

IS EL NIÑO SPORADIC OR CYCLIC?

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■ **Abstract** Is El Niño one phase of a continual, self-sustaining natural mode of the coupled ocean-atmosphere that has La Niña as the complementary phase? Or is El Niño a temporary departure from “normal” conditions “triggered” by a random disturbance such as a burst of westerly winds? A growing body of evidence—stability analyses, studies of the energetics, simulations that reproduce the statistics of sea surface temperature variations in the eastern equatorial Pacific—indicates that reality corresponds to a compromise between these two possibilities: The observed Southern Oscillation between El Niño and La Niña corresponds to a weakly damped mode that is sustained by random disturbances. This means that the predictability of El Niño is limited by the continual presence of “noise” so that forecasts should be probabilistic. The Southern Oscillation is also subject to decadal modulations. How it will be influenced by global warming is a matter of considerable uncertainty.

INTRODUCTION

Thirty years ago, very little was known about El Niño; few people even knew of the phenomenon. Today, matters are very different, in part because scientists have made enormous strides in observing, explaining, simulating by means of numerical models, and predicting El Niño. An impressive array of instruments, shown in Figure 1, now monitors the equatorial Pacific continuously. Models that simulate the ocean realistically are being used operationally to assimilate the available data and to provide regular maps of conditions in the tropical Pacific, the counterparts of weather maps (Leetmaa & Ji 1989). It is now possible to follow the major changes in the circulation of the tropical Pacific Ocean that accompany the alternate warming and cooling of the surface waters of the eastern equatorial Pacific as they happen; the signatures of El Niño and its complement La Niña are shown in Figure 2. Those changes effect an essentially adiabatic, horizontal redistribution of warm surface water: **Strong winds during La Niña pile up the warm water in the west, causing the thermocline to slope downwards to the west and exposing cold water to the surface in the east; relaxed winds during El Niño permit the warm water to flow back eastward so that the thermocline becomes more horizontal.** [Figure 3 shows these changes schematically.] The

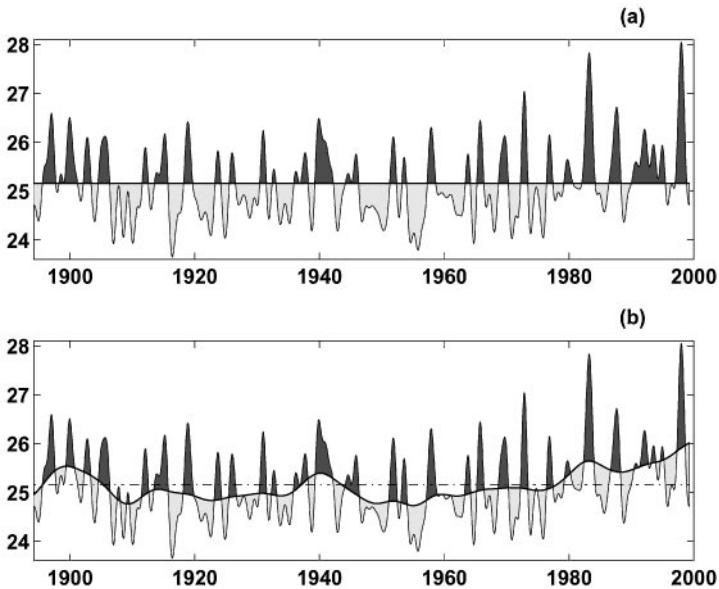


Figure 2 (a) The sea surface temperature fluctuations in the eastern equatorial Pacific over the past 100 years after low pass filtering of the data to remove frequencies higher than that of the seasonal cycle. (b) The same data as in (a), but now the reference line, rather than the average temperature for the past century, is the ten-year running mean temperature.

fluctuations of the trade winds that induce this oceanic response are in turn strongly influenced by that response, specifically by the sea surface temperature changes. This circular argument—the wind fluctuations are both the cause and consequence of the sea surface temperature variations—has prompted extensive investigations of the interactions between the ocean and atmosphere. Those interactions permit a variety of natural modes of oscillation. The phenomena observed in the tropical Pacific presumably correspond to one of or some combination of those modes that, to varying degrees, are captured by the coupled ocean-atmosphere models that have been developed.

Despite these considerable observational and theoretical advances over the past few decades—for an excellent summary, see the series of review articles that constitute Volume 103, June 1998, of the *Journal of Geophysical Research*—many issues are still being debated, and each El Niño still brings surprises. The prolonged persistence of warm conditions in the early 1990s was as unexpected as the exceptional intensity of El Niño in 1982 and again in 1997; nobody knew what to expect of El Niño in 2002. To the following questions, different investigators give different answers: Why is the observed Southern Oscillation so irregular? How predictable is El Niño? What are the reasons for the decadal

modulation of El Niño, the apparent change in its properties that occurred in the 1970s? How will global warming influence El Niño? This review addresses these important, unresolved issues and attempts to reconcile some of the divergent perspectives.

The current disagreements concerning El Niño have their origins in the recent history of research on the phenomenon. When the available datasets were scant, during the 1960s and 1970s, we regarded El Niño as a departure from normal conditions, as the response of the coupled ocean-atmosphere to certain “triggers.” This implied that measurements should be made during the abnormal or anomalous periods when El Niño happens to appear in the Pacific, the way meteorologists make special efforts to observe hurricanes when those cyclones appear. Wyrski (1975) tentatively identified a sudden collapse of the trade winds as the most important trigger, but intense El Niño of 1982 was not preceded by such a collapse. The availability of more detailed wind datasets in the 1980s led to the identification of sporadic westerly wind bursts that last for a few weeks along the equator in the neighborhood of the dateline as important triggers of El Niño. Such bursts contributed to the development of El Niño in 1997, but similar bursts on other occasions failed to have a similar effect. There must be more to the story than westerly wind bursts.

The availability, in the 1980s, of relatively long time-series similar to those in Figure 2 prompted some investigators to question whether each El Niño is an independent, transient phenomenon in response to a trigger, with a definite beginning followed by growth and, finally, decay. Instead, they adopted a radically different perspective and regarded El Niño as part of a continual oscillation without a beginning or end. El Niño therefore has a complement, usually referred to as La Niña. Conditions in the Pacific correspond either to the one or the other; very seldom are conditions “normal,” as is evident in Figure 2. The main challenge is not to identify triggers but to explain the properties of the oscillation, its period, spatial structure, etc. This new perspective implied a different measurement strategy. Sporadic measurements when the phenomenon happens to appear gave way to arrays of instruments, for example, the one in Figure 1 that monitors the tropical Pacific continuously.

The debate between those who regard each El Niño as an independent event and those who see it as part of a continual oscillation is vaguely reminiscent of the nineteenth century debate between “catastrophists” who believed that the Earth was created at a definite time, where-after certain events occurred sequentially, and “uniformitarians,” the followers of Hutton who believed that there is “no vestige of a beginning, no prospect of an end.” Explanations for the geological records require a compromise between these extreme points of view. Similarly, in the case of El Niño, explanations for what is observed call for compromises. The available records give clear evidence of a continual oscillation with a period of several years and also indicate that on shorter timescales of weeks and months, westerly wind bursts and other random disturbances influence the development of El Niño.

IRREGULARITIES OF THE SOUTHERN OSCILLATION

Although the Southern Oscillation has a distinctive timescale of approximately four years—a spectral analysis of the time-series in Figure 2 has a peak at that period—the oscillation is very irregular: The interval between successive El Niño episodes varies from approximately three to seven years, and the intensity of different episodes can be very different. Several factors contribute to this irregularity. Figure 4 illustrates a few. These numerical experiments, with an idealized coupled ocean-atmosphere model without weather or other random atmospheric disturbances, explore how changes in the intensity of ocean-atmosphere interactions affect the Southern Oscillation. In the left-hand panel of Figure 4, ocean-atmosphere interactions are weak and the simulated Southern Oscillation is damped. An imposed initial burst of westerly winds that lasts for a month induces El Niño

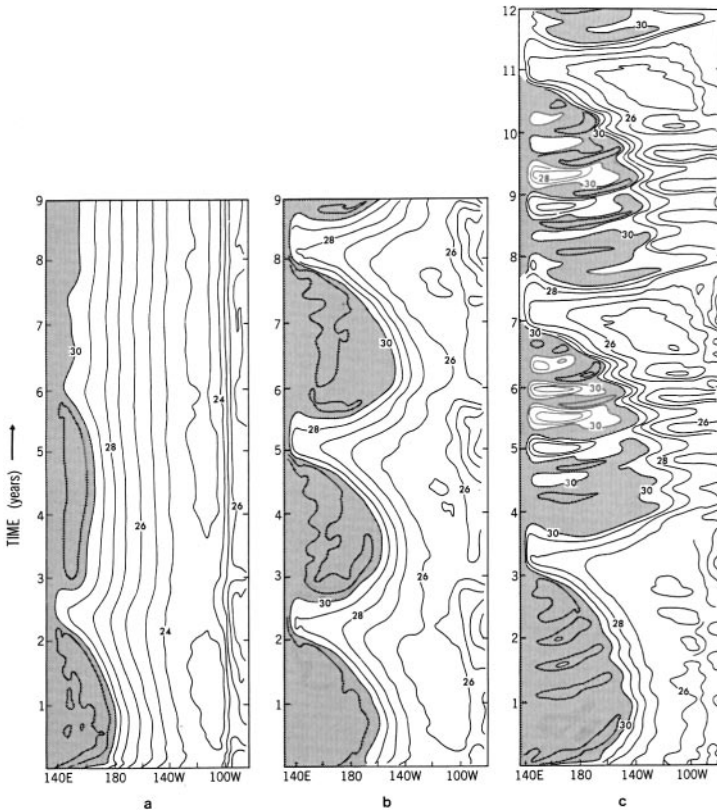


Figure 4 Evolution of sea surface temperature along the equator in the coupled model of Neelin (1990). The strength of the coupling between the ocean and atmosphere increases from (a) to (b) to (c). The evolution over a 9-year period is given in (a) and (b) and that over a 12-year period in (c). Regions warmer than 30°C are shaded.

conditions that persist for a while and then decay. More intense ocean-atmosphere interactions in the central panel result in a self-sustaining Southern Oscillation. The right-hand panel of Figure 4 shows a further intensification of ocean-atmosphere interactions, which causes the Southern Oscillation to grow to such a large amplitude that secondary instabilities appear. Which panel corresponds to reality? Some investigators favor the right-hand panel. In that case, the Southern Oscillation is similar to weather in having as its source of irregularity not externally imposed disturbances, but internal nonlinear processes. However, there is persuasive evidence that random atmospheric disturbances, for example, westerly wind bursts along the equator in the neighborhood of the dateline, influence the development of El Niño on some occasions, as happened in 1997 (McPhaden & Yu 1999). Because of such observations, some scientists believe that the Southern Oscillation is damped and is sustained by noise so that the left-hand panel is the realistic one. If that were the case, then each El Niño would be independent of the next and would depend, for its initiation, on noise. It is then difficult to explain why very similar westerly wind bursts lead to the development of El Niño on some occasions but not others, and why the Southern Oscillation has a distinctive timescale of a few years. A compromise that accommodates the various points of view posits that the Southern Oscillation is weakly damped and is sustained by random disturbances; the panel in Figure 4 that corresponds to reality is then midway between the one on the left and the central one.

The coupled ocean-atmosphere model that yields the results in Figure 4 has an atmospheric component that produces surface winds strictly in response to sea surface temperature changes; atmospheric noise is absent from the model. The series of experiments in Figure 4 has been repeated with a few changes, one of which is particularly important: The observed atmospheric noise was added to the simulated winds. (To determine the noise, the component of the observed wind field that is correlated with sea surface temperature changes is subtracted from the total observed winds, and the remainder is the noise.) In each of the counterparts of the panels of Figure 4, an irregular interannual oscillation now appears. Which simulated interannual oscillation has statistics—the position, width, and intensity of a peak in an energy spectrum, for example—comparable to the statistics of the observed Southern Oscillation? These calculations indicate that the most realistic oscillation in this statistical sense is weakly damped and is sustained by atmospheric noise (Neelin et al. 1998; Thompson & Battisti 2000, 2001; Chang et al. 1996, Eckert & Latif 1997; Blanke et al. 1997; Roulston & Neelin 2000).

THE ENERGETICS OF THE SOUTHERN OSCILLATION

A useful analogy for the Southern Oscillation, even though it has limited validity, is a damped pendulum subject to modest blows at random times. Let us explore to what extent, in the observed irregular oscillation shown in Figure 2, an harmonic oscillator (or pendulum) is discernable. If the observed phenomenon was indeed analogous to a simple pendulum, then the following equation would describe its energetics:

$$dE/dt = W, \quad (1)$$

so that the potential energy E and kinetic energy W would be a quarter period out of phase. In a study of the energetics of the Southern Oscillation, Goddard & Philander (2000) find that an equation similar to Equation 1 is approximately valid, with E denoting the available potential energy of the ocean and W denoting the work done by the wind on the ocean. Apparently, the latent heat lost by the ocean to the atmosphere, although it is of critical importance to the atmosphere, is unimportant to the ocean. Also unimportant are the variations in kinetic energy associated with the occasional disappearance of the Equatorial Undercurrent, for example. What matters to the ocean is that the work done by the wind causes the thermocline to slope, thus creating available potential energy E . If Equation 1 was accurate, then E and W would be perfectly correlated, with E lagging behind W by a year. Fedorov et al. (2003) find that, for the period 1960–2000, the correlation between E and W has a maximum value of 0.65 for E , lagging W by about eight months. These differences amount to a measure of the degree to which the irregular oscillation in reality (in Figure 2) departs from a perfectly regular oscillation. The result also implies that El Niño can be anticipated approximately eight months in advance by monitoring the wind-work W . (This occurs because variations in E are very highly correlated with, and in phase with, sea surface temperature variations in the eastern tropical Pacific, the signature of El Niño.)

On a phase diagram with E and W as axes, Equation 1 becomes a circle. In the presence of damping, the circle becomes a spiral into the origin. In reality, for the period 1980–1998, the phase diagrams are those shown in Figure 5. [These plots are based on data generated by forcing, with the observed winds, a General Circulation Model (GCM) of the ocean capable of simulating El Niño and La Niña realistically (Fedorov et al. 2003). Ideally, the model would also assimilate the available measurements, but datasets from such a procedure were not available at the time of this study.] A prominent feature of the curves in Figure 5 is that they are all consistently anticlockwise spirals, rather than chaotic. This suggests that we are dealing not with chaotic fluctuations that arise from highly nonlinear instabilities, but with a coherent oscillation. The spirals uncoil in 1982, 1987, 1992, and 1997 when El Niño episodes develop, apparently in response to wind bursts at the times of the shaded lines. Thereafter, they tend to spiral inwards, consistent with the behavior of a damped mode sustained by random disturbances.

The energetics tell us about phase lags between W and E , but presumably other variables also have phase lags. Kessler (2003) finds that Q , the volume of warm water above the thermocline between 5°N and 5°S, leads sea surface temperature variations in the eastern equatorial Pacific by a quarter period. Hence, Q and W should be essentially in phase. Apparently the wind-work on the ocean not only creates variations in available potential energy with a certain lag, but also effects fluctuations in Q with no lag. Thus, the wind-work causes a latitudinal redistribution of warm surface waters. The spatial structure of that redistribution is complex, a topic to be discussed later in connection with the top panel in Figure 7. In principle, it should be possible to derive a relationship between W and Q from the

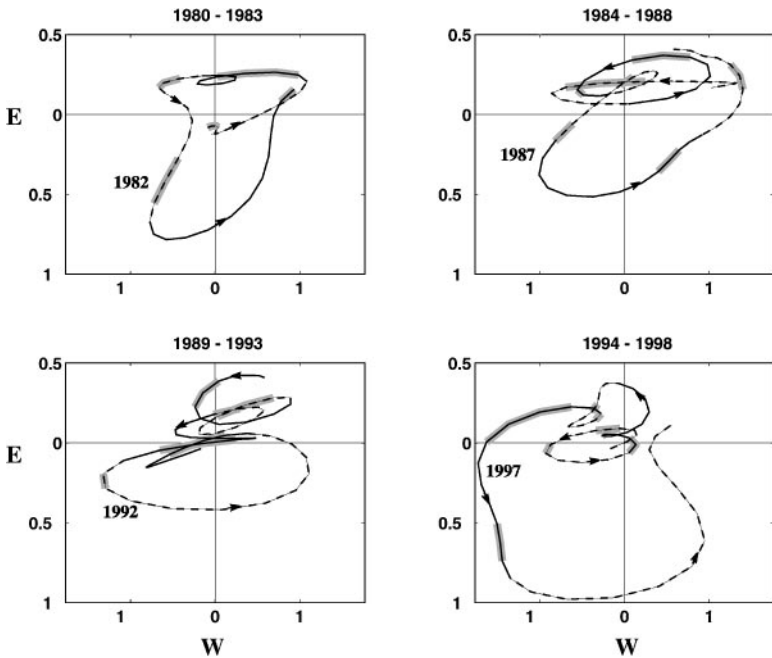


Figure 5 Phase diagrams, with potential energy E and wind-work W as axes, for the period 1979–1998. Alternate years are shown in solid and dashed lines. The heavily shaded portions of each plot indicate the occurrence of westerly wind bursts (whose intensities and spatial structures vary considerably).

governing equations of motion. Jin (1997), who refers to the latitudinal redistribution as a “recharge mechanism,” attempts to find the mathematical relationship but finds it necessary to make a number of ad hoc assumptions.

The continual oscillation, if it were linear, would be sinusoidal, but in reality it is skewed (nonsinusoidal.) For example, in 1982 and in 1997, El Niño was brief—warm conditions persisted for about a year—after which La Niña continued for several years before the return of El Niño five years later. This is evident in Figure 5 where the trajectories spend much time in the upper La Niña quadrants and relatively little time in the lower El Niño quadrant. The nonlinearity responsible for this skewness has not been identified yet. This is a matter of some importance because the skewness affects the transition from La Niña to El Niño and hence the predictability of El Niño.

THE PREDICTABILITY OF EL NIÑO

The Southern Oscillation involves phenomena with two timescales: an oscillation with a period of several years and rapid developments over a period of weeks or months in response to random disturbances. Hence, it should be possible to

anticipate certain aspects of the Southern Oscillation far in advance. Since the 1980s, for example, the intensity of El Niño has varied enormously from one event to the next, but the phenomenon has nonetheless appeared with remarkable regularity every five years, in 1982, 1987, 1992, 1997, and 2002. Phase diagrams, such as that of Figure 5, which are tools for isolating the presumably predictable low frequency aspect of the Southern Oscillation, indicate that this predictability varies with time and can be very limited. For example, when the “pendulum hangs vertically,” when the trajectory in the phase diagram is close to the origin as was the case in the early 1990s, then predictability is minimal. Once El Niño has started to develop, in mid-1982 and 1997 for example, developments over the next several months are highly predictable. (In June 1997, Californians were alerted to expect heavy rains six months later.)

The transition from La Niña to El Niño is generally difficult to anticipate (Latif et al. 1998) because of the skewness, mentioned above, and because of the seasonal cycle, which involves considerable fluctuations in W but not in E . (The small loops between the two top quadrants in Figure 5 correspond to the seasonal cycle.) Low-pass filtering of the data will of course remove the seasonal cycle, but then much of the lead time for predictions is sacrificed. Further evidence that the seasonal cycle does not involve vertical movements of the thermocline (and hence variations in E) are available in the measurements described by McPhaden et al. (1998)—see their Figure 9. Why does vertical movement of the equatorial thermocline characterize the interannual oscillations between La Niña and El Niño, but not the seasonal cycle? We return to this matter in the next section of this paper.

The transition from La Niña to El Niño, which can happen on a relatively short timescale of a few months, can be effected by westerly wind bursts. The timing of a burst relative to the phase of the longer-term oscillation is of crucial importance (Fedorov 2002). Not only the timing, but also the detailed structure of the wind disturbances affect the response. To explore this matter, it is necessary to recognize that, unlike a simple pendulum that has only one mode of oscillation, the coupled ocean-atmosphere system is far more complex and has a multitude of modes. When data are low-pass filtered, as in Figure 2, then it is likely that only the most unstable mode is evident. However, the other less unstable, and even damped, modes can come into play over relatively brief periods in response to random disturbances with the appropriate spatial structures. Such developments can be described in terms of nonnormal modes (Moore & Kleeman 1999a,b). We next investigate the different possible modes of oscillation.

NATURAL MODES OF OSCILLATION OF THE COUPLED OCEAN-ATMOSPHERE

The properties of an oscillation usually depend on external parameters that define a certain background state. (The period of a pendulum, for example, depends on its length.) The natural modes of oscillation of the coupled ocean-atmosphere have properties that depend on parameters such as the following: the spatially averaged

depth of the thermocline, H ; the intensity, τ , of the time-averaged zonal wind along the equator that causes the thermocline to slope down to the west; and the temperature difference across the thermocline, ΔT . Ocean-atmosphere interactions require that the winds bring cold water from below the thermocline to the surface. Hence, we can anticipate that a deep thermocline and a large temperature difference across the thermocline—large values for H and ΔT —will favor damped rather than amplifying or self-sustaining modes. The results from linear stability analyses (which assume a world with perfectly sinusoidal oscillations) confirm this expectation as can be seen in Figure 6. Those plots show how the period and growth rate of the most unstable mode depend on the parameters H and τ . (The dashed line is the boundary between amplifying and decaying modes; in the white area there are no coherent modes.) In addition to the most unstable mode for given values of the parameters H , etc., there are other modes that are less unstable or more strongly damped. They can all come into play in response to forcing with the appropriate structure and can then amount to a nonnormal mode.

An unexpected condition for self-sustaining modes that depend on ocean-atmosphere interactions is evident in Figure 6: The winds must have a certain minimum intensity. Apparently, a basic state with no winds and a horizontal thermocline cannot support such modes. In Figure 6 the modes are seen to belong mainly to two families: One is prominent when the thermocline is shallow, the other when the thermocline is deep, in the neighborhood of points E and D, respectively. [See Neelin et al. (1998) for a discussion of similar results in terms of nondimensional parameters.]

The spatial structures of the two main families of modes are shown in Figure 7. The upper panel shows the departures from the background state associated with the mode that is dominant when the thermocline is deep and the winds intense. The wind fluctuations are mainly in the western equatorial Pacific and give rise to vertical movements of the thermocline that affect sea surface temperatures mainly in the eastern equatorial Pacific. The deepening of the thermocline in the east during El Niño, when surface waters are warm, is associated with a shoaling in the west that is most pronounced off the equator. In this mode, the response of the winds to changes in sea surface temperature is, for practical purposes, instantaneous, but the ocean has more inertia than does the atmosphere and its adjustment to changes in the winds is delayed. This can therefore be referred to as a “delayed oscillator” mode that depends on interactions between two media, one with a quick adjustment time and the other with a slow adjustment time (Schopf & Suarez 1988, Battisti & Hirst 1989). An equation that captures the essence of this mode is

$$T_t = aT + bT(t - d), \quad (2)$$

where T is temperature, a and b are constants, t is time, and d is a constant time lag. The first two terms represent the positive feedbacks between the ocean and atmosphere. The presence of the third term, which represents the delayed response of the ocean, permits oscillations whose period depends on the values of a , b , and d . This equation, which cannot formally be derived from the original equations

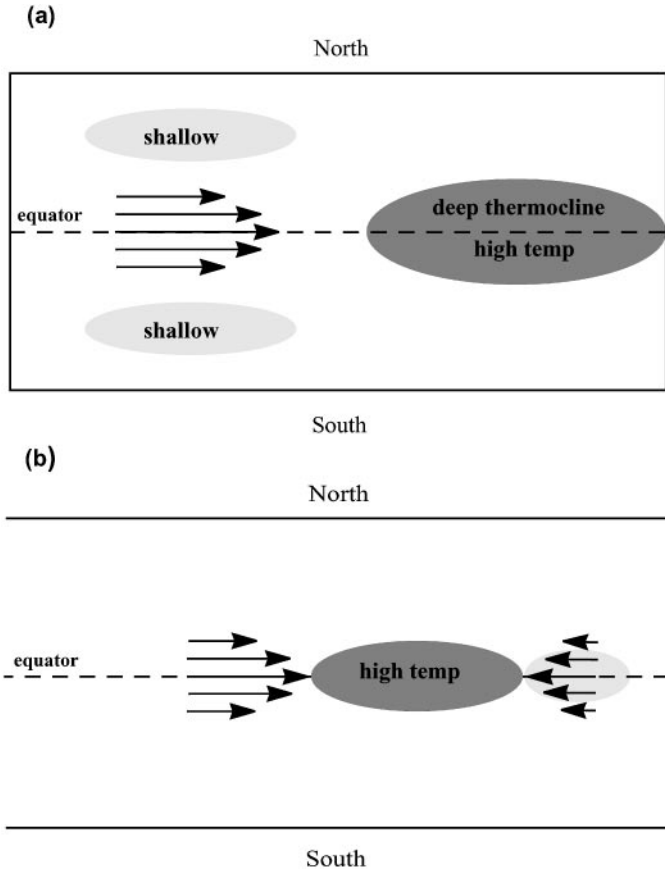


Figure 7 A schematic of the spatial structures of the delayed oscillator mode (*top*) and local mode (*bottom*). Arrows indicate winds, shaded areas show changes in thermocline depth, and “temp” refers to surface temperature. These conditions during El Niño correspond to departures from a background state. The structure of the observed Southern Oscillation is a hybrid of these two.

of motion without making some questionable assumptions—see Neelin et al. (1998)—is nonetheless useful for exploring the effects of a delayed response.

The term delayed oscillator in connection with the Southern Oscillation appears frequently in the literature but seems to mean different things to different people. There is much confusion concerning the roles of oceanic Kelvin and Rossby waves, which some people seem to regard as the salient features of the delayed oscillator mode. Such waves are often observed and are of central importance in the oceanic adjustment to changes in the winds. The waves are explicitly evident when the winds change abruptly but are implicit when gradually varying winds excite a

host of waves, all superimposed. The measurements in Figure 8 show explicit evidence of Kelvin waves—the heavy, dashed lines—and clearly show them to be entirely separate from the far more gradual eastward movement of warm water associated with the onset of El Niño of 1997. For the purpose of determining whether the observed Southern Oscillation corresponds to a “delayed oscillator mode,” observations of explicit Kelvin (and for that matter, individual Rossby) waves are irrelevant. The gradual eastward movement of warm water in Figure 8 is the forced response of the ocean and cannot be a wave that satisfies the unforced equations of motion. The characteristic timescale of the Southern Oscillation, several years, is so long that low-pass filtering is required to isolate its structure. That filtering eliminates individual Kelvin waves.

The bottom panel in Figure 7 shows the structure of a mode very different from the delayed oscillator. The winds to the west of the region of unusually high surface temperature drive convergent currents that advect warm water toward the region. To the east, the currents advect cold water and are divergent. The net result is that the region of warm water expands on its western side, contracts on its eastern side, and in effect drifts westward. Whereas the wind and sea surface temperature fluctuations are in regions far from each other in the case of the delayed oscillator mode, they are colocated in the case of the mode in the bottom panel of Figure 7, which we therefore refer to as a local mode. [Neelin (1991) describes a similar structure as a slow sea surface temperature mode.] The annual harmonic at the equator—surface temperatures in the east are at a maximum in March and a minimum in October—is associated with this type of mode. As mentioned before, the associated seasonal sea surface temperature variations in the eastern equatorial Pacific hardly involve any vertical movements of the thermocline. Implicit in these arguments concerning the local mode is a background zonal temperature gradient at the surface, maintained by background westward winds. Hence, the presence of such winds is necessary for this mode to be amplifying. In the case of the delayed oscillator, similar winds are necessary but for a different purpose: The winds cause the thermocline to slope down to the west so that in the east it is sufficiently shallow for its vertical movements to influence surface temperatures.

Background conditions close to point D in Figure 6 favor the delayed oscillator mode, and conditions close to point E favor the local mode. At other points on the diagram, the modes are hybrid, with the properties of either type becoming more prominent as points D or E are approached. The observed Southern Oscillation corresponds to a hybrid mode with properties of both the local and delayed oscillator modes (Neelin et al. 1998, Fedorov & Philander 2001). This means that interannual sea surface temperature variations in the eastern tropical Pacific depend on vertical movements of the thermocline (a property of the delayed oscillator mode) and also on advection and local upwelling, properties of the local mode. [See Vialard et al. (2001) for a discussion of the mechanisms affecting surface temperatures.] During the 1960s and 1970s, conditions in the tropical Pacific corresponded to the neighborhood of point B in Figure 6 but shifted toward point A in the 1980s and 1990s. A change in the period of the Southern Oscillation, from about three to five years,

can be discerned in Figure 2 and is consistent with such a shift. There are also hints of a change in the structure of the mode: Westward propagation characterized the development of some El Niño episodes before 1980 (Rasmussen & Carpenter 1982), but since 1982, El Niño first appears in the western equatorial Pacific and then expands eastward. This apparent decadal change in the structure of the Southern Oscillation is overwhelmed by the differences between one El Niño and the next: for example, the very modest amplitude of El Niño in 1992 in contrast to its intensity in 1997. Note that conditions are approximately neutrally stable—both points A and B are close to the line of neutral stability—which is consistent with the earlier statement that the Southern Oscillation is weakly damped.

The possibility that conditions in the tropical Pacific shifted from point B to point A in Figure 6 over the past few decades sheds light on a debate about recent changes in the properties of El Niño. Figure 2*a* shows that the most intense El Niño episodes of the past century both occurred during the past 20 years, that the most prolonged episode in the record was in the early 1990s, and that La Niña has been almost absent during the past few decades. Trenberth & Hoar (1997) suggest that these could be indications that global warming is affecting El Niño. A number of investigators object and insist that Figure 2*a* shows the random fluctuations of a stationary time-series with a spectral peak at a single period (Rajagopalan et al. 1997, Wunsch 1999.) To these investigators, the Southern Oscillation is a damped mode subject to random disturbances. The results in Figure 2*a* can be viewed in a different light by choosing as a reference not the average temperature for the past century—the horizontal axis—but instead the average over a ten-year period, for example. The latter approach, which is adopted in Figure 2*b*, acknowledges that the properties of the Southern Oscillation depend on a background state that changes gradually and continuously. In the late 1970s, a transition from relatively cold to warm surface waters was accompanied by a relaxation of the background trade winds and an increase in the spatially averaged depth of the thermocline. From the perspective of Figure 2*b*, La Niña is present throughout the record, and the amplitude of the Southern Oscillation has not increased, but the background state has become warmer. Hence, the debate about the appropriate interpretation of Figure 2*a* really concerns two separate issues with separate timescales: The first, a gradual decadal fluctuation (Kirtman & Schopf 2001), modulates the second, an interannual fluctuation. The origin of the decadal fluctuations in Figure 2*b* is not known and at present is a matter of considerable debate.

The powerful tool that produces the results in Figure 6 is a modified version of the coupled ocean-atmosphere model originally developed by Zebiak & Cane (1987). In that model, a background state—the spatially averaged depth of the thermocline, for example—is specified and only departures from that background state are calculated. Coupled GCMs of the ocean and atmosphere are far more ambitious and attempt to calculate not only the interannual fluctuations, but also the background state, given forcing functions such as the solar radiation incident on the planet. A recent intercomparison of 24 of these models (Latif et al. 2001) developed at institutions worldwide finds that these models reproduce a great variety

of interannual modes of oscillation. Some of those modes bear some resemblance to the observed Southern Oscillation, but none can be said to be very realistic. (The period of the dominant oscillation is as short as two years in some models, as long as ten years in others; the amplitude is negligible in some, but is too large in others.) If the different models are regarded as simulating different worlds, each with its own background state, then the results in Figure 6 could prove useful because the different models presumably correspond to different points on Figure 6. Unfortunately, matters are not as simple because Figure 6 shows only two of the many parameters that determine the properties of the possible Southern Oscillations. In Figure 6, a change in the spatially averaged depth of the thermocline changes the period and structure of a mode. In these models, such changes can be effected by altering the manner in which a model copes with atmospheric convection. The relationship between the winds and sea surface temperature—whether the winds are far as in the top panel of Figure 7 or close as in the bottom panel—depends on the convection scheme in a model. Hence, a model can be biased either toward a delayed oscillator type mode or toward a local mode depending on its convection scheme. Developing realistic coupled GCMs is proving a challenge.

The results in Figure 6 and Figure 7 can assist with the interpretation of measurements—the change in the properties of El Niño from the 1960s to the 1980s—but there is also a need to use measurements to check the results in those figures. Of considerable value for the latter purpose are descriptions of El Niño in the distant past, when Earth's climate was very different from what it is today. Records from corals (Tudhope et al. 2001) and from lake sediments (Rodbell et al. 1999) have been used to determine changes in the amplitude and in frequency of occurrence of El Niño in the past. To check the results in Figure 5 and Figure 6 requires additional information concerning the background conditions (the values of H and τ) at those times. Of special interest are conditions some 7000 years ago (early in the Holocene), when El Niño apparently failed to appear interannually. Rodbell et al. (1999) find that, at that time, the period of the Southern Oscillation was significantly longer than it is today: The period was on the order of a decade. If so, then according to Figure 6, the thermocline was deeper than today and the zonal winds were more intense. The modeling studies of Liu et al. (2000) show that the trades of the Pacific, and the monsoons of the Indian Ocean too, were more intense because of precessional effects. Was that the case in reality? What was the depth of the thermocline? The answers to these questions will help determine the validity of the results in Figure 6.

CONCLUSIONS

A perusal of the literature on El Niño gives the impression that the perspectives of different investigators are divergent. Some see El Niño as one phase of a continual oscillation; others regard it as a sporadic phenomenon initiated by random westerly wind bursts. A growing body of evidence—modeling studies that reproduce the

statistics of the observed Southern Oscillation, the energetics of that phenomenon, stability analyses, etc.—indicates that reality corresponds to a compromise between these different perspectives: El Niño is one phase of a damped oscillation that is sustained by random “noise.” Thus far, the discussion of the noise has focused on westerly wind bursts near the dateline; there is a need for a more complete study of the random atmospheric disturbances. The damped mode does not involve explicit oceanic Kelvin or Rossby waves and is not a strict delayed oscillator (if that is defined as a mode in which sea surface temperature variations depend strictly on thermocline movements.) Rather, the observed mode is of a hybrid type with properties of both families in Figure 7. The properties of the mode are subject to decadal modulations of unknown origin.

The predictability of El Niño requires accurate information about the initial phase of the Southern Oscillation and is limited by the effect of external, random disturbances on a relatively slow oscillation. Probability forecasts, based on ensembles of calculations each with a different realization of the noise, are likely to prove the most reliable and useful sources of information. Such a forecast for El Niño of 1997 would have given a higher probability to a modest event than to the intense one that actually occurred and that depended on an unusual combination of disturbances (Fedorov et al. 2003). [The actual forecasts made for El Niño of 1997 turned out to have very little skill (Landsea & Knaff 2000) mainly because they were deterministic.]

The development of coupled GCMs of the ocean and atmosphere is proving a challenge because it requires simulation of the ocean-atmosphere interactions that influence not only the background state, but also the interannual fluctuations and the seasonal cycle. Particularly difficult is a realistic reproduction of the climatic asymmetries relative to the equator that are evident in Figure 3. At this stage, none of the models reproduces a realistic El Niño; the results concerning the effect of global warming on El Niño therefore have enormous uncertainties.

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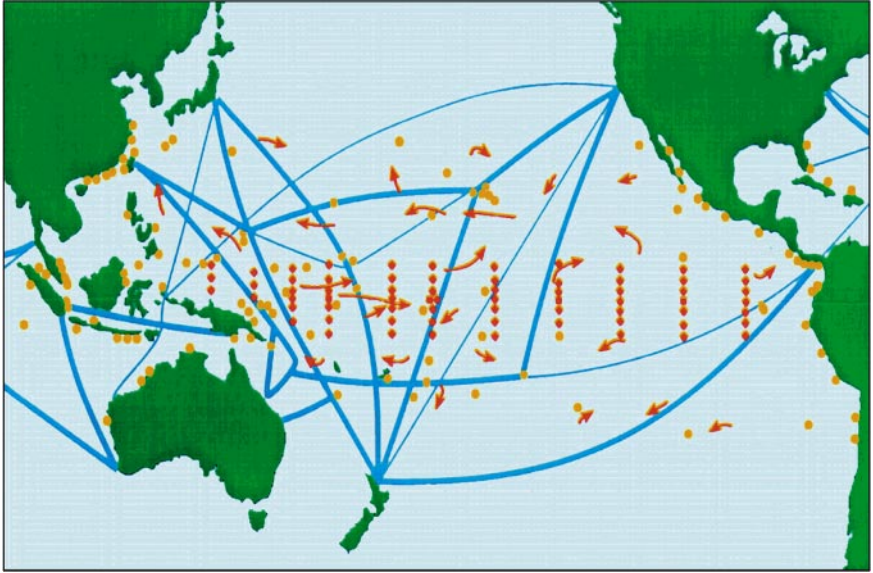


Figure 1 The TOGA array of instruments that currently monitors oceanic conditions in the tropical Pacific Ocean. (The data are available at the web-site www.pmel.noaa.gov/toga-tao/.) The core of the array (the red diamonds) is the network of buoys, moored to the ocean floor, with attached instruments that measure temperature and currents over the upper few hundred meters of the ocean (McPhaden et al. 1998). The arrows are drifting buoys on the ocean surface that measure the temperature and the wind, and whose movements, tracked by satellites, yield information about surface currents. The extended lines are the tracks of commercial ships that deploy instruments that measure temperature to a depth of a few hundred meters. The orange circles are tide gauges that measure sea level.

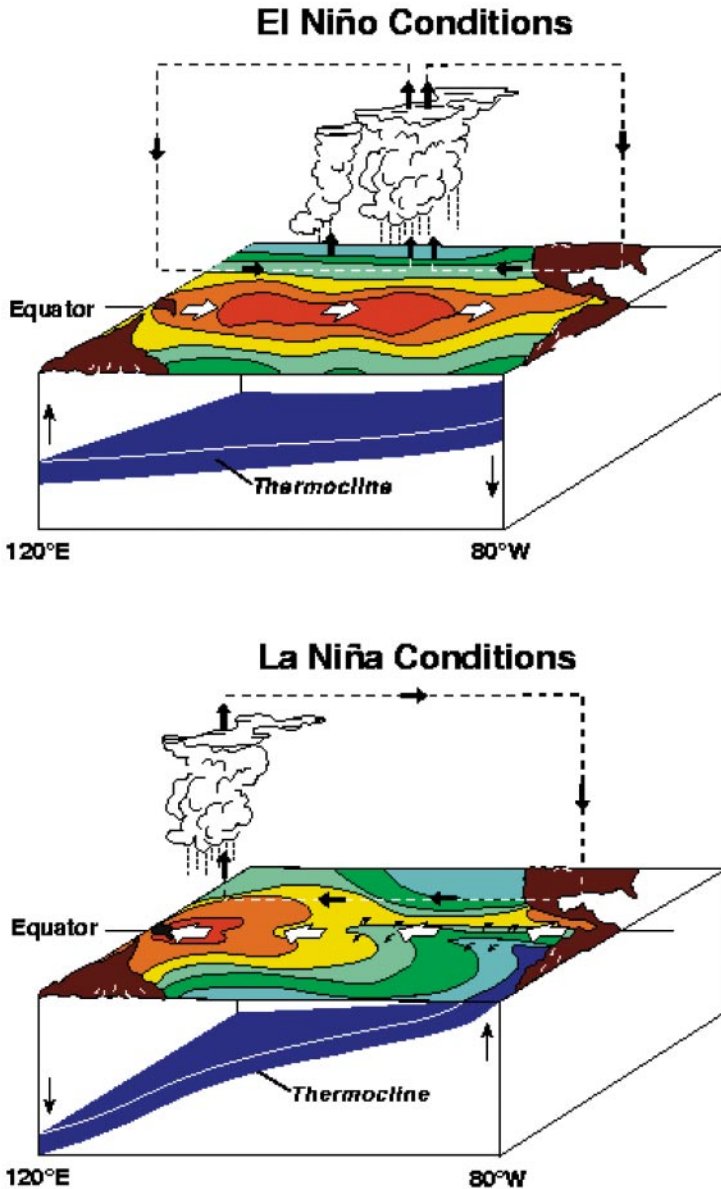


Figure 3 A schematic of conditions during La Niña (*bottom*) and El Niño (*top*). The black arrows indicate atmospheric motion. The Contours on the ocean surface correspond to sea surface temperatures; white arrows are currents at the equator. During La Niña, strong easterly winds cause the thermocline to slope steeply down to the west, thus exposing cold water to the surface in the east. The winds and the slope relax during El Niño when warm surface water flows eastward.

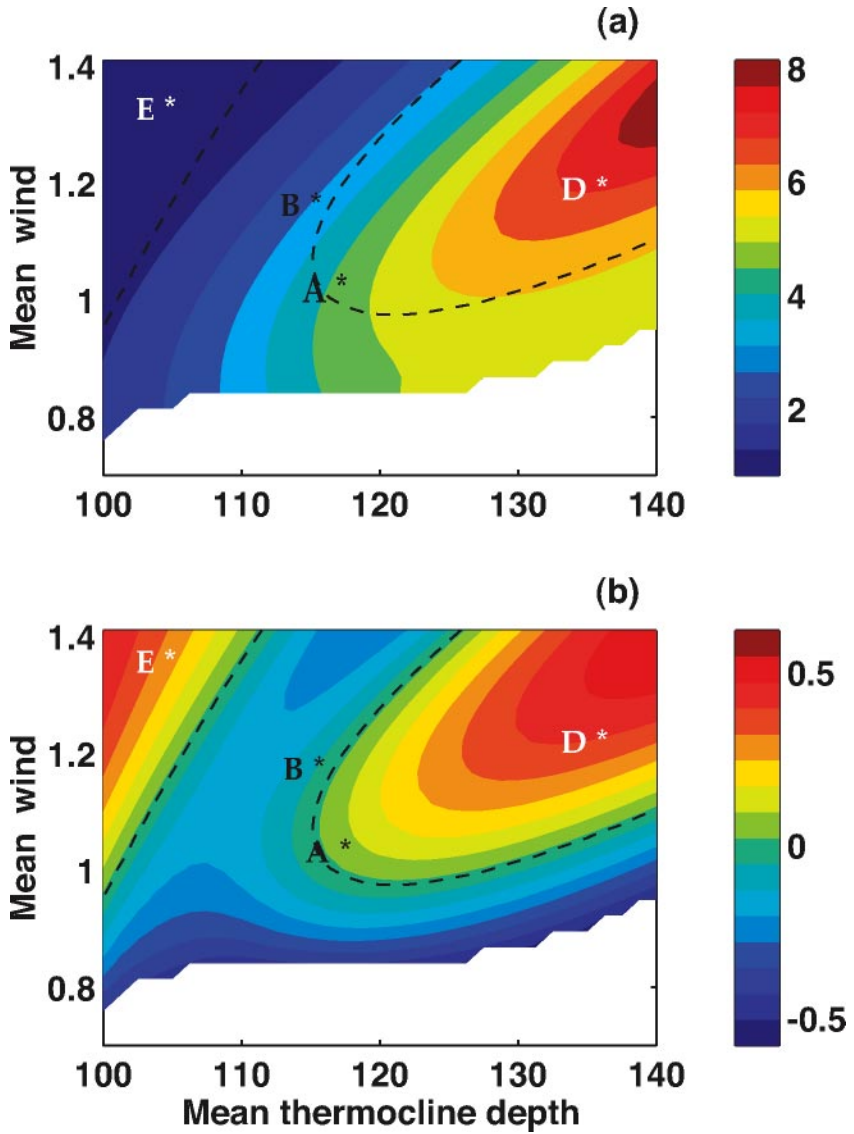


Figure 6 (a) The period (in years) and (b) the growth rate (in 1/years) of the most unstable oscillation as a function of thermocline depth (in meters) and the intensity of the easterly equatorial winds (in units of $.5 \text{ cm}^2/\text{sec}^2$). Dashed lines indicate the zero growth rate or neutral stability. Modes with a coherent structure are absent from the white areas. See the text for the significance of the letters.

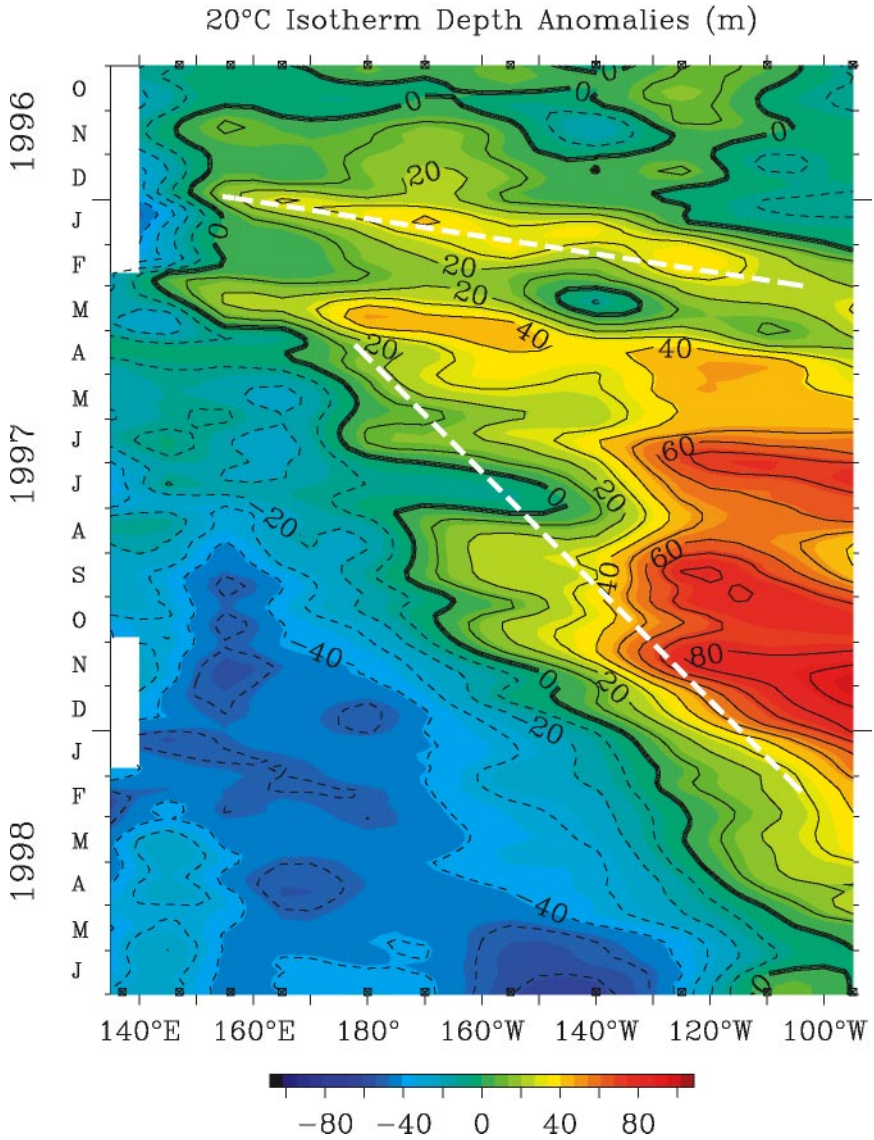


Figure 8 Departures from the long-term averaged depth of the 20°C isotherm, in meters, along the equator in the Pacific during the development of El Niño of 1997. The upper dashed line corresponds to a Kelvin wave rapidly traveling across the Pacific. The lower dashed line shows the slower eastward progression of warm water.

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