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A review of tropical ocean–atmosphere interactions

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ABSTRACT

Enormous strides have been made towards the goal of operational predictions of seasonal and interannual climate fluctuations, especially as regards the phenomenon El Niño. To initialize models, measurements are available from an impressive array of instruments that monitor the tropical Pacific continually; coupled general circulation models of the ocean and atmosphere are already capable of reproducing many aspects of the earth's climate, its seasonal cycle, and the Southern Oscillation. These achievements crown the studies, over the past few decades, that describe, explain and simulate the atmospheric response to sea-surface temperature variations, the oceanic response to different types of wind fluctuations, and the broad spectrum of coupled ocean–atmosphere modes that results from interactions between the two media. Those modes, which are involved, not only in the Southern Oscillation but also in the seasonal cycle and the climatology, differ primarily as regards the main mechanisms that determine sea-surface temperature variations in the central and eastern tropical Pacific: advection by surface currents, and vertical movements of the thermocline induced by either local winds or, in the case of the delayed oscillator mode, by non-local winds. The observed Southern Oscillation appears to be a hybrid mode that changes from one episode to the next so that El Niño can evolve in a variety of ways — advection and nonlocally generated thermocline displacements are important to different degrees on different occassions. The extent to which random disturbances, such as westerly wind bursts over the western equatorial Pacific, influence El Niño depends on whether the southern oscillation is self-sustaining or damped. Attention is now turning to the factors that determine this aspect of the Southern Oscillation, its decadal modulation which causes it to be more energetic in some decades than others. Those factors include interactions between the tropics and extratropics that affect the mean depth of the thermocline, and the intensity of the climatological trade winds.

1. Introduction

Although El Niño first received world-wide publicity in 1997, we have been studying the phenomenon for more than a century. During that time, El Niño has grown from a child, a modest seasonal current off the coast of Peru, into a complex giant of global dimensions that reveals new facets of its personality each time it visits. We originally welcomed El Niño, Spanish for Child Jesus, as a blessing, but now anticipate it with dread; we now associate El Niño with disastrous floods in some regions, devastating droughts in other regions, and unusual weather patterns over large parts of the globe. This may sound like the story of a fallen angel, but it is not. El Niño has not changed, we have. The growth in our numbers, in our economy, and in our scientific ability to measure and explain the atmosphere and oceans, has altered our perceptions of this phenomenon.

At first, the term El Niño referred to a warm, seasonal southward coastal current that appears along the barren shores of Peru around Christmas when it brings a respite from the cold northward current that otherwise prevails. Every few years, the southward current is unusually intense and

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persistent, brings gifts that, on occasion, have included bananas, coconuts and even alligators, and is associated with rains that literally transform the northern Peruvian desert into a garden (Murphy, 1926; Philander, 1998). Today the term El Niño is reserved for these interannual events rather than the annual coastal current. This change in terminology has been accompanied by a change in the way we view El Niño. Its visits ceased to be joyous occasions when it started affecting the economy of Peru and Ecuador adversely. The rains still turn the desert into a garden but they also wash away homes, roads and bridges, the fruits of economic growth. The Peruvian economy has become so dependent on the fish that are usually abundant in the cold waters that the temporary disappearance of those fish can amount to a disaster. El Niño is a reminder of the paradox that our economic growth seems to bring greater vulnerability to certain natural phenomena.

Everyone now associates El Niño with calamities, to such a degree that the term is sometimes used metaphorically to designate a mischievous gremlin. Stockbrokers invoke it when the market is erratic, commuters do the same when the traffic is bad. El Niño, however, is not entirely malevolent. It is bringing riches to the field of oceanography — the impressive array of instruments in Fig. 1 serves to monitor the Pacific so that we can be informed about the whereabouts of El Niño at all times — and it is integrating two seemingly independent groups, atmospheric and oceanic scientists. This marriage is essential if we are to escape the circular argument in which oceanographers attribute the appearance of warm surface waters in the eastern equatorial Pacific, the signature of El Niño, to changes in the surface winds that drive the tropical Pacific, while meteorologists claim that the surface winds change for oceanic reasons, because of the changes in sea-surface temperature patterns. Not until the late 1950s were we fully aware that El Niño has both oceanic and atmospheric aspects, and that the circular argument implies that El Niño is literally a child of water and air, the product of interactions between the ocean and atmosphere. It is but one of a broad class of climate phenomena that can be explained in neither strictly oceanic nor atmospheric terms, that requires collaboration between oceanographers and atmospheric scientists. The long-term goal of that collaboration is the routine, operational prediction of seasonal and interannual climate fluctuations, the counterpart of daily weather forecasts. The firsts steps towards that goal, which requires the joint efforts of observa-

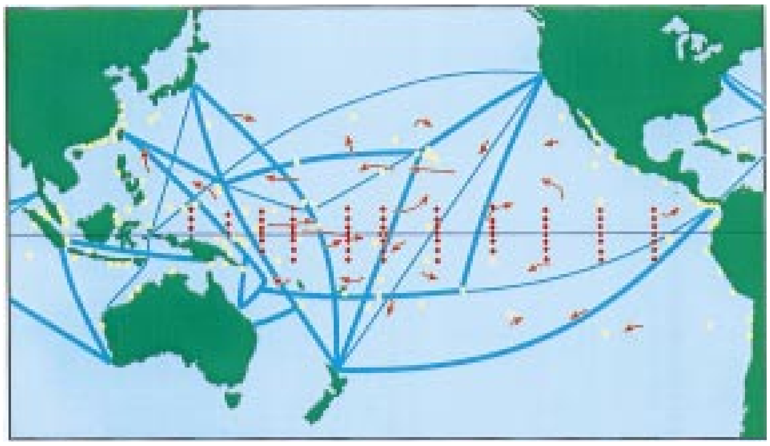


Fig. 1. The array of instruments that monitors oceanic conditions. All these measurements are relayed to stations on land, in “real time”. The blue lines are the tracks of commercial ships that deploy instruments that measure temperature to a depth of a few hundred meters. The arrows are drifting buoys that measure temperature and the winds, and whose movements yield information about surface currents. The yellow dots are tide gauges that measure sea level which depends on the average temperature of a water column. The red diamonds, buoys moored to the ocean floor, are locations where temperature is measured over the upper few hundred meters of the ocean. The red squares indicate where oceanic currents are measured.

tionalists and theoreticians, have been taken: the array in Fig. 1 continually monitors the tropical Pacific; and coupled ocean–atmosphere models are simulating the interactions between the two media with considerable success. The array in Fig. 1, our response to El Niño of 1982 which caught everyone by surprise, enabled us to follow the development of El Niño of 1997 as it happened, thus permitting scientists to alert the public in a timely manner. (The data are available on the world-wide-web at www.pmel.noaa.gov/toga-tao/).

El Niño is a match-maker: it is integrating observational and theoretical activities, and is marrying the atmospheric and oceanic sciences. Now it faces a much bigger challenge, bridging science and policy, two very different worlds. At present, policy-makers seem to have firm belief in the efficacy of the "market-place" which favors short-term benefits and products in which everyone has confidence. Will the policy-makers have patience with the scientific method of trial-and-error that requires constant skepticism on the part of its practitioners, and explicit acknowledgment of the shortcomings of theories and predictions? To illustrate the power of this method, we should refrain from telling the story of El Niño as a seamless progression from one success to the next, with no mention of the tortuous paths, with many false steps and wrong turns, that led to the admirable results. Instead we should relate how, on several occasions, we underestimated the complexity and subtlety of the phenomenon we somewhat dismissively refer to as "the Child". El Niño has surprised us repeatedly, even as recently as the 1990s. Progress stems from these setbacks; improvements in our models come from evidence, and recognition of the evidence, that the models are too idealized.

Recently we have become aware that a newly discovered facet of El Niño, its decadal modulation, has all along been modulating the advances in our understanding of this phenomenon! El Niño was energetic up to 1920, the period of the original research on its atmospheric aspects, the study of the Southern Oscillation primarily by Walker and Bliss (1932). During the subsequent decades El Niño practically disappeared, and the work of Walker and Bliss fell into oblivion. Interest revived in the late 1950s when El Niño reappeared and then gained in frequency and amplitude. The years 1957 and 1982 are of particular importance because our ideas concerning El Niño changed markedly on those occasions. Only in 1957 did we realize that El Niño is far more than a coastal phenomenon along the shores of Peru, that it involves the entire tropical Pacific Ocean, and also the global atmosphere. We next proceeded to describe and model its properties in detail, only to discover, in 1982, that we underestimated its complexity. The confounding El Niño of 1982 motivated the highly successful ten-year, international research program TOGA (= Tropical Oceans and Global Atmosphere). TOGA nonetheless concluded with a puzzle, the unexpected persistence, for several years, of warm conditions following El Niño of 1992. With the increasing likelihood of global warming, because of the rapid rise in the atmospheric concentration of greenhouse gases, we have to start wondering what El Niño next has in store for us.

The precise meaning of the term El Niño is at present a matter of some confusion (Trenberth, 1997). El Niño gained so much publicity during 1997 that everyone is now familiar with the term and associates it with droughts in Indonesia, torrential rains in Peru and California, and unusually warm surface waters in the eastern tropical Pacific Ocean. This means that the term as used today refers to a phenomenon with both atmospheric and oceanic aspects. For scientists to insist that El Niño refers to the appearance of warm waters along the coast of Peru, and nothing more, is to use the term in a sense that is rapidly becoming archaic. A common error is to describe El Niño as a departure from "normal" conditions. Fig. 2 clearly shows that normal conditions seldom prevail. The tropical ocean and atmosphere interact to produce a continual, irregular, interannual oscillation, the Southern Oscillation, between El Niño and its complement La Niña. If we accept that all these phenomena have both atmospheric and oceanic aspects, then the tautological and entirely unnecessary acronym ENSO should fall into disuse. In the early 1980s an august committee of scientists attempted a strict definition of El Niño (SCOR, 1983) but nobody paid attention, in part because the development of El Niño of 1982 was inconsistent with that definition. This phenomenon is so complex that any strict definition in terms of a few numbers is futile. The term El Niño is useful in the same way that the term winter is useful even though each winter is distinct. No one

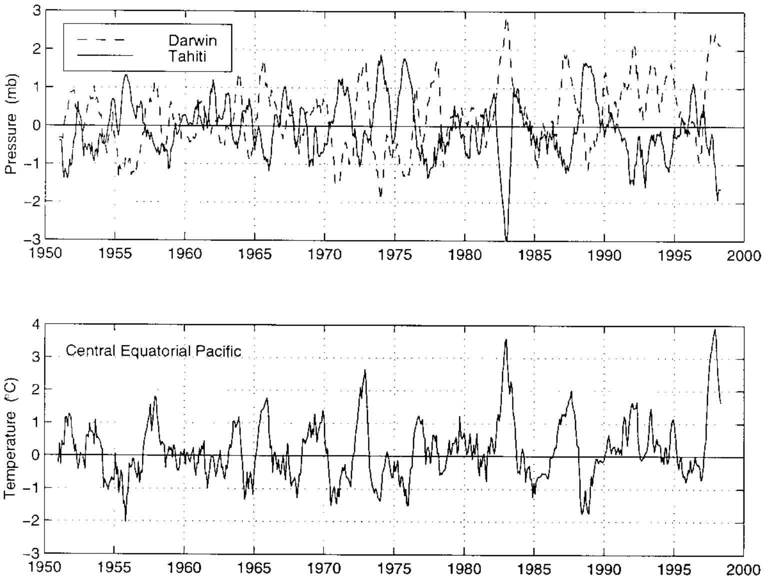


Fig. 2. The southern oscillation as reflected in the interannual fluctuations in pressure that are out of phase at Darwin (Australia) and Tahiti (top panel). These variations are highly coherent with those in sea-surface temperature as measured in the eastern equatorial Pacific over an area that extends from 5°N to 5°S, 160°W to 90°W (bottom panel).

wishes for narrow, quantitative definitions of winter and summer after reading the following lines of Shakespeare: Now is the winter of our discontent made glorious summer by this Sun of York. Hopefully a poet will soon use the term El Niño so imaginatively that the cognoscenti will stop debating its precise definition.

2. Pre-1957

Although the narrow coastal zone of Peru and Ecuador is a barren desert, the adjacent ocean teems with a rich variety of marine life. Those waters flow northward and are cold, not so much because they come from the neighborhood of Antarctica, but because of coastal upwelling: the southeast trades that are parallel to the coast drive off-shore Ekman drift that brings to the surface cold water, rich in nutrients. During the early calendar months of the year, there is a seasonal warming of the waters off Peru and Ecuador, that is part of the oceanic response to a seasonal relaxation of the southeast trades, associated with a southward movement of the Intertropical Convergence Zone. Every few years, during interannual El Niño events, this warming is unusually intense and persistent. This phenomenon is a puzzle because it is not associated with a corresponding weakening of the local along-shore winds. Only in 1957 did clues about the cause of this warming become available. That year, a year of El Niño, also happened to be an International Geophysical Year of intensive measurements of our planet. From the enhanced measurements of sea-surface temperatures across the Pacific it emerged that El Niño is much more than a local, coastal phenomenon. The data showed that the warm surface waters along the shores of Peru were not confined to a few tens of kilometers from the coast, but extended thousands of kilometers westward, across the entire tropical Pacific. El Niño of 1957, and in fact all El Niño episodes, involve changes in the circulation of the entire tropical Pacific Ocean, changes that affect such a vast area that they profoundly influence the global atmospheric circulation. It turned out that atmospheric scientists had been studying these atmospheric effects for several decades, without realizing that they are related to El Niño. Sir Gilbert Walker pioneered those studies.

Walker arrived in India as Director General of

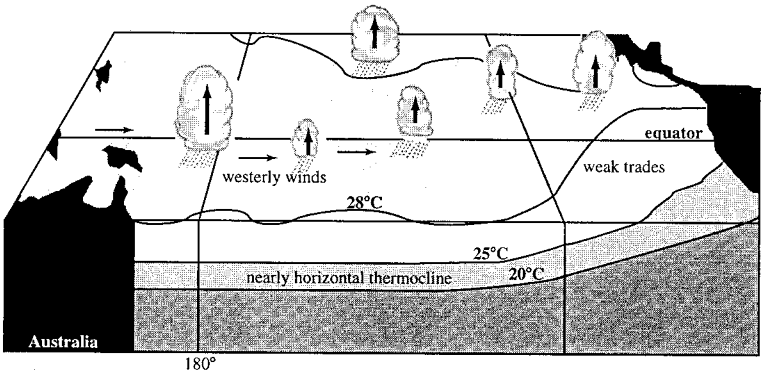
Observatories shortly after a disastrous famine that in part stemmed from a failure of the monsoons in 1899. Motivated by the desire to anticipate future failures of the monsoons, phenomena he believed to be part of a global climate fluctuation, he and his associates analyzed atmospheric data from stations around the globe in search of such a fluctuation. They discovered the Southern Oscillation, the see-saw in sea level pressure across the Pacific depicted in Fig. 2 (see Wallace et al. (1998) for a detailed discussion of early work on the southern oscillation). Walker and Bliss (1932) found that periods of poor monsoons over India tend to coincide with that phase of the Southern Oscillation when the pressure difference across the tropical Pacific is small, when the trade winds along the equator are relaxed, and when rainfall increases in the central and eastern equatorial Pacific while it decreases over the western equatorial Pacific. During the complementary phase of the Southern Oscillation, when the pressure difference across the Pacific is large, the trades are intense, and rainfall along the equator is confined mainly to the western Pacific. These fascinating results of Walker were neglected for several decades after their publication, in part because he was unable to convert the results into a scheme for predicting the monsoons, and in part because he failed to identify the mechanisms responsible for the Southern Oscillation. The data needed for that identification, extensive measurements of sea-surface temperature variations in the tropical Pacific during El Niño, became available only from the 1950s onward.

El Niño of 1957 led Bjerknes (1966) and others to the realization that El Niño, rather than a sporadic departure from normal conditions, is one phase of the continual, irregular, interannual Southern Oscillation. It corresponds to that phase during which the pressure difference across the Pacific is small. (The complementary phase, during which the pressure difference across the tropical Pacific is large, is known as La Niña (Philander, 1990).) In a remarkable synthesis, Bjerknes (1969) explained this oscillation by invoking a tantalizingly circular argument: the interannual sea-surface temperature variations of the tropical Pacific are both the cause and consequence of the fluctuations in atmospheric conditions associated with the Southern Oscillation. From this argument Bjerknes (1969) inferred that interactions between the ocean and atmosphere are at the heart of the matter. The next three paragraphs summarize the three components of Bjerknes' explanation: the atmospheric response to sea-surface temperature variations, the reason for those variations, and the nature of interactions between the ocean and atmosphere.

The atmospheric circulation in the tropics corresponds essentially to a direct thermal circulation with intense convection, heavy rainfall, and low surface pressures over the regions with the highest surface temperatures, onto which the surface winds converge. The most important of those regions are the Amazon and Congo river basins, and the "maritime" continent of the western tropical Pacific, southeastern Asia and northern Australia. The latter region expands far eastward during El Niño when the region of warm surface waters in the tropical Pacific expands eastward, causing the convection to move in that direction, and the trade winds along the equator to relax. During La Niña, the warm waters contract westward as the eastern Pacific cools, while the trades intensify. Fig. 3 depicts these conditions schematically.

Interannual sea-surface temperature changes cause the Southern Oscillation, but what causes the temperatures to change? Over large parts of the globe, variations in the heat flux into the ocean control the temperature of the surface waters, but low latitudes, and certain coastal zones such as those of Peru and Ecuador where the winds are parallel to the shore, are different. In those regions, sea-surface temperature patterns reflect the spatial structure of the thermocline that separates warm surface waters from cold water at depth: temperatures are low where the thermocline is shallow, and are high where it is deep. Winds parallel to a coast can induce upwelling and a shallow thermocline, as happen off Peru. An additional factor that comes into play is the dynamical response of the tropical Pacific to changes in the winds. The prevailing easterly trade winds along the equator cause the thermocline to slope downward to the west. When these winds relax, during El Niño, the thermocline becomes more horizontal. This change is associated with an eastward flow of warm surface waters; it causes the depth of the thermocline to decrease in the west, and to increase in the east where sea-surface temperatures rise. Thus the interannual variations in sea-surface temperatures amount to a basin-wide horizontal

El Niño Conditions



La Niña Conditions

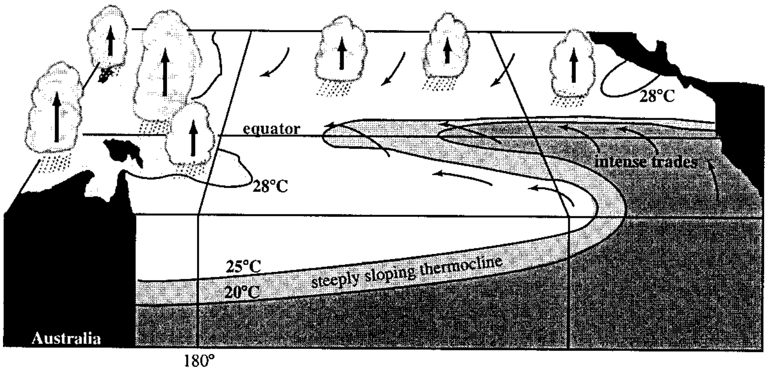


Fig. 3. A schematic view of El Niño (top) and La Niña (bottom) conditions. During La Niña, intense Trade winds cause the thermocline to have a pronounced slope from east to west so that the equatorial Pacific is cold in the east, warm in the west where moist air rises into cumulus towers. The air subsides in the east, a region with little rainfall except in the doldrums where the northeast and southeast Trades converge. During El Niño, the Trades along the equator relax, as does the slope of the thermocline when the warm surface waters flow eastward. The change in sea-surface temperatures is associated with an eastward shift in the region of rising air and heavy precipitation.

redistribution of the warm waters above the thermocline, in response to the interannual variations in the winds. That is how conditions along the coast of Peru can be affected by changes in the winds in remote regions such as the western equatorial Pacific.

If interannual variations in the intensity of the trade winds over the equatorial Pacific cause the interannual sea-surface temperature changes, which in turn cause the wind fluctuations, then interactions between the tropical ocean and atmosphere amount to a positive feedback. Consider a random disturbance that causes a slight weakening of those winds during La Niña. This change in the winds induces a slight eastward expansion of the pool of warm surface waters in the western equatorial Pacific. That expansion reinforces the relaxation of the winds, so that the warm pool expands even further eastward. That is how La Niña comes to an end and El Niño develops.

These arguments of Bjerknes were based on scant data sets, were qualitative, and left many questions unanswered. (What causes the turnabout from El Niño to La Niña? Why does the Southern Oscillation have a timescale of approximately 4 years?) The next tasks were therefore the acquisition of larger data sets, by means of newly designed instruments in some cases, and the development of models that simulate how the ocean adjusts to changes in the winds, how the atmosphere responds to sea-surface temperature variations, and how the ocean and atmosphere interact.

3. 1957 to 1982

In 1957, El Niño visited, scientists conducted an International Geophysical Year of intensive measurements of our planet, and the former Soviet Union launched Sputnik. The latter event, by contributing to a surge in the number of people engaged in scientific research, and in the resources available to them, contributed to an improved understanding of the atmospheric and oceanic processes that determine the properties of El Niño. The growth in the atmospheric sciences was related mainly to numerical weather prediction, a topic Bengtson (1999) reviews elsewhere in this volume. A group of meteorologists, led by von Neumann who had been involved with the invention of the electronic computer, started exploring that subject in Princeton New Jersey in the early 1950s. The activities of that influential group included research on geophysical fluid dynamics, which concerns the effects of stratification and rotation on fluids such as the atmospheres of the earth and other planets, the oceans, and the liquid core of the interior of the earth. The relevance of these theoretical studies to phenomena observed in the oceans was initially unclear. Soon the study of tropical phenomena related to the response of the ocean to variable winds, the response that is of central importance to El Niño, would provide convincing agreement between oceanic measurements and theories.

Bjerknes proposed that the appearance of warm surface waters in the eastern equatorial Pacific during El Niño is part of the oceanic response to changes in the surface winds. Theoretical studies of that response were initiated by Veronis and Stommel (1956) who explored the generation of the Gulf Stream in an ocean initially at rest. How long, after the sudden onset of the winds, before a Gulf Stream appears? They found that the oceanic adjustment-time, the time it takes to reach equilibrium after an abrupt change in the winds, depends on the time it takes Rossby waves to propagate across the ocean, and that the speed of these waves increases with decreasing latitude. Attention therefore turned to low latitudes where it should be possible to acquire measurements to test these ideas, in a relatively short period. Fortuitously, the three tropical oceans have similarities and differences that provide a wealth of information about the oceanic response to different wind-stress patterns. The Indian and Atlantic Oceans have similar dimensions, and hence should have similar adjustment-times, but the winds over these oceans behave very differently. Over the Indian Ocean, the seasonal changes include the abrupt onset of the monsoons that generate the intense Somali Current (Leetmaa, 1972) and, at the time of the equinoxes, the sudden appearance of westerly winds along the equator where they drive intense equatorial jets (Wyrtki, 1973; Knox, 1974). The seasonal cycle in the tropical Atlantic, in contrast to that in the Indian Ocean, is a far more gradual phenomenon because the wind fluctuations are mainly sinusoidal with a period of one year. The much larger Pacific, which therefore has the longest adjustment-time, has winds that vary seasonally the way they do in the Atlantic, and that in addition vary interannually, because of the Southern Oscillation. To explore these various phenomena in the three tropical oceans, observationalists and theoreticians collaborated closely during the 1970s and 1980s, and scientists from various nations, including the former Soviet Union, often joined forces in large, international research programs.

To explore tropical phenomena under idealized conditions, theoreticians developed a hierarchy of models of which the simplest is the shallow water model. Because its free surface is a good analog of the very sharp, shallow tropical thermocline, this model is a powerful tools for the study of equatorial waves (Matsuno, 1966; Moore, 1968), and their role in the oceanic adjustment to changes in the winds (Lighthill, 1969; Anderson and Gill, 1975; Cane and Sarachik, 1976). However, this model excludes features such as the Equatorial Undercurrent and it does not have sea-surface temperature as a variable. Cane (1979), and

Zebiak and Cane (1987) remedied these shortcomings by means of a versatile, nonlinear, two-layer model that is now used extensively in studies of ocean–atmosphere interactions. Results from these models contributed to the development of general circulation models capable of remarkably realistic simulations of the seasonal generation of the Somali Current in the Indian Ocean (Bryan, 1969; Cox, 1979), and of the seasonal and interannual variations of the complex current-system of the Atlantic and Pacific Ocean (Philander and Pacanowski, 1980).

One of the main results from these models concerns the effect of a change in the winds over one part of an ocean basin, the western equatorial Pacific say, on oceanic conditions in a different and remote part of the basin, off the coast of Peru say. The models show that the warming of the surface waters along the coast of Peru could be a consequence of a change in the winds over the western equatorial Pacific (Hurlburt et al., 1976; McCreary, 1976). If the change in the winds is abrupt, then waves are explicitly present in the oceanic response. In Fig. 4 for example, equatorial Kelvin and Rossby waves are prominent. If the winds should change very slowly, with a time-scale long compared to the adjustment time of the ocean, then the waves are strictly implicit because the response is an equilibrium one. For example, in the relatively small equatorial Atlantic Ocean, the adjustment time is so short that the seasonal fluctuations should be in phase with the seasonal changes in the winds. The data analyzed by Katz and collaborators (1977) confirm this result. In the much larger Pacific Ocean, the adjustment-time is so long, that the response lags behind the forcing even on interannual time-scale. This lag turns out to be of vital importance to the

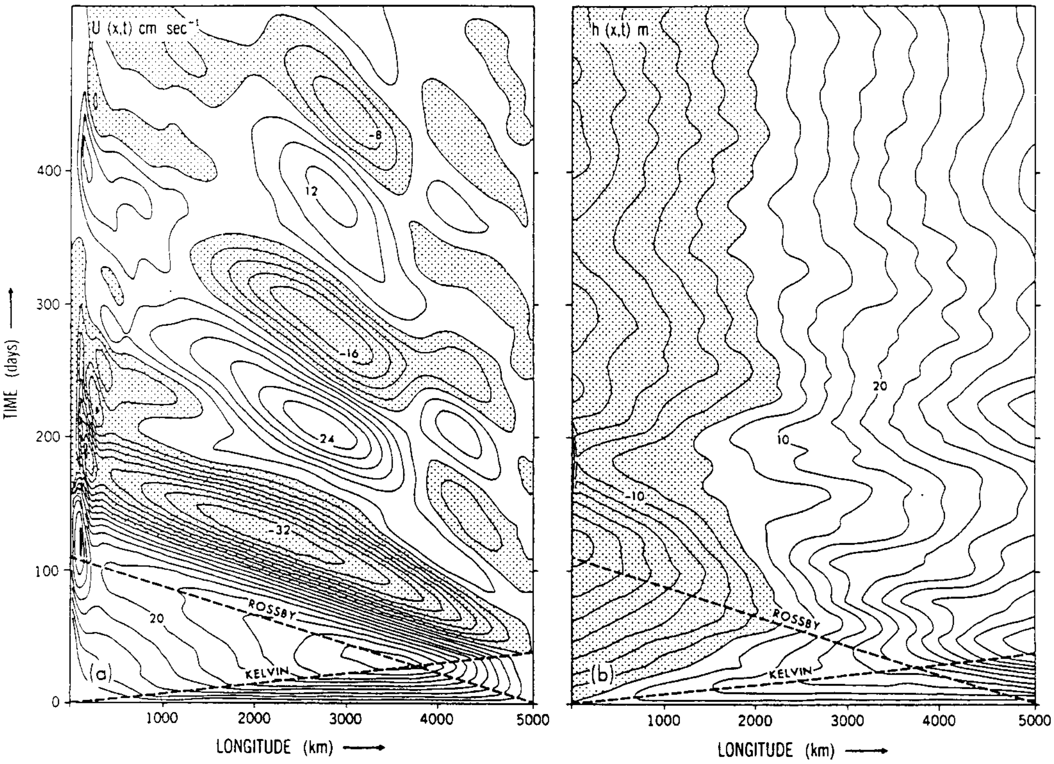


Fig. 4. The zonal velocity component (left) and thermocline depth variations (right) along the equator after the sudden onset of spatially uniform eastward winds over a shallow water model. Shaded regions indicate westward flow or a shoaling of the thermocline above its original depth of 100 m. The dashed lines correspond to the phase speeds of the equatorial Kelvin wave and the gravest Rossby waves (from Philander and Pacanowski (1980)).

turn-about from El Niño to La Niña. Fig. 5 shows an example of the oceanic response to gradually varying winds; contrast this with Fig. 4.

The first data with which to check the validity of these result came from tidal records from islands in the Pacific — variations in sea level reflect changes in the depth of the thermocline. Wyrtki (1975) established that the collapse of the trade winds over the western and central equatorial Pacific during El Niño does indeed result in a basin-wide horizontal redistribution of warm surface waters from the west to the east: sea level falls in the western but rises in the eastern Pacific during El Niño. At first there was no information about the waves and currents that effect this redistribution; measurements of the subsurface currents and thermal fields are necessary. The development of moorings capable of providing such time-series proved a challenge, in part because the equatorial currents near the surface have enormous vertical shear. These difficulties were overcome by the late 1970s when Halpern — see Halpern et al. (1983), Halpern (1987) — started time-series measurements of the currents on the equator at 110°W. Those, and other measurements (of sea-surface temperature from satellites for example) provided detailed information about a spectrum of waves. Some are equatorially trapped inertia-gravity waves excited by the wind (Wunsch and Gill, 1976), some are Kelvin waves generated by westerly wind bursts over the western equatorial Pacific (Ripa and Hayes, 1981); some result from instabilities of the intense equatorial currents (Legeckis, 1977; Philander et al., 1985). The good agreement between the theories for these phenomena, and the measurements, bolstered confidence in the models. An interesting test for the models was El Niño of 1982.

When, in 1982, El Niño started to develop, the moorings were in place and could document the evolution of that event: the eastward progression of westerly winds that replaced the easterly trades, the concurrent eastward penetration of warm surface waters that involved dramatic changes in the tropical currents, including the disappearance (for a while) of the intense Equatorial Undercurrent, and the shoaling of the thermocline in the west, its deepening in the east. A general circulation model, forced with the observed winds, realistically reproduced all these features (Philander and

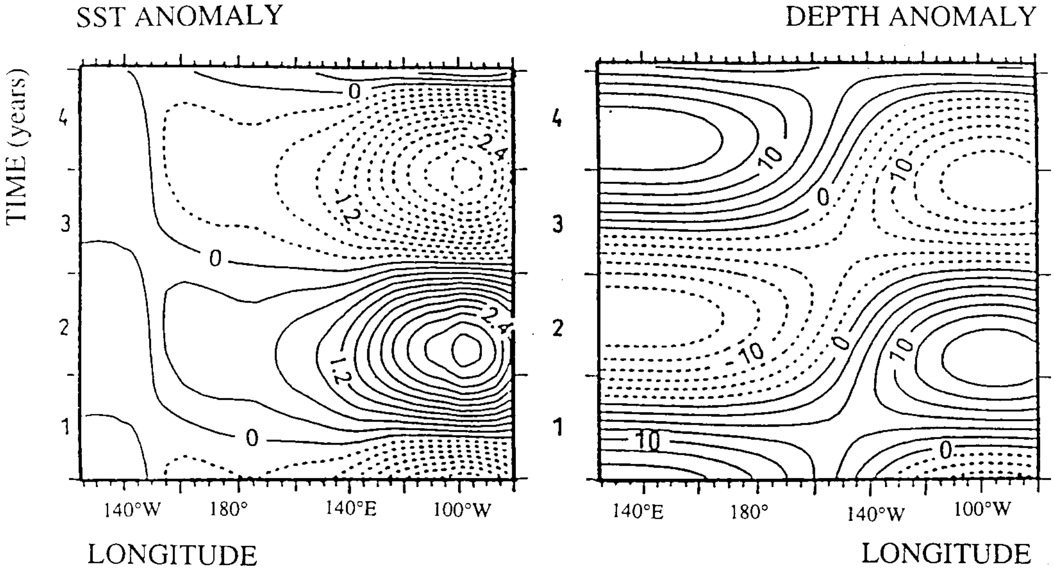


Fig. 5. The departure, from the time-average, of sea-surface temperatures (left) and thermocline depth (right) along the equator over a period of 4 years in the coupled ocean–atmosphere model of Battisti and Hirst (1989), that simulates a perfectly periodic southern oscillation. This is in effect the oceanic response to surface winds that vary sinusoidally with a period of 4 years. Contrast this response with that in Fig. 4 for the case of winds that change abruptly.

Siegel, 1985). The same model demonstrated that it is possible to reproduce, deterministically, the oceanic aspects of the southern oscillation between El Niño and La Niña over an extended period, provided the surface winds are specified.

In parallel with these developments in oceanography, atmospheric scientists analyzed data to determine exactly how El Niño evolves, and developed models to simulate the Southern Oscillation. Rasmusson and Carpenter (1982), in a valuable synthesis of the measurements since the 1950s, described the morphology of a typical (or "canonical") El Niño. Modest sea-surface temperatures first appear off the coast of Peru in March and April (when sea-surface temperatures in that region attain their seasonal maximum) and then gradually migrate westward, amplifying as they do so. The associated changes in the winds include the early appearance of anomalous surface westerlies near the date-line, and the subsequent collapse of the trade winds as El Niño peaks. If, during the northern summer, sea-surface temperature anomalies in the tropical Pacific are already large, then there are likely to be poor monsoons over India, and a reduction in the frequency of hurricanes over the Atlantic. El Niño usually reaches its maximum amplitude towards the end of the calendar year, at which time it affects weather patterns over northern America (Wallace and Gutzler, 1981). The factors that come into play include poleward propagating waves (Hoskins and Karoly, 1981), and an intensification of the Hadley Circulation that causes the Jet Stream to move equatorward, thus altering storm-tracks across the Pacific (Bjerknes, 1969). As a result, California and the Gulf states can be battered by severe storms, while the northwestern United States enjoy a relatively mild winter.

To explore the effect of sea-surface temperature variations on the atmosphere, scientists developed a hierarchy of models. In the shallow water model of Gill (1980) a warm sea-surface temperature anomaly is associated with a local atmospheric heat source onto which the surface winds converge. The moisture carried by those winds can amplify the magnitude of the heat source (Zebiak, 1986). In the model of Lindzen and Nigam (1987), sea-surface temperature gradients give rise to pressure gradients, in the atmospheric boundary layer, that drive the surface winds. These models of Gill (1980) and of Lindzen and Nigam (1987); which are physically different but mathematically equivalent (Neelin, 1989) are widely used as the atmospheric components of relatively simple coupled ocean–atmosphere models. (For a more detailed discussion of the atmospheric response to heat sources, see Hoskins (1999) elsewhere in this volume.)

Studies with atmospheric general circulation models established that the Southern Oscillation can be reproduced, deterministically, by means of models in which the sea-surface temperatures are specified as lower boundary conditions. That oscillation is absent from general circulation models in which the specified sea-surface temperatures have seasonal but no interannual variations (Shukla and Charney, 1981; Lau, 1985). This important result implies that, although weather prediction is limited to a matter of weeks, coupled ocean–atmosphere models should be capable of extended forecasts of certain averaged fields, those associated with the southern oscillation for example.

Much was known about El Niño when it arrived unexpectedly in 1982. The reasons why it caught everyone by surprise are varied. Satellites did measure an increase in sea-surface temperatures of the eastern equatorial Pacific during 1982, but scientists attributed the unusually large increase to measurement problems introduced by the explosion of the volcano El Chichon. Subsurface oceanic measurements were being made as El Niño evolved, but the data were available only after the instruments had been recovered, after the peak of El Niño had passed. The most confounding aspect of El Niño of 1982 was the manner in which it evolved. Rather than follow the development of a "canonical" event, which starts in the east and moves westward while amplifying, this one progressed from west to east. Until El Niño of 1982, we did not fully appreciate that each El Niño is distinct. Subsequent El Niño episodes would display even more variety.

4. Post-1982

El Niño of 1982, which was intense and caused disasters world-wide, impressed on everyone the need to monitor the tropical Pacific, and to develop coupled models for the purpose of predictions. On the atmospheric side, the activities associated with weather prediction provide much of what is needed for climate predictions. In oceanography, the new era of operational activities had to be introduced. Soon after El Niño of 1982, Hayes et al. (1991) started to augment the modest array of instruments that had documented that event. By the mid-1990s, the array had grown into the one shown in Fig. 1. The measurements are assimilated into a realistic general circulation model of the ocean forced with the observed winds, to produce gridded data sets of various fields, for studies of the energetics, heat and mass budgets of the ocean, for example, and as initial conditions for forecasts with coupled models (Leetmaa and Ji, 1989; Ji et al., 1994; McPhaden et al., 1998). The development of coupled general circulation models of the ocean and atmosphere is well under way. This is a major challenge because the models need to reproduce the climatology, seasonal cycle and interannual variability of the tropical Pacific. All these phenomena involve interactions between the ocean and atmosphere. Consider, for example, the climatic asymmetry in which the warmest surface waters and the ITCZ are mostly north of the equator. From an atmospheric point of view, the location of the ITCZ is determined by oceanic conditions, the location of the warmest waters. From an oceanic perspective, however, the meridional winds that converge onto the ITCZ cause upwelling and low surface temperatures along the coasts of Ecuador and Peru so that the maximum temperatures are further north, off Panama. Circular arguments, which imply ocean–atmosphere interactions, similarly explain the intensity of the climatological trade winds; those winds both depend on and cause the zonal sea-surface temperature gradient in the Pacific. The exploration of these phenomena, and of the ocean–atmosphere interactions on which they depend, by means of simple coupled models, facilitates the development of coupled general circulation models.

The first simple coupled model to reproduce many aspects of the southern oscillation, developed by Cane and Zebiak (1985), specifies the climatology and seasonal cycle of the tropical Pacific on the basis of measurements. That model has been used for forecasts (Cane et al., 1986; Barnett et al., 1988) and has also become a widely used tool for the analyses of interactions between the ocean and atmosphere (see Neelin et al. (1998) for a review and an extensive list of references). The interactions give rise to a broad spectrum of natural modes of oscillation whose time-scales depend on oceanic rather than atmospheric processes because of a key difference between the ocean and atmosphere: whereas the atmosphere adjusts rapidly, within a week or two, to changes in sea-surface temperature, oceanic timescales are significantly longer. For example, because of its considerable inertia, the state of the ocean at any given time depends not only on the winds that prevail at that time, but also on earlier winds to which the ocean is still adjusting. Of particular importance are the processes that affect sea-surface temperature, which is practically the only oceanic parameter that influences the atmosphere on the time-scales of interest here. Those processes include advection by wind-driven ocean currents, vertical movements of the thermocline induced by the local winds, and vertical movements of the thermocline induced by waves that are excited by the winds in remote regions and that propagate along the thermocline.

Consider a confined region of anomalously warm surface waters, centered on the equator, that induces westerly winds to the west of that region, easterlies to the east. These winds drive currents that are eastward, and hence convergent, on the western side but westward and hence divergent on the eastern side. As a consequence, the thermocline deepend in the west, shoals in the east. There is an east-west asymmetry, however, because oceanic Kelvin waves excited on the western side propagate eastward and increase the depth of the thermocline there. If sea-surface temperatures depend mainly on thermocline depth, then the net result is an eastward migration of the warm anomaly; the coupled mode that is involved has eastward phase propagation. If sea-surface temperatures are relatively independent of thermocline depth but depend instead on advection by the currents generated by the winds, then the coupled mode propagates westward (if surface temperatures increase from east to west in the background state). An advective mode of this type is involved in the annual harmonic that is the dominant feature of the seasonal cycle in the eastern equatorial Pacific. The following properties of the annual signal are consistent with the presence of this mode: westward phase propagation, at a speed near 50 cm/sec, of the surface winds, and of the sea-surface temperature; and the absence of significant vertical movements of the thermocline (Li and Philander, 1996; Xie, 1994).

Modes that depend on vertical movements of the thermocline induced by propagating wave disturbances excited in remote regions were first studied by Schopf and Suarez (1988) and Battisti and Hirst (1989). The essence of these "delayed oscillator" modes is captured by the following equation:

$$F_t = aF(t) - bF(t - \tau)$$

Here F is a parameter such as sea-surface temperature in the eastern equatorial Pacific, t measures time, and a, b and τ are constants. The first term on the right-hand-side contributes to exponential growth (if a is positive) and represents positive feedbacks between the ocean and atmosphere. For example, unusually warm surface waters in the eastern equatorial Pacific induce westerly winds to the west and those winds amplify the warming in the east where the thermocline deepens steadily. Those winds also excite off-equatorial Rossby waves that propagate westward, and that reflect off the western coast as equatorial Kelvin waves that elevate the thermocline. In the west, where the thermocline is deep, this vertical movement of the thermocline has little effect on sea-surface temperatures. In the east where the thermocline is shallow, this elevation of the thermocline counters its initial tendency to deepen. The latter effect is represented by the second, delayed term in the equation above. It limits the growth associated with the first two terms and introduces oscillatory behavior (for certain values of "b"). The delay time τ, the travel time of the Rossby and Kelvin waves, determines the period of the oscillations in a complicated manner.

This interpretation of the Southern Oscillation in terms of a delayed oscillator is problematic. The difficulty is not with the identification of Rossby and Kelvin waves — there is abundant evidence of such waves in the ocean (McPhaden et al., 1998). The problem is with the role that isolated Kelvin waves are supposed to play. For an individual wave-front to be explicitly evident, as in Fig. 4 for example, changes in the winds have to be abrupt or have a short timescale. The Southern Oscillation, however, is a low frequency phenomenon distinct from the sudden wind bursts that can excite individual waves; it can be reproduced by models from which such bursts are entirely absent. Fig. 5 shows results from a model, that of Battisti and Hirst (1989), in which the Southern Oscillation corresponds to a delayed oscillator. So many waves are superimposed in the oceanic response to the gradually varying winds that individual waves can not be discerned. The plot of thermocline depth variations shows phase differences between the east and west but they do not correspond to a Kelvin wave. The key aspect of a delayed oscillator is the lag between the atmospheric forcing and the oceanic response, the "memory" of the ocean that is represented by the delay time τ in the equation. At any time, the ocean is responding not only to the winds at that time, but is still adjusting to earlier winds. That adjustment can affect future developments of the coupled system. Hence, during one phase of the Southern Oscillation, El Niño say, the seeds are being planted for the next phase, La Niña.

Different coupled ocean–atmosphere models, because their sea-surface temperature variations are controlled by different processes, capture different ocean–atmosphere modes. Hence El Niño, in the various simulations, develops in an eastward direction in some models, in a westward direction in others, and in a third group corresponds to a stationary mode. To which coupled mode does the observed southern oscillation correspond? Measurements suggest that it is a hybrid that has aspects of both the advective, and the delayed oscillator modes. The evolution in time is shown in Fig. 6 for the case of El Niño of 1982. The prominent feature is eastward propagation but neither the speed of propagation, nor the spatial structure corresponds to that of an oceanic, equatorial Kelvin wave. The reason is the overwhelming importance of the wind forcing; as the warm surface waters expanded eastward, so did the westerly wind anomalies. The eastward movement of warm surface waters is not only a consequence of vertical displacements of the thermocline, but also of advection by surface currents (Picaut et al., 1996). The mechanisms that determine sea-surface temperature probably vary from one El Niño episode to the next so that different El Niño episodes correspond to different coupled ocean–atmosphere modes. That is probably why some episodes start in the eastern Pacific and migrate westward, while others evolve in the opposite direction. Those that move eastward sometimes start doing so in the early months of the year, as in 1997, or in the middle of the year, as in 1982. Despite these differences, all episodes seem to have certain features in common: wind fluctuations have their largest amplitude in the central and western equatorial Pacific, sea-surface

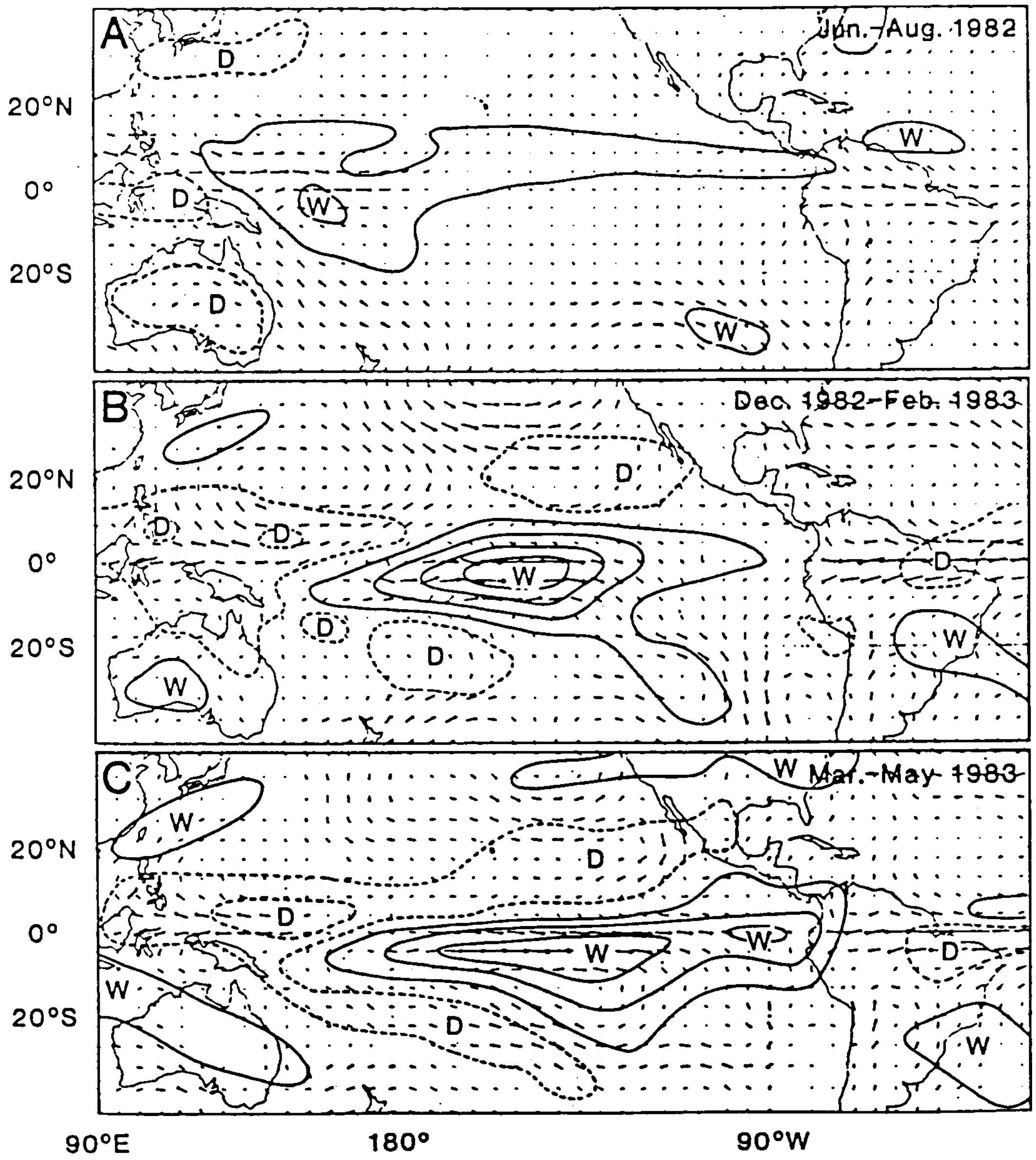


Fig. 6. In 1982, El Niño conditions first appeared to the west of the date line and gradually expanded eastward. The panels show how, along the equator, the easterly Trade winds collapsed and were replaced by westerly winds while the zone of heavy precipitation migrated eastward. The arrows indicate the anomalous winds (the departure from the expected winds); the contours are the regions of unusually high precipitation with D indicating dry, W wet (from Rasmusson and Wallace (1983)).

temperature variations theirs in the eastern equatorial Pacific, and thermocline displacements are centered on the equator in the east, but have two off-equatorial maxima in the west.

Each El Niño is distinct; each corresponds to a different hybrid coupled mode that has some aspects of the delayed oscillator mode, some aspects of the advective mode. Other modes, yet to be explored, could also be involved. One of the main results from TOGA is that El Niño involves not only an east-west redistribution of warm water because of changes in the zonal winds, but that north-south changes are also important (Wallace et al., 1998). The band of heavy rainfall that is the ITCZ, onto which the northeast and southeast trades converge, moves equatorward during El Niño. Presumably coupled modes that are antisymmetrical about the equator come into play (Chang and Philander, 1994). Another matter that requires further study is the relation between El Niño and the seasonal cycle which, close to the coast of South America has an amplitude larger than that of the interannual variability. On some occassions El Niño is phase locked to the seasonal cycle and starts as an amplification of that signal. Neelin et al. (1998), Tziperman et al. (1994) and Chang et al. (1994) have started to explore this matter.

The relation between westerly wind bursts that last for a week or two over the western equatorial Pacific, and El Niño, has recently been a matter of much discussion. To ask why the Southern Oscillation, between complementary El Niño and La Niña, occurs is equivalent to asking why a bell rings or a violin string vibrates; it is a natural mode of oscillation of the coupled ocean–atmosphere system. There is, however, a possibly important difference between a bell and the Southern Oscillation: for a bell to ring it needs to be struck. Is the Southern Oscillation self-sustaining? Or is it damped, so that disturbances such as westerly wind bursts are necessary to get it excited? These brief wind bursts have the capability to interact strongly with the much lower frequency Southern Oscillation, because their spatial structure is close to that of the winds that characterize the interannual Southern Oscillation.

The importance of random disturbances depends on the degree to which the coupled system is unstable. In Fig. 7a the system permits only damped oscillations; in (b) the oscillations are self-sustaining; in (c) the fluctuations are so energetic that secondary instabilities appear. Fig. 7c is not of relevance to the observed Southern Oscillation, in part because evaporation strongly limits the maximum temperature of the surface waters, and hence limits the amplitude of the southern oscillation. The damped oscillation of Fig. 7a is relevant to the Atlantic, an ocean that has intriguing similarities and differences with the Pacific. The prevailing winds in the tropical Atlantic are trades that drive the warm surface waters westward. The coastal zone of southwestern Africa, like that of Peru, is a barren desert adjacent to a cold ocean rich in marine life.

Occasionally, the equatorial Atlantic has a phenomenon very similar to El Niño in the Pacific: the trades relax, the warm surface waters surge eastward and bring rain to the otherwise arid coastal zone of southwestern Africa (Hisard, 1980; Merle, 1980). These events, and complementary La Niña episodes, are sporadic phenomena, with very limited predictability because their excitation depends on random wind fluctuations (Zebiak, 1993; Chang et al., 1997).

The main difference between the Atlantic and Pacific is in their zonal dimensions. Continental influences are much stronger in the Atlantic, so that its seasonal cycle is more dominant over interannual variability than is the case in the Pacific. The smaller dimensions of the Atlantic Ocean imply that its adjustment-time is shorter than that of the Pacific so that the time τ in the delayed oscillator equation is shorter. These differences translate into interannual modes that are less damped in the Pacific than Atlantic. How does that difference account for interannual variability without a distinctive timescale in the Atlantic, but with a timescale of four years approximately in the Pacific? There are two possible explanations. In a weakly damped system such as the Pacific (as opposed to the strongly damped Atlantic), continual excitation of a mode by random disturbances (noise) can cause the energy spectrum of the fluctuations to have a peak at a period that corresponds to that of the dominant mode. In that case the predictability of the Southern Oscillation is very limited because its irregularity depends on random disturbances. An alternative explanation for the spectral peak assumes that the coupled system is so unstable — the appropriate range of parameters is between those of Figs. 7b,c — that it is self-sustaining and is irregular because of weak nonlinearities (low order chaos). In the latter case, El Niño and La Niña are the complementary phases of a continual, irregular oscillation and have relatively high predictability.

In an attempt to decide between these two explanations for the peak in the energy spectrum of the Southern Oscillation, Chang et al. (1996) analysed available time-series. They determined that in the case of the various models that repro-

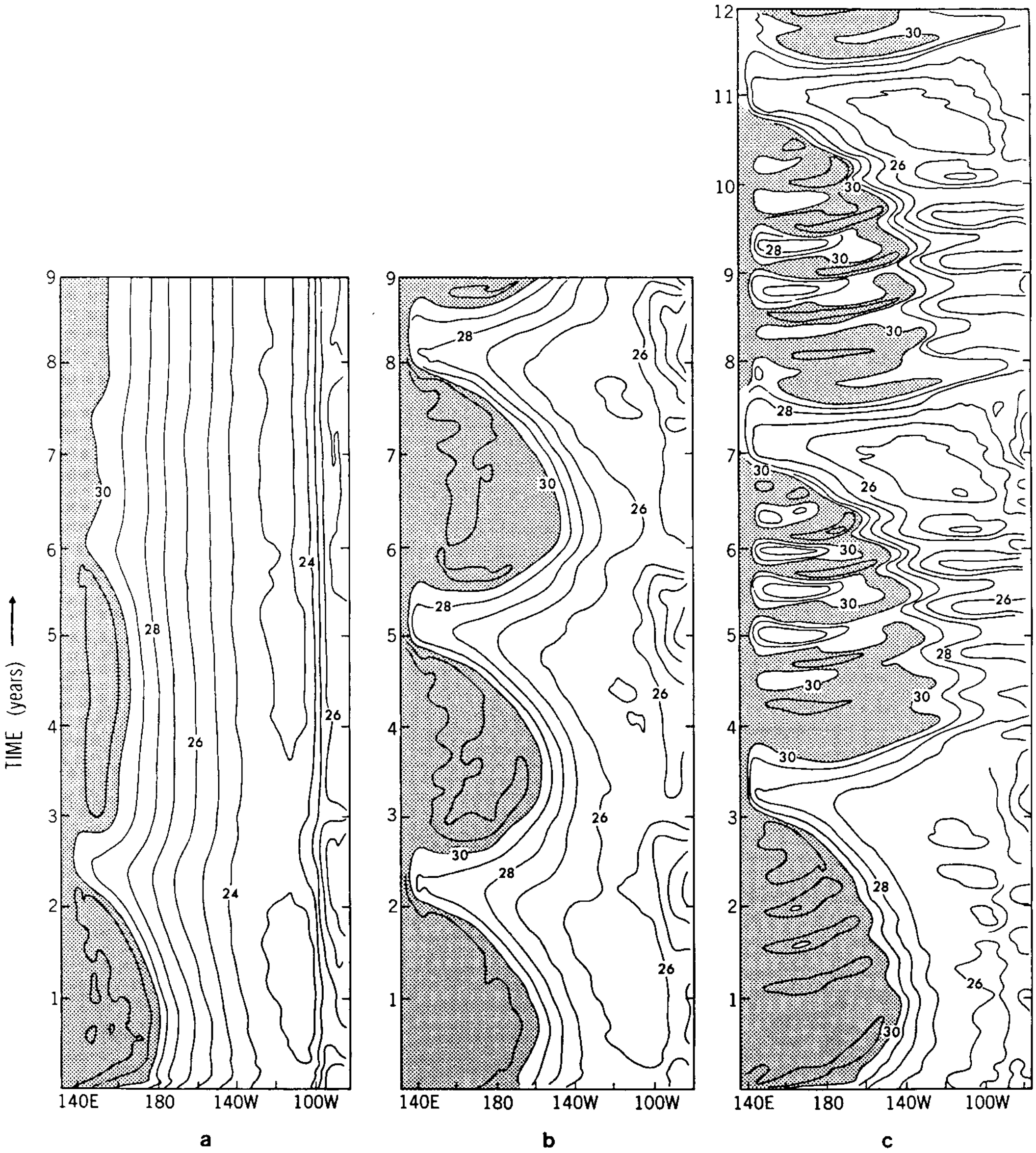


Fig. 7. The evolution of sea-surface temperature (°C) along the equator in the coupled ocean–atmosphere model of Neelin (1989). The intensity of the coupling between the ocean and atmosphere increases from (a) to (b) to (c). Regions warmer than 30°C are shaded.

duce a Southern Oscillation, some require random disturbances for a continual oscillation, some do not. In the case of the observed phenomenon; Chang et al. (1996) concluded that the available records are too short to determine whether or not the Southern Oscillation is self-sustaining. An alternative interpretation is that the time-series are nonstationary; the Southern Oscillation could be damped during some periods, self-sustaining during others. This possibility offers a plausible explanation for an apparent change that seemed to have occurred from the 1980s to the 1990s.

Certain coupled ocean–atmosphere models successfully predicted El Niño of 1987 (Barnett et al., 1988) and also that of 1992, but then started having difficulties. They failed to anticipate the persistence of warm conditions following El Niño of 1992, and had mixed success, at best, with forecasting El Niño of 1997. A possible reason for these problems is the specification of the time-averaged state on the basis of measurements over a certain relatively short period. A change in those conditions affects the character of the simulated southern oscillation. For example, Zebiak and Cane (1987) find that, in their model, the amplitude of El Niño decreases sharply as the depth of the specified thermocline is increased from 75 m to 100 m to 125 m. Could it be that a change of this type occurred from the 1980s to the 1990s so that the Southern Oscillation changed from being self-sustaining and hence highly predictable during the 1980s, to being damped and more dependent on excitation by random disturbances during the 1990s? The answer to this question requires further analyses of data. In the meanwhile it is of considerable interest that the records do provide evidence for a decadal modulation of El Niño. For example, the correlation between sea level pressure variations at Darwin and Honolulu, a measure of the southern oscillation, is 0.66 for the period 1880 to 1920 of energetic El Niño episodes, then falls to 0.12 for the period 1920 to 1950 of almost no El Niño events (Trenberth and Shea, 1987) during which the trades were relaxed, and the zonal temperature gradient along the equator was reduced (Gu and Philander, 1995). In an analysis of more recent data, Zhang et al. (1997) find that the equatorial Pacific was warmer during the period 1977 to 1993 than during the period 1950 to 1976. The structure of the warm anomalies is similar to that of El Niño except for being less equatorially confined, especially in the east.

Whereas the tropics can be studied in isolation from the rest of the ocean if the focus is on interannual variability, decadal fluctuations involve interactions between the tropics and extratropics. Of particular interest is the shallow, wind-driven meridional circulation in which surface waters subduct off the coasts of California and Peru, flow adiabatically to the equator, well up into the surface layers and return to the subtropics in the Ekman layer. That circulation maintains the sharp, shallow tropical thermocline, whose depth determines how energetic the southern oscillation is. A change in extratropical conditions, such as a decrease in surface temperatures, can alter the depth of the equatorial thermocline, and change sea-surface temperatures, whereafter interactions between the tropical ocean and atmosphere come into play (Liu et al., 1994; McCreary and Lu, 1994). There are also low frequency atmospheric links between the tropics and extratopics. For example, the intensity of the trades in low latitudes is related to the intensity of westerlies in midlatitudes, and a change in one band of latitudes affects the other. Dijkstra and Neelin (1995) have explored how tropical ocean–atmosphere interactions can amplify a change in the trades induced from the extratropics. These results may be relevant to the decadal modulation of El Niño mentioned in the previous paragraph (Gu and Philander, 1997).

For coupled general circulation models of the ocean and atmosphere to reproduce the climatology, the Southern Oscillation, and the seasonal cycle, they have to capture a variety of coupled modes. The seasonal cycle depends on an advective type mode, interannual variability on the delayed oscillator type mode, and climatological features such as the warmest surface waters and the ITCZ mostly in the northern hemisphere, depend on antisymmetrical ocean–atmosphere modes that can convert the symmetrical response to the incident, symmetrical solar radiation, into an asymmetrical response (Chang and Philander, 1994; Philander et al., 1996). Several of the coupled general circulation models have trouble reproducing this climatic asymmetry; sea-surface temperatures are unrealistically high off the coast of Peru where low stratus clouds keep the surface waters of the ocean cold. The positive feedback in which the cold waters promote more clouds, which in turn favor colder water, proves difficult to reproduce accurately (Mechoso et al., 1995). Because of this, and other problematic feedbacks, some models suffer from climate-drift, the tendency for the models to favor a climate state different from the observed one. In spite of these difficulties, the models seem to have some skill in forecasting changes in the spatially averaged temperature of a region to the west of the Galapagos Islands, if not the correct spatial patterns for the sea-surface temperature. The rate at which these models are improving is such that some are already being used in attempts to predict seasonal and interannual variability.

5. Conclusions

El Niño of 1997 received enormous publicity, mostly because, for the first time, the public could be alerted well in advance that a major event was imminent. The basis for this alert was mainly the measurements from the array in Fig. 1. Once it was evident that El Niño would occur, statistics of past events could then be used to anticipate how different regions would be affected. For example, California could be warned of a likely increase in the number of severe storms because approximately one in three El Niño episodes brings such storms to that state. The statistics also indicate that India should experience poor monsoons during El Niño, while Zimbabwe (in southeastern Africa) should have rainfall that is below average. These forecasts were partially correct for 1997–1998: California had unusually heavy rains, but precipitation was normal over India and Zimbabwe. The statistics have a physical basis and, in principle, it should be possible to improve the forecasts by exploiting the physical law that govern atmospheric and oceanic motion. The models that do so should predict, not merely that El Niño will occur, but how it will evolve, how sea-surface temperature patterns, rainfall and other fields will develop over a period of several months, and affect regions far from the tropical Pacific. Enormous strides have been made towards the goal of providing such forecasts routinely: measurements are available from the array in Fig. 1 to initialize the oceanic models; coupled general circulation models have been developed and already can reproduce realistically many aspects of the earth's climate and its seasonal and interannual fluctuations (Latif et al., 1993). These achievements crown the studies, over the past few decades, that describe, explain and simulate the atmospheric response to sea-surface variations, the oceanic response to different types of wind fluctuations, and the broad spectrum of coupled ocean–atmosphere modes that result from interactions between the two media. Those modes, which can be divided into groups whose properties depend on the processes that determine sea-surface temperature variations, can be associated with eastward, westward or no zonal phase propagation depending on the degree to which sea-surface temperatures are influenced by advection, on locally, or on non-locally induced movements of the thermocline. Different models capture one or another of these modes and hence reproduce southern oscillations with somewhat different properties. In reality, El Niño corresponds to a hybrid mode with some aspects of the delayed oscillator mode, some aspects of the advective mode. It can evolve in a variety of ways because, from one episode to the next, different processes have the dominant effect on sea-surface temperature.

To ask why El Niño occurs is equivalent to asking why a bell rings or a pendulum swings; it is a natural mode of oscillation. A bell, of course, needs to be struck in order to ring. Is the Southern Osillation damped (like a bell) or is it self-sustaining? It appears that the phenomenon is subject to decadal modulations that cause it to be self-sustaining during certain periods, damped during other periods when random disturbances (such a westerly wind bursts) are needed to excite it. To investigate this matter, scientists have started to explore the interactions between the tropics and extratropics. Those interactions influence factors, the intensity of the trades, and the mean depth of the thermocline for example, that affect the properties of El Niño. Results from these studies should enable us to anticipate how global warming — which is inevitable if the atmospheric concentration of greenhouse gases continues to rise at the present rate — will affect El Niño. It is wise to keep in mind, however, that El Niño has repeatedly surprised us in the past. As long as we maintain the array in Fig. 1, we can anticipate developments over the next several months with considerable confidence. How El Niño will behave over the next decade and longer is another matter altogether.

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REFERENCES

Excellent, and more detailed reviews of the topics discussed here, each with an extensive list of references, can be found in the *Journal of Geophysical Research* vol. **103**, 1998.

Anderson, D. L. T. and Gill, A. E. 1975. Spin up of a stratified ocean with applications to upwelling. *Deep-Sea Res.* **22**, 583–596.

Barnett, T. P ., Graham, N. E., Cane, M. A., Zebiak, S. E., Dolan, S. C., O'Brien, J. J. and Legler, D. M. 1988. On the prediction of the El Niño of 1986–1987. *Science* **241**, 192–196.

Battisti, D. S. and Hirst, A. C. 1989. Interannual variability in a tropical atmosphere–ocean model. Influence of the basic state, ocean geometry and non-linearity. *J. Atmos. Sci.* **46**, 1687–1712.

Bengtson, L. 1999. From short range barotropic modelling to extend range global weather prediction — a 40-year perspective. *Tellus* **51A/B**, this issue.

Bjerknes, J. 1966. A possible response of the atmospheric Hadley circulation to anomalies of ocean temperature. *Tellus* **18**, 820–828.

Bjerknes, J. 1969. Atmospheric teleconnections from the equatorial Pacific. *Mon. Weather Rev.* **97**, 163–172.

Bryan, K. 1969. A numerical method for the study of the world ocean. *J. Comp. Phys.* **4**, 347–376.

Cane, M. A. 1979. The response of an equatorial ocean to simple wind stress patterns (I). Model formulation and analytic results. *J. Marine Res.* **37**, 233–252.

Cane, M. A. and Sarachik, E. S. 1977. Forced baroclinic ocean motions. II. The linear equatorial bounded case. *J. Mar. Res.* **35**, 395–432.

Cane, M. A. and Zebiak, S. E. 1985. A theory for El Niño and the Southern Oscillation. *Science* **228**, 1085–1087.

Cane, M. A., Zebiak, S. E. and Dolan, S. C. 1986. Experimental forecasts of El Niño. *Nature* **321**, 827–832.

Chang, P., Wang, B., Li, T. and Ji, L. 1994. Interactions between the seasonal cycle and ENSO-Frequency, entrainment, and chaos in a coupled atmosphere–ocean model. *Geophys. Res. Lett.* **21**, 2817–2820.

Chang P. and Philander, S. G. 1994. A coupled ocean–atmosphere instability of relevance to the seasonal cycle. *J. Atm. Res.* **51**, 3627–3648.

Chang, P, Ji, L., Li, H. and Flügel, M. 1996. Chaotic dynamics versus stochastic processes in El Niño–Southern Oscillation in coupled ocean–atmosphere models. *Physica D* **98**, 301–320.

Chang, P, Ji, L. and Li, H. 1997. A decadal climate variation in the tropical Atlantic Ocean from thermodynamic air–sea interactions. *Nature* **385**, 516–518.

Cole, J. E. and Fairbanks, R. E. 1990. The Southern Oscillation recorded in the O of corals from Tarawa atoll. *Paleoceanography* **5**, 669–683.

Dijkstra, H. A. and Neelin, J. D. 1995. Ocean–atmosphere interaction and the tropical climatology, Part II: Why the Pacific cold tongue is in the east. *J. Climate* **8**, 1343–1359.

Gill, A. E. 1980. Some simple solutions for heat-induced tropical circulation. *Quart. J. Roy. Meteorol. Soc.* **106**, 447–462.

Gu, D. and Philander, S. G. H. 1995. Secular changes of annual and interannual variabiliby in the tropics during the past century. *J. Climate* **8**, 864–876.

Gu, D. and Philander, S. G. H. 1997. Interdecadal climate fluctuations that depend on exchanges between the tropics and extratropics. *Science* **27**, 805–807.

Halpern, D., Hayes, S. P., Leetmaa, A., Hansen, D. and Philander, S. G. H. 1983. Oceanographic observations of the 1982 warming of the tropical eastern Pacific. *Science* **221**, 1173–1175.

Halpern, D. 1987. Observations of annual and El Niño thermal and flow variations along the equator at 0°, 110°W and 0°, 95°W during 1980–1985. *J. Geophys. Res.* **92**, 8197–8212.

Hayes, S. P., Mangum, L. J. Picaut, J., Sumi, A. and Takeuchi, K. 1991. TOGA-TAO: A moored array for real-time measurements in the tropical Pacific Ocean. *Bull. Am. Meteorol. Soc.* **72**, 339–347.

Hisard, P. 1980. Observation de reponses de type "El Nino" dans l'Atlantique tropical oriental Golfe de Guinee. *Oceanol. Acta* **3**, 69–78.

Hoskins, B. J. and Karoly, D. 1981. The steady linear response of a spherical atmosphere to thermal and orographic forcing. *J. Atmos. Sci.* **38**, 1179–1196.

Hoskins, B. J., Neale, R., Rodwell, M. and Yang, G.-Y. 1999. Aspects of the large-scale tropical atmospheric circulation. *Tellus* **51A/B**, this issue.

Hurlburt, H. J., Kindle, J. and O'Brien, J. J. 1976. A numerical simulation of the onset of El Niño. *J. Phys. Oceanogr.* **6**, 621–631.

Ji, M., Kumar, A. and Leetmaa, A. 1994a. A multi-season climate forecast system at the National Meteorological Center. *Bull. Am. Meteorol. Soc.* **75**, 569–577.

Ji, M., Kumar, A. and Leetmaa, A. 1994b. An experimental coupled forecast system at the National Meteorological Center: Some early results. *Tellus* **46A**, 398–418.

Katz, E. J. et al. 1977. Zonal pressure gradient along the equatorial Atlantic. *J. Mar. Res.* **35**, 293–307.

Knox, R. A. 1974. Reconnaissance of the Indian Ocean equatorial undercurrent near Addu Atoll. *Deep-Sea Res.* **21**, 123–129.

Latif, M., Sterl, A., Maier-Reimer, E. and Junge, M. M. 1993. Climate variability in a coupled GCM. Part I. The tropical Pacific. *J. Climate* **6**, 5–21.

Lau, N.-C. 1985. Modelling the seasonal dependence of the atmospheric response to observed El Niños in 1962–76. *Mon. Wea. Rev.* **113**, 1970–1996.

Leetmaa, A. 1972. The response of the Somali Current to the southwest monsoon of 1970. *Deep-Sea Res.* **19**, 319–325.

Leetmaa, A. and Ji, M. 1989. Operational hindcasting of the tropical Pacific. *Dyn. Atmos. Ocean* **13**, 465–490.

Legeckis, R. 1986. A satellite time series of sea surface temperatures in the eastern equatorial Pacific Ocean, 1982–1986. JGR. *J. Geophys. Res.* **91**, 12,879–12,886.

Li, T. and Philander, S. G. H. 1996. On the annual cycle of the eastern equatorial Pacific. *J. Climate* **9**, 2986–2998.

Lighthill, M. J. 1969. Dynamic response to the Indian Ocean to the onset of the Southwest Monsoon. *Philos. Trans. R. Soc. London, Ser. A.* **265**, 45–93.

Lindzen, R. S. and Nigam, S. 1987. On the role of sea surface temperature gradients in forcing low-level winds and convergence in the tropics. *J. Atmos. Sci.* **44**, 2418–2436.

Liu, Z. and Philander, S. G. H. 1994. A GCM Study of Tropical–Subtropical upper-ocean water exchange. *J. Phys. Oceanogr.* **24**, 2606–2623.

Matsuno, T. 1966. Quasi-geostrophic motions in the equatorial area. *J. Met. Soc. Japan* **44**, 25–42.

McCreary, J. P. 1976. Eastern tropical ocean response to changing wind systems with application to El Niño. *J. Phys. Oceanogr.* **6**, 632–645.

McCreary, J. P. and Lu, P. 1994. On the interaction between the subtropical and equatorial ocean circulations: The subtropical cell. *J. Phys. Oceanogr.* **24**, 466–497.

McPhaden M. J., Busalacchi, A. J., Cheney, R., Donguy, J., Gage, K. S., Halpern, D., Ji, M., Julian, P., Meyers, G., Mitchum, G. T., Niiler, P. P., Picaut, J., Reynolds, R. W., Smith, N. and Takeuchi, K. 1998. The tropical ocean–global atmosphere observing system: a decade of progress. *J. Geophys. Res.* **103**, C7, 14,167–14,168.

Mechoso, C. R., Robertson, A. W., Barth, N., Davey, M. K., Delecluse, P., Gent, P. R., Ineson, S., Kirtman, B., Latif, M., Le Treut, H., Nagai, T., Neelin, J. D., Philander, S. G. H., Polcher, J., Schopf, P. S., Stockdale, T., Suarez, M. J., Terray, L. Thual, O. and Tribbia, J. J. 1995. The seasonal cycle over the tropical Pacific in coupled atmospheric–ocean general-circulation models. *Mon. Wea. Rev.* **123**, 2825–2838.

Merle J. 1980. Variabilite thermique annuelle et interannuelle de l'ocean Atlantique equatorial est. L'hypothe se d'un "El Niño" Atlantique. *Oceanol. Acta* **3**, 209–220.

Moore, D. W. 1968. *Planetary-gravity waves in an equatorial ocean.* Ph.D. thesis, Harvard University, Cambridge, Mass., 207 pp.

Murphy, R. C. 1926. Oceanic and climatic phenomena along the west coast of South America during 1925. *Geogr. Rev.* **16**, 26–54.

Neelin, J. D. 1989a. On the interpretation of the Gill model. *J. Atmos. Sci.* **46**, 2466–2468.

Neelin, J. D. 1989b. Interannual oscillations in an ocean general circulation model coupled to a simple atmosphere model. *Phil. Trans. Roy. Soc. Lond. A* **329**, 189–205.

Neelin, J. D. 1991. The slow sea surface temperature mode and the fast-wave limit: analytic theory for tropical interannual oscillations and experiments in a hybrid coupled model. *J. Atmos. Sci.* **48**, 584–606.

Neelin J. D., Battisti, D., Hirst, A., Jin, F.-F., Wakata, Y., Yamagata, T. and Zebiak, S. 1998. ENSO Theory. *J. Geophys. Res.* **103**, C7, 14,261–14,290.

Philander, S. G. H. 1990. *El Niño, La Niña and the southern oscillation.* Academic Press, NY, 289 pp.

Philander, S. G. H. 1998. *Is the temperature rising? The uncertain science of global warming.* Princeton University Press, 262 pp.

Philander, S. G. H. and Pacanowski, R. C. 1980. The generation of equatorial currents. *J. Geophys. Res.* **85**, 1123–1136.

Philander, S. G. H. and Siegel, A. D. 1985. Simulation of El Niño of 1982–1983. In: *Coupled ocean–atmosphere models* (ed. Nihoul, J.). Elsevier, Amsterdam, 517–541.

Philander, S. G. H., Halpern, D., Hansen, D., Legeckis, R., Miller, L., Paul, C., Watts, R., Weisberg, R. and Wimbush, M. 1985. Long waves in the equatorial pacific Ocean. EOS. *Trans. Am. Geophys. Union* **66**, 154.

Philander, S. G. H., Gu, D., Lambert, G., Lau, N.-C., Li, T. and Pacanowski, R. C. 1996. Why the ITCZ is mostly north of the equator. *J. Climate* **9**, 2958–2972.

Picaut, J., Ioualalen, M., Menkes, C., Delcroix, T. and McPhaden, M. J. 1996. Mechanisms of the zonal displacement of the Pacific warm pool. *Science* **274**, 1486–1489.

Rasmusson, E. M. and Carpenter, T. 1982. Variations in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Niño. *Mon. Wea. Rev.* **110**, 354–384.

Rasmusson, E. M. and Wallace, J. M. 1983. Meteorological aspects of El Niño/Southern Oscillation. *Science* **222**, 1195–1202.

Ripa, P. and Hayes, S. 1981. Evidence for equatorially trapped waves at the Galápagos Islands. *J. Geophys. Res.* **86**, 6509–6516.

Schopf, P. S. and Suarez, M. J. 1988. Vacillations in a coupled ocean–atmosphere model. *J. Atmos. Sci.* **45**, 549–566.

SCOR, 1983. Scientific Committee for Ocean Research of the International Oceanic Commission, United Nations Educational, Scientific and Cultural Organization, Working Group 55. *Prediction of El Niño.*

Shukla, H. and Charney, J. G. 1981. Predictability of the monsoons. In: *Monsoon Dynamics* (eds. Lighthill, J. and Pierce, R.). Cambridge Univ. Press., 99–110.

Suarez, M. J. and Schopf, P. S. 1988. A delayed action oscillator for ENSO. *J. Atmos. Sci.* **45**, 3283–3287.

Trenbert, K. E. 1998. The definition of El Niño. *Bull. Amer. Meteorol. Soc.* **78**, 2771–2777.

Trenberth, K. E. and Shea, D. J. 1987. On the evolution of the Southern Oscillation. *Mon. Wea. Rev.* 115, 3078–3096.

Tziperman, E., Stone, L., Cane, M. and Jarosh, H. 1994. El Niño chaos: Over-lapping of resonances between the seasonal cycle and the Pacific ocean–atmosphere oscillator. *Science* **264**, 72–74.

Veronis, G. and Stommel, H. 1956. The action of variable wind-stresses on a straified ocean. *J. Mar. Res.* **15**, 43–69.

Walker, G. T. and Bliss, E. W. 1930. World Weather IV. *Mem. R. Meteorol. Soc.* **3**, 81–95.

Wallace, J. M. and Gutzler, D. S. 1981. Teleconnections in the geopotential height field during the northern hemisphere winter. *Mon. Wea. Rev.* **109**, 784–812.

Wallace, J. M., Rasmusson, E. M., Mitchell, T. P., Kousky, V. E., Sarachik, E. S. and von Storch, H. 1998. On the structure and evolution of ENSO-related climate variability in the tropical Pacific: lessons from TOGA. *J. Geophys. Res.* **103**, C7, 14,241–14,259.

Wunsch, C. and Gill, A. E. 1976. Observations of equatorially trapped waves in Pacific sea level variations. *Deep-Sea Res.* **23**, 371–390.

Wyrtki, K. 1973. An equatorial jet in the Indian Ocean. *Science* **181**, 262–264.

Wyrtki, K. 1975. El Niño — The dynamic response of the equatorial Pacific Ocean to atmospheric forcing. *J. Phys. Oceanogr.* **5**, 572–584.

Xie, S. P. 1994. On the genesis of the equatorial annual cycle. *J. Climate* **7**, 2008–2013.

Zebiak, S. E. 1986. Atmospheric convergence feedback in a simple model for El Niño. *Mon. Wea. Rev.* **114**, 1263–1271.

Zebiak, S. E. and Cane, M. A. 1987. A model El Niño/southern oscillation. *Mon. Wea. Rev.* **115**, 2262–2278.

Zebiak, S. E. 1993. Air–sea interaction in the equatorial Atlantic region. *J. Climate* **6**, 1567–1586.

Zhang, Y., Wallace, J. M. and Battisti, D. S. 1997. ENSO-like interdecadal variability: 1900–93. *J. Climate* **10**, 1003–1020.