes in wind patterns, sea level, and land area that must have accompanied the passage of Quaternary climatic epochs?

One convenient way to subdivide ELNAR research is according to the time periods before the present (B.P.) that the studies cover. The most intensive area of research involves the last four to five centuries following the Spanish conquest, for which written records exist and the greatest number of proxy variables can be analyzed. Ideally suited to this time scale are the growth, cadmium content, and other properties found in the skeletal remains of tropical corals extracted from continuous cores [*Shen et al.*, 1987], and dust horizons, water accumulation, and oxygen isotope content in the annual layers of ice cores extracted from ice caps and glaciers in Peru and Tibet [*Thompson et al.*, 1984]. Such records seem to correlate with the modern record of ENSOs. The researchers are now trying to extend their correlation analyses to include the El Niño events compiled by *Quinn et al.* [1987] from written records and anecdotal information dating back to the early sixteenth century.

Ice core signals apparently associated with El Niño events occurred throughout this period, in spite of the large secular oscillation between the "Little Ice Age" in the sixteenth and seventeenth centuries and the global warming of the present. Unfortunately, nonstationarities exist in the relative importance of different proxy variables, depending on the background climate, such that analysis techniques must be chosen and applied with great care (L. G. Thompson, personal communication, 1988). One of the ultimate goals of this research is to develop hindcast methods based on comparisons between proxy variables and the high-quality environmental data of the twentieth century. If hindcasts for the previous four centuries verify against the compilation by *Quinn et al.* [1987], they might then be extended for the entire length of the proxy records (at least 1500 years for ice cores and as much as 1000 years for corals).

Shen et al. [1987] find large variations in cadmium/calcium (Cd/Ca) ratios that correlate very well with Galapagos anomalies for 1965-1979 (Figure 18). In their ongoing research (unpublished), they have extended the coral record back to A. D. 1600 but with less than the seasonal resolution of *Shen et al.* [1987]. The Cd/Ca

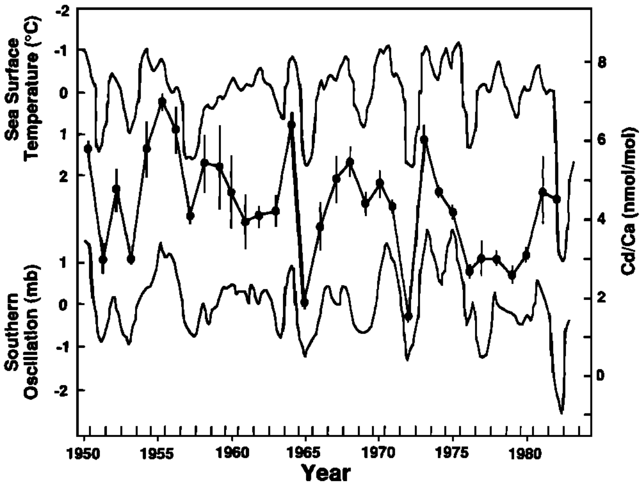


Figure 18. Skeletal Cd/Ca mole ratios (right axis) from a core section of Galapagos coral compared against historical SST anomalies at Puerto Chicama, Peru, and the SOI (left axes). (After *Shen et al.* [1987].)

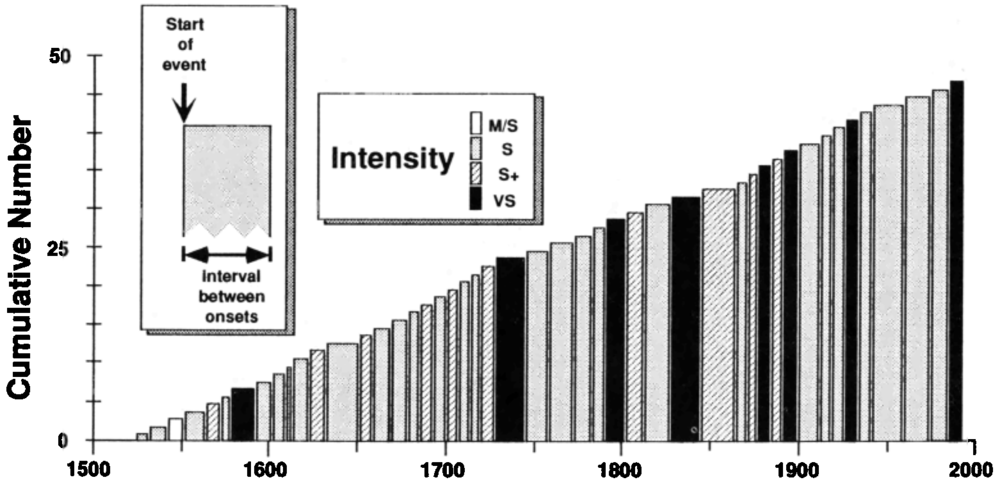


Figure 19. Occurrences of El Niño since records began in Peru, based on the chronology of *Quinn et al.* [1987]. The width of each bar represents the time interval between successive onsets of El Niño, and the height is the cumulative number of events since 1525. Intensities shade-coded in the legend are moderate-to-strong (M/S), strong (S), quite strong (S+) and very strong (VS). (From *Enfield* [1988].)

fluctuations, which are caused by changes in nutrient availability, suggest that the Galapagos corals were largely unaffected by nutrient limitation during the Little Ice Age, 150-400 years B.P. If this is extrapolated (from present correlations) to mean that El Niño-like SST anomalies over the eastern Pacific region were absent, then the concept of El Niño as a persistent feature influencing the eastern tropical Pacific during the past millenium may have to be reexamined (G.T. Shen, personal communication, 1988).

The tree ring records from arid-site conifers in northern Mexico and the southwestern United States tell a different story [*Michaelsen*, 1989]. Fluctuations in the growth rings are thought to reflect local rainfall anomalies that correlate with equatorial Pacific ENSO developments through the teleconnection process. The ENSO variability over the last four centuries, inferred by regression on modern, large-scale Indo-Pacific indices, has amplitude and frequency statistics very similar to those of the twentieth century. In an effort to resolve the apparent conflict between the coral and tree ring results, *Enfield* [1988] examined the statistics of strong El Niño occurrences compiled by *Quinn et al.* [1987] for a similar time period (Figure 19). He concludes that the frequency of occurrence of El Niño has remained unchanged over the last 450 years and that the statistics of El Niño variability "are stationary within the parameter range of climatic changes that have occurred within the last several centuries."

DeVries [1987] has summarized the efforts of geologists, archeologists, and paleontologists to detect El Niño manifestations over the last 34,000 years. On the time scale of millenia, only ice cores hold the potential to resolve interannual variability at the subdecadal time scale, with 1500 years B.P. being the most extensive core taken to this point [*Thompson et al.*, 1984].

Studies of Holocene shell middens (garbage heaps) left by the early inhabitants along the north-central Peru coast (up to 10,000 years B.P.) identify 5000 years B.P. as an important date: sea level had stabilized at a high level following a period of rapid rise, and the shellfish diet of the indigenous coastal population changed from predominantly warm-water to cold-water species [*Rollins et al.*, 1986]. The colder environment was apparently accompanied by an onset of El Niño events, confirmed by a series of beach ridges deposited after large coastal floods [*Sandweiss*, 1986]. (See note 10.) The existence of El Niños is confirmed by studies of the coastal river deposits [*Wells*, 1987]. The suggestion from the middens is of a geologically rapid transition from a warm environment without El Niño episodes to the present cooler background climate interrupted by El Niños every few years. Although the evidence of El Niño activity in the last 5000 years seems acceptable, DeVries points out that the rapidly rising Holocene sea renders the midden evidence only fragmentary and contradictory before that, and that alternate interpretations for the warm-water species exist. As for the last five millenia, it seems likely that the beach ridges correspond to catastrophic events and can say little about the frequency of moderate and strong El Niños as we know them today.

DeVries [1987] cites clear indications of climate changes along the Peruvian littoral during the Pleistocene, with alternations between arid and savanna environments. It is not as clear, however, how the ocean and atmosphere circulations had changed, and there is no conclusive evidence that the statistical nature of El Niño activity was significantly different. Unfortunately, the ability to resolve El Niño variability becomes seriously degraded as the researchers delve further into the past and as ambiguities in the interpretation of their findings become more commonplace. DeVries argues that to identify El Niño episodes in proxy records unambiguously, the methods must resolve event durations of a few months to 2 years and establish unequivocal anomalous warming along the Peru-Ecuador coast.

All that we can presently say with confidence is that El Niño-like environmental variations have occurred in the South American region over prehistoric time scales and are not unique to the postconquest period. We cannot say that the variability has been statistically stationary in the sense that oceanographers and meteorologists understand, and there are indications that the variability in previous periods may have been different in ways that numerical modelers would find interesting.

DISCUSSION

The most intriguing (and controversial) aspect of the coupled numerical models of ENSO is that they do not require an externally imposed or stochastic wind forcing to produce a change of state: it can be prompted simply by the off-equatorial Rossby wave activity that returns ULT anomalies to the equatorial waveguide through Kelvin waves reflected off the western boundary. Why, then, are the simple, forced models without thermodynamics or feedback effects [e.g., *Busalacchi et al.*, 1983] so successful? Or, why do composite analyses of data fields show weak westerly wind anomalies west of the date line prior to the onset of ENSO [*Rasmusson and Carpenter*, 1982], properly timed to force Kelvin waves and set off another sequence?

The coupled models produce their own wind anomalies, synchronized to the ENSO cycle, as part of the equatorial instability phase. If the models are correct, then the western Pacific wind anomalies that appear to initiate the ENSO instability may themselves be due to the internal dynamics of the oscillator system, possibly prompted by the effects of the propagated ULT anomalies on the SST distribution of the western Pacific (which is known to be warm prior to the onset of instability growth). This would explain the success of other methods based upon observed winds. It might also explain why the coupled model of *Zebiak and Cane* [1987] has proven successful in predicting the onset of ENSO, whereas the statistical models forced by large-scale gridded wind fields have not, although they do show skill in anticipating the further development of an event (N.E. Graham, personal communication, 1988). One of the shortcomings of the *Zebiak and Cane* [1987] model is that the delicate ocean-atmosphere interactions in the western Pacific are inadequately parameterized, whereby details such as the earliest wind anomalies west of the date line are typically missed (S.E. Zebiak, personal communication, 1988). This does not imply that the oscillatory mechanism is wrong, only that the timing and longitude zone for the initial wind anomalies are incorrect. Seen in this light, both the heat storage anomalies and the western Pacific wind forcing are necessary elements.

Both observationalists and modelers are beginning to focus on the mixed layer dynamics and ocean-atmosphere interactions in the western Pacific as the key to reconciling the apparent dichotomy. It appears that the western Pacific is far from being a simple warm pool that is much deeper than the wind-mixed layer (which extends only a few tens of meters) [*Lindstrom et al.*, 1987]. Seasonal, heavy rainfall can make the wind-mixed layer much fresher (less saline). This creates a shallow salinity gradient (halocline) of great stability that acts as a barrier to deeper mixing of heat gained from the atmosphere. If this happens, SST can be increased in a temperature range where convection depends critically on SST, enhancing the production of westerly wind bursts in the fall-winter season of particular years. Does the halocine build itself up during the rainy phase of the Southern Oscillation (in the western Pacific) until anomalous convection is generated? This could be an alternate or additional restoring force. Or, does this sort of preconditioning occur only in certain years, when positive ULT anomalies appear in the western Pacific? Is so, what is their connection? Perhaps interannual variations in preconditioning are insignificant and/or unimportant to the production of unusual convective activity. If this is the case, it may be that the normal, seasonal occurrence of westerly wind events is sufficient to start the instability process, provided the proper ULT anomalies appear, giving the system the potential energy it requires to push the instability process past some critical point.

Future research must somehow address the puzzling matter of the respective roles of ULT anomalies, western Pacific winds, and instability triggers. However, the entire question of whether the ENSO process arises from a purely internal (Pacific) mechanism or in response to external forcing must be examined. A number of alternate scenarios have merit in explaining the ENSO phenomenon. A possible explanation for their success is that the ocean-atmosphere system is coupled and has a highly coherent, large-scale structure that extends beyond the Pacific basin (regardless of how it oscillates). Thus the intercorrelations between the fields of pressure, temperature, currents, and winds guarantee a measure of success in relating them, independent of whether the interpretations of cause and effect are correct or not.

As a final commentary, let me resurrect the question posed by *Vallis* [1986]: Is El Niño chaotic? Vallis shows that a simple nonlinear system with a highly parameterized

ENSO mechanism (no wave dynamics, for example) can reproduce a plausible ENSO-like behavior that is essentially chaotic. Are the coupled models themselves chaotic? *Schopf and Suarez* [1988] claim that their model is not because it has a preferred time scale, yet so do the synoptic weather systems that prompted Lorenz to do his pioneering work in the field of chaos. As with many examples of chaotic phenomena, the coupled models use deterministic, nonlinear dynamics to generate a nonrepetitive (see note 11), oscillatory behavior that "bifurcates" between physical states in phase space. Under very minor modifications to initial conditions the models produce divergent solutions with statistics essentially identical to those of the previous run, yet basically unpredictable beyond a certain lead time (perhaps one or two cycles) (S. E. Zebiak, personal communication, 1988).

Of course, even if the models are chaotic, it does not follow that Nature is also. Yet, in fact, Nature appears to be quite chaotic, and the examples abound [*Gleick*, 1987]. If ENSO is not a chaotic system, it is more likely the exception rather than the rule. The telltale signs of chaos can be seen in the observed behavior of the Pacific ocean-atmosphere system. Thus, for example, El Niño is notorious for occurring in unique configurations; they have many aspects in common, but no two events are replicates of each other or of some canonical model. El Niño occurs with a quasi-, but not exact, periodicity. Like chaotic pehnomena, the physical mechanism of convective instability found in ENSO is self-similar on smaller scales, such as the 40- to 60-day intraseasonal oscillation, convective clusters with several-day "bursts" of westerly winds and/or paired cyclones, and ultimately, individual convective cells. If the coupled models are not chaotic, perhaps the modelers should be concerned.

We should note, however, that a chaotic behavior does not imply that useful predictions are not feasible. Under reasonable permutations of initial conditions, the most important aspects of the first ENSO cycle (from a forecast standpoint) are preserved, and lead times of the order of a year or more appear feasible [*Barnett et al.*, 1988*b*]. When larger changes are introduced, the system behavior will differ; for example, 30 years may pass without an El Niño. This too is typical of chaotic phenomena. What tickles the imagination is the suggestion from ELNAR investigations that sufficiently different background states in the past may have been associated with the existence of El Niños, but with a different set of statistics; e.g., they may have been less frequent and/or more severe. This does not seem to have happened in the last half millenium, i.e., during the cooler climate of the Little Ice Age. Should the greenhouse effect increase global temperatures by significant amounts in the next century, will ENSO behave in a significantly different manner than now?

NOTES

1. It appears that the term "El Niño" did not originally connote an anomalous phenomenon in the minds of the coastal inhabitants of Paita, the port from which coastal fishermen presumably observed the annual current and named it [*Schweigger*, 1945]. In fact, Schweigger argued vehemently against the anomalous connotation introduced by foreign oceanographers, such as *Schott* [1931], noting that the annual and interannual occurrences are fundamentally different. *Carranza* [1891] did not even mention the term "El Niño," even though he was reporting one of the most severe anomalies in recorded history. He, like other early Peruvian geographers, simply referred to an unusual southward countercurrent that brought extraordinarily warm water and unusual fauna and (allegedly) displaced the cool Humboldt Current offshore.

2. The best documented cases are those of the twentieth century, when climatic archives were more systematically maintained and conditions were monitored by the guano and fishing industries of Peru and occasional scientific expeditions. Increasingly into the past, Quinn et al. rely on anecdotal accounts from military campaigns, missionaries, privateers (ship logs), and explorers and on information from the economic sectors (e.g., grain manifests).

3. Because of a lack of data, W and M events are not reported prior to the nineteenth century. The S events of the twentieth century were in 1911-1912, 1917, 1932, 1957-1958, and 1972-1973. VS events occurred in 1578, 1728, 1791, 1828, 1877-1878, 1891, 1925-1926, and 1982-1983. A number of events are rated as S+, bordering on VS. Even if all of these are considered to be very strong, the shortest VS interval would be 26 years.

4. Early SO investigators used Easter Island instead of Tahiti to represent the SE Pacific end of the SOI. It has since been shown that Tahiti behaves more contemporaneously with Darwin, whereas Easter Island usually leads Darwin [*Trenberth*, 1976]. Hence most reearchers presently embrace the Tahiti-Darwin index as a proxy for the state of the SO system. The statistical properties of this index have been carefully examined by *Trenberth* [1984]. However, W. H. Quinn (personal communication, 1988) warns us that no single pressure index will faithfully trace the SO history because the intensity of pressure swings within various regions of the Pacific will vary from one SO episode to another. Only the combined use of several indices can ameliorate this problem.

5. This has been later confirmed in more detail by *Enfield* [1981], *Horel and Cornejo-Garrido* [1986], and *Huyer et al.* [1987] using independent observations from coastal weather stations. The coastal winds do weaken (or occasionally reverse) north of 6°S and appear to be associated with anomalous rainfall over the adjacent Sechura Desert. Farther south, however, the winds remain upwelling favorable during most of the El Niño episode, and the physical process of upwelling continues.

6. The remainder of this paper will frequently—but somewhat grudgingly—use the shorthand term "ENSO" where the large-scale interaction between ocean and atmosphere is implied. This customary usage carries a burden of oversimplification, because portions of the overall ENSO scenario occasionally occur in the absence of others and without a fully developed, large-scale interaction [*Deser and Wallace*, 1987].

7. In both the antecedent and the onset phases, a band of higher than normal SSTs stretches from central Chile to NE

Australia, and the prevailing winds at 20°-30°S off Chile are weaker than normal. The anomalies become intensified off northern Chile in the onset phase. Although the authors warn that data scarcity off Chile makes this precursor signal suspect, it is perhaps significant that both variables change in a mutually consistent way, i.e., since the surface layer can be heated due to reduced evaporation as the wind speed decreases.

8. From the perspective of rainfall anomalies in northern Peru, the 1982-1983 El Niño may have been the most intense event in the four and one-half centuries of Spanish and Peruvian records [*Woodman*, 1984].

9. It has come to the point that the equatorial Pacific has usurped the name El Niño from the Peru coastal region where it originated, a situation that some South American scientists find difficult to accept.

10. Eight beach ridges dating back to 4200 years B.P. indicate massive flooding events, which the author attributes to severe El Niño episodes. This method does not pretend to resolve El Niño variability with the annual resolution of ice cores and should not be used to infer that El Niño variability occurred then with the intensity or frequency of the twentieth century.

11. The term "nonrepetitive" is taken quite literally in this context; i.e., it does not connote "nonrecurring." It means that no two occurrences are repeated in the same way, or that the system never returns to a previous state vector. This is an essential element of chaotic systems [*Gleick*, 1987].

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