scale vagaries in weather that are not predictable. Vulnerability of individuals will also vary according to the diversity of the operation: whether there is irrigation available, whether the farmer has insurance, and whether he or she can work off the farm to help out in times of adversity.

See also

Carbon Dioxide (CO_2) Cycle. El Niño Southern Oscillation (ENSO) Models. Evaporation and Humidity. Fisheries and Climate. Heat Transport and Climate. Ocean Circulation. Pacific Ocean Equatorial Currents.

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EL NIÑO SOUTHERN OSCILLATION (ENSO) MODELS

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Introduction

The signature of El Niño is the interannual appearance of unusually warm surface waters in the eastern tropical Pacific Ocean. That area is so vast that the effect on the atmosphere is profound. Rainfall patterns are altered throughout the tropics – some regions experience floods, others droughts – and even weather patterns outside the tropics are affected significantly. From an atmospheric perspective, these various phenomena are attributable to the change in the sea surface temperature pattern of the tropical Pacific. Why does the pattern change? Whereas sea surface temperatures depend mainly on the incident solar radiation over most of the globe, the tropics are different. There the winds are of primary importance because of the shallowness of the thermocline, the thin layer of large temperature gradients, at a depth of approximately 100 m, that separates warm surface waters from the cold water at depth. The winds, by causing variations in the depth of the thermocline, literally bring the deep, cold water to the surface in regions where the thermocline shoals. For example, the trade winds that drive warm surface waters westward along the equator expose cold, deep water to the surface in the eastern equatorial Pacific. A relaxation of the winds, such as occurs during El Niño, permits the warm water to flow back eastward. The changes in the winds are part of the atmospheric response to the altered sea surface temperatures. This circular argument – the winds are both the cause and consequence of sea surface temperature changes – suggests that interactions between the ocean and atmosphere are at the heart of the matter. Those interactions give rise to a broad spectrum of natural modes of oscillation. This result has several important implications. One is that El Niño, even though we tend to regard him as an isolated phenomenon that visits sporadically, is part of a continual fluctuation, known as the Southern Oscillation. El Niño corresponds to one phase of this oscillation, the phase during which sea surface temperatures in the eastern tropical Pacific are unusually high. La Niña is the name for the complementary phase, when temperatures are below normal. (Very seldom are temperatures 'normal', as is evident in **Figure 1**.) To ask why El Niño, or La Niña, occur, is equivalent to asking why a pendulum spontaneously swings back and forth. Far more interesting questions concern the factors that determine the period and other properties of the oscillation, and the degree to which it is self-sustaining or damped. Only strongly damped oscillations, that disappear at times, require

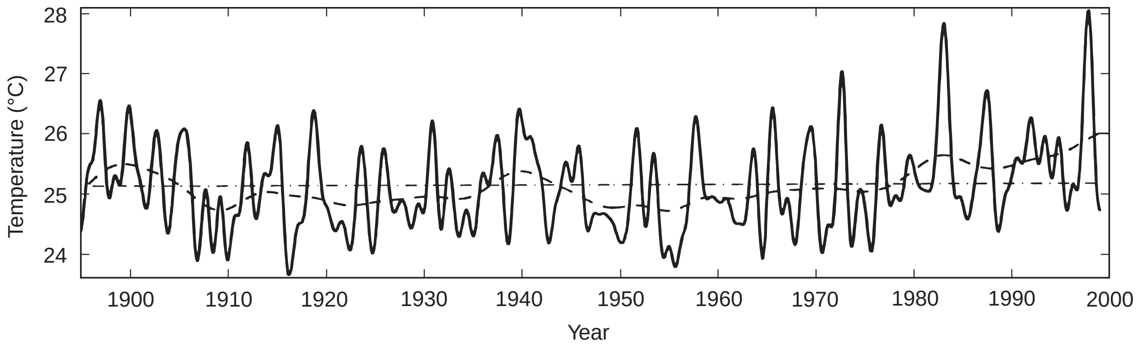

Figure 1 Surface temperature fluctuations at the equator (in °C) in the eastern equatorial Pacific (after removal of the seasonal cycle) over the past 100 years. Temperature maxima correspond to El Niño, minima to La Niña. The smoothly varying dashed line is a 10-year running mean.

a trigger to get going again. Hence a search for the disturbance that triggered a particular El Niño is based on an implicit assumption, which may not be correct at all times, that the Southern Oscillation was damped and had disappeared for a while.

The tools for predicting El Niño are coupled models of the ocean and atmosphere; each provides boundary conditions for the other, sea surface temperatures in the one case, the winds in the other case. The following discussion concerns first atmospheric then oceanic models, and finally coupled models.

The Atmosphere

The atmospheric circulation in low latitudes corresponds mainly to direct thermal circulations driven by convection over the regions with the highest surface temperatures. Moisture-bearing trade winds converge onto these regions where the air rises in cumulus towers that provide plentiful rainfall locally. The three main convective zones – they can easily be identified in satellite photographs of the Earth's cloud cover – are over the Congo and Amazon River basins, and the 'maritime continent' of the western equatorial Pacific, south-eastern Asia, and northern Australia. The latter region includes an enormous pool of very warm water that extends to the vicinity of the dateline. Much of the air that rises there subsides over the relatively cold eastern equatorial Pacific where rainfall is minimal; the deserts along the coasts of Peru and California in effect extend far westward over the adjacent ocean. The only region of warm surface waters and heavy rainfall in the eastern tropical Pacific is the doldrums, also known as the Intertropical Convergence Zone, a narrow band between 3° and 10°N approximately, onto which the south-east and north-east trade winds converge.

A warming of the eastern tropical Pacific, such as occurs during El Niño, amounts to an eastward expansion of the pool of warm waters over the western Pacific and causes an eastward migration of the convective zone, thus bringing rains to the east, droughts to the west. The east–west Intertropical Convergence Zone, simultaneously moves equatorward. During La Niña, a westward contraction of the warm waters shifts the convection zone back westward and intensifies the trades. The Southern Oscillation is this interannual back-and-forth movement of air masses across the tropical Pacific. **Figure 2** depicts its complementary El Niño and La Niña states.

A hierarchy of models is available to simulate the atmospheric response to changes in tropical sea surface temperature patterns. The most realistic, the general circulation models used for weather prediction, attempt to incorporate all the important physical processes that determine the atmospheric circulation. Simpler models isolate a few specific processes and, by elucidating their roles, provide physical insight. Particularly useful for capturing the essence of the Southern Oscillation – the departure from the time-averaged state – is a model that treats the atmosphere as a one-layer fluid on a rotating sphere. Motion is driven either by a heat source over the region of unusually high surface temperatures (the moisture carried by the winds that converge onto the source can amplify the magnitude of the heat source), or is driven by sea surface temperature gradients that give rise to pressure gradients in the lower layer of the atmosphere. Such models are widely used as the atmospheric components of relatively simple coupled ocean–atmosphere models.

The complex general circulation models reproduce practically all aspects of the interannual Southern Oscillation over several decades if, in the

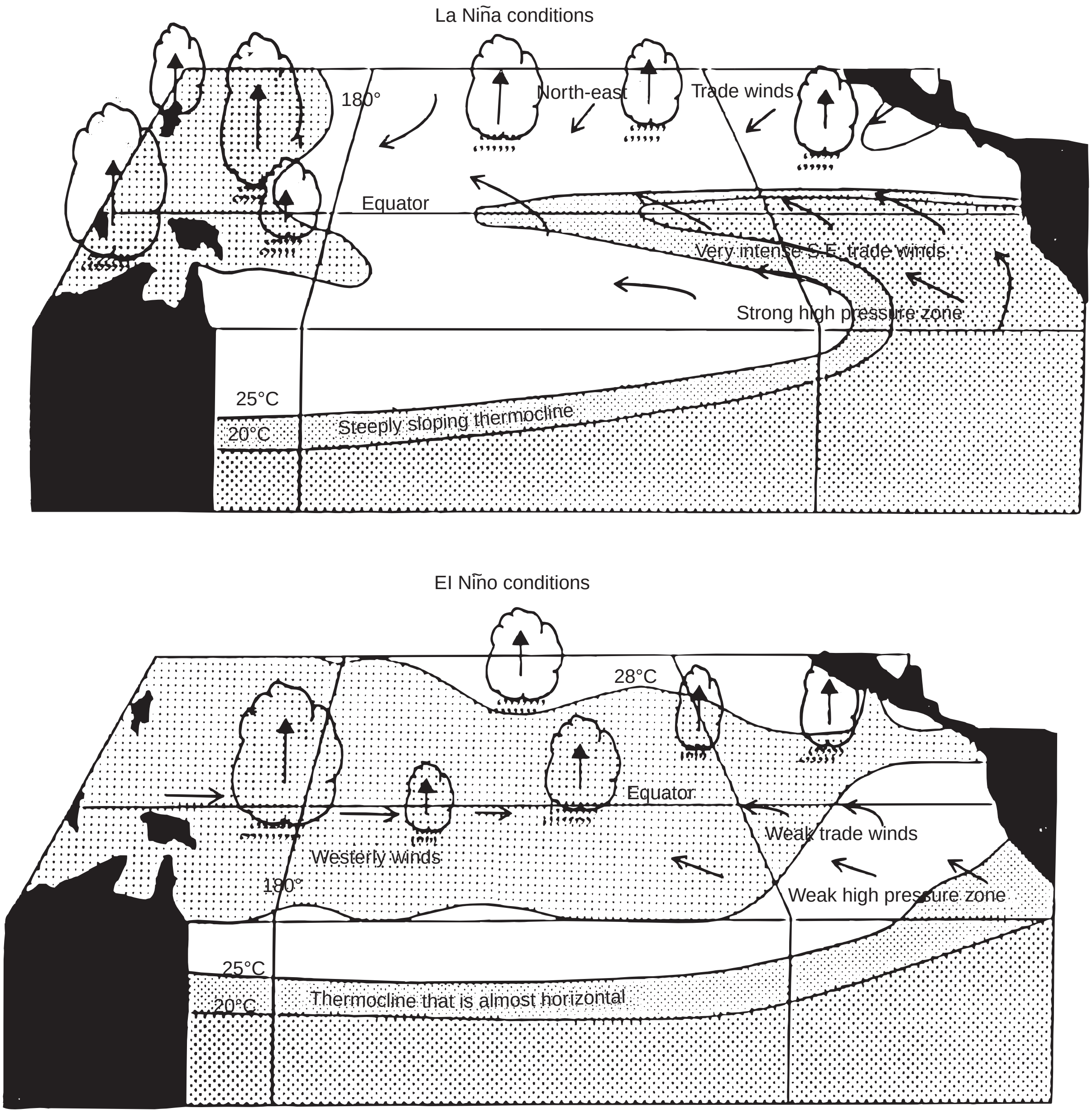

Figure 2 A schematic view of La Niña (top) and El Niño (bottom) conditions. During La Niña, intense trade winds cause the thermocline to have a pronounced slope, down to the west, so that the equatorial Pacific is cold in the east, warm in the west where moist air rises into cumulus towers. The air subsides in the east, a region of little rainfall, except in the doldrums where the south-east and north-east 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 surface temperatures is associated with an eastward shift of the region of heavy precipitation.

simulations, the observed sea surface temperature patterns are specified. The models fail to do so if the temperature patterns are allowed only seasonal, not interannual variability. 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. The key difference between weather and climate is that the first is an initial value problem – a forecast of the weather tomorrow requires an accurate description of the atmosphere – whereas climate (from an atmospheric perspective) is a boundary value problem; a change in climate can be induced by altering conditions at the lower boundary of the atmosphere. The crucial conditions are sea surface temperatures in the case of El Niño.

The Oceans

The salient feature of the thermal structure of the tropical oceans is the thermocline, the thin layer of large vertical temperature gradients at a depth of approximately 100 m, that separates warm surface waters from colder water at depth. Sea surface temperature patterns in the tropics tend to reflect variations in the depth of the thermocline and those variations are controlled by the winds. Thus the surface waters are cold where the thermocline is shallow, in the eastern equatorial Pacific for example, and are warm where the thermocline is deep, in the western tropical Pacific. The downward slope of the thermocline, from east to west in the equatorial Pacific, is a consequence of the westward trade winds that, along the equator where the Coriolis force vanishes, drive the surface waters westward. When those winds relax, during El Niño, the warm surface waters in the west return to the east so that the thermocline there deepens and sea surface temperatures rise. To a first approximation, the change from La Niña to El Niño amounts to a horizontal (east–west), adiabatic redistribution of warm surface waters, and is the dynamical response of the ocean to the changes in the winds.

Theoretical studies of the oceanic response to changes in the wind started with studies of the generation of the Gulf Stream. How long, after the sudden onset of the winds, before a Gulf Stream appears and the ocean reaches a state of equilibrium? The answer to this question provides an estimate of the 'memory', or adjustment-time of the ocean, a timescale that turns out to be relevant to the timescale of the Southern Oscillation. In an unbounded ocean, a Gulf Stream is impossible, so that the generation of such a current depends on the time it takes for information concerning the presence of coasts to propagate east–west across the ocean basin. The speed of the oceanic waves that carry this information, known as Rossby waves, increases with decreasing latitude. It should take on the order of a decade to generate the Gulf Stream from a state of rest, a matter of months to generate the same current near the equator. Fortuitously, the three tropical oceans have similarities and differences that provide a wealth of information about the oceanic response to different wind stress patterns. To explain and simulate tropical phenomena, oceanographers developed a hierarchy of models of which the simplest is the shallow-water model whose free surface is a good analog of the very sharp, shallow tropical thermocline. Studies with that tool showed how a change in the winds over one part of an ocean basin (e.g. the western equatorial Pacific), can influence oceanic conditions in a different and remote part of the basin (e.g. off the coast of Peru). Thus a warming of the surface waters along the coast of Peru during El Niño could be a consequence of a change in the winds over the western equatorial Pacific. The roles of waves and currents in effecting such changes depend on the manner in which the winds vary. If the winds change abruptly, then waves are explicitly present, but if the winds vary slowly, with a timescale that is long compared with the adjustment time of the ocean, then the waves are strictly implicit because the response is an equilibrium one. A detailed description of the response of the Pacific to slowly varying winds first became available for El Niño of 1982 and provided a stringent test for sophisticated general circulation models of the ocean. The success of such models in simulating the measurements bolstered confidence in the models which are capable of reproducing, deterministically, the oceanic aspects of the Southern Oscillation between El Niño and La Niña over an extended period, provided that the surface winds are specified. Today such models serve, on a monthly operational basis, to interpolate measurements from a permanent array of instruments in the Pacific, thus providing a detailed description of current conditions in the Pacific Ocean, a description required as initial conditions for coupled ocean–atmosphere models that predict El Niño.

Interactions between the Ocean and Atmosphere

Suppose that, during La Niña, when intense trades drive the surface waters at the equator westward, a random disturbance causes a slight relaxation of the trades. Some of the warm water in the west then starts flowing eastward, thus decreasing the east–west temperature gradient that maintains the trades. The initial weakening of the winds is therefore reinforced, causing even more warm water to flow eastward. This tit-for-tat (positive feedback) leads to the demise of La Niña, the rise of El Niño. The latter state can similarly be shown to be unstable to random perturbations.

A broad spectrum of natural modes of oscillation – the Southern Oscillation is but one – is possible because of unstable interactions between the ocean and atmosphere. The properties of the different modes depend mainly on the mechanisms that control sea surface temperature, because that is the only oceanic parameter that affects the atmosphere on the timescales of interest here. Those mechanisms include advection by oceanic currents, and vertical movements of the thermocline caused either by local winds, or by remote winds that excite waves that propagate along the thermocline. In one class of coupled ocean–atmosphere modes, sea surface temperature variations depend primarily on advection. Consider an initial perturbation in the form of a confined equatorial region of unusually high sea surface temperatures. That warm patch, superimposed on waters that get progressively warmer from west to east, induces westerly winds to its west, easterly winds to its east. The westerly winds drive convergent currents that advect warm water, in effect extending the patch westward. The easterly winds induce divergent currents that advect cold water, thus lowering sea surface temperatures and contracting the warm patch on its eastern side. The net result is a westward displacement of the original disturbance. A mode of this type is involved in the response of the eastern equatorial Pacific to the seasonal variations in solar radiation.

In certain coupled ocean–atmosphere modes the slow adjustment of the ocean (over a period of months and longer) to a change in winds, in contrast to the short period (weeks) the atmosphere takes to come into equilibrium with altered sea surface temperature, is of great importance. (That is why the ocean, far more than the atmosphere, needs to be monitored to anticipate future developments.) These modes, which are known as 'delayed oscillator' modes because of the lagged response of the oceans, differ from those discussed in the previous paragraph, in being affected by the boundedness of the ocean basin – the presence of north–south coasts. Furthermore, sea surface temperatures now depend mainly on thermocline displacements, not on upwelling induced by local winds. The effect of winds to the west of an, initially, equatorially confined region of unusually warm surface waters can extend far eastward because of certain waves that travel efficiently in that direction along the equator. This type of mode is associated with long timescales, of several years, on which the oceanic response is almost, but not quite, in equilibrium with the gradually changing winds. That distinction is of vital importance because the small departure from equilibrium, the 'memory' of the system, brings about the transition from one phase of the oscillation to the next. If El Niño conditions are in existence then the delayed response of the ocean causes El Niño to start waning after a while, thus setting the stage for La Niña.

To which of the various modes does the observed Southern Oscillation correspond? The answer depends on the period under consideration, because the properties of the dominant mode at a given time (the one likely to be observed) depend on the background state at the time. For example, if the thermocline is too deep then the winds may be unable to bring cold water to the surface so that ocean–atmosphere interactions, and a Southern Oscillation, are impossible. Such a state of affairs can be countered by sufficiently intense easterly winds along the equator because they slope the thermocline down towards the west, shoaling it in the east. These considerations indicate that the time-averaged depth of the thermocline, and the intensity of the easterly winds, are factors that determine the properties of the observed Southern Oscillation. (The temperature difference across the thermocline is another factor.) If the thermocline is shallow, and the winds are intense (this was apparently the case some 20 000 years ago during the last Ice Age), then the Southern Oscillation is likely to have a short period of 1 or 2 years, and to resemble the mode excited by the seasonal variation in solar radiation. In general, the observed mode is likely to be a hybrid one with properties intermediate between those associated with the seasonal cycle, and those known as the delayed oscillator type. During the 1960s and 1970s the thermocline was sufficiently shallow, and the trade winds sufficiently intense, for the dominant mode to have some of the characteristics of the annual mode – a relatively high frequency of approximately 3 years, and westward phase propagation. Since the late 1970s, the background state has changed because of a slight relaxation of the trades, a deepening of the thermocline in the eastern tropical, and a rise in the surface temperatures of that region. This has contributed to a change in the properties of El Niño. During the 1980s and 1990s it was often associated with eastward phase propagation, and with a longer period of recurrence, 5 years. This gradual modulation of the Southern Oscillation cannot explain the differences between one El Niño and the next, why El Niño was very weak in 1992, exceptionally intense in 1997. Those differences are attributable to random disturbances, such as westerly wind bursts that last for a week or two over the far western equatorial Pacific. They can be influential because the background state, for the past few decades, has always been such that interactions between the ocean and atmosphere are marginally unstable at most, or slightly damped so that the continual Southern Oscillation is sustained by sporadic perturbations. A useful analogy is a swinging pendulum that is subject to modest blows at random times. A blow, depending on its timing, can either amplify the oscillation – that apparently happened in 1997 when a burst of westerly winds in March of that year led to a very intense El Niño – or can damp the oscillation. The predictability of El Niño is therefore limited, because the westerly wind bursts cannot be anticipated far in advance. (Several models predicted that El Niño would occur in 1997, but none anticipated its large amplitude.)

These results concerning the stability properties of ocean–atmosphere modes come from analyses of relatively simple coupled models: the ocean is a shallow-water model with a mixed, surface layer in which sea surface temperatures have horizontal variations; the atmosphere is also a single layer of fluid driven by heat sources proportional to sea surface temperature variations. These models deal only with modest departures from a specified background state that can be altered to explore various possible worlds. The results are very helpful in the development of more sophisticated coupled general circulation models of the ocean and atmosphere which have to simulate, not only the interannual Southern Oscillation, but also the background state. At this time the models are capable of simulating with encouraging realism various aspects of the Earth's climate, and of the Southern Oscillation. As yet, the properties of the simulated oscillations do not coincide with those of the Southern Oscillation as observed during the 1980s and 1990s, presumably because the background state has inaccuracies. The models are improving rapidly.

Conclusions

The Southern Oscillation, between complementary El Niño and La Niña states, results from interactions between the tropical oceans and atmosphere. The detailed properties of the oscillation (e.g. its period and spatial structure) depend on long-term averaged background conditions and hence change gradually with time as those conditions change. The ocean, because its inertia exceeds that of the atmosphere by a large factor (oceanic adjustment to a change in forcing is far more gradual than atmospheric adjustment), needs to be monitored in order to anticipate future developments. The development of computer models capable of predicting El Niño is advancing rapidly.

See also

Elemental Distribution: Overview. El Niño Southern Oscillation (ENSO). Rossby Waves. Satellite Remote Sensing of Sea Surface Temperatures. Wave Generation by Wind.

Further Reading

The *Journal of Geophysical Research* Volume 103 (1998) is devoted to a series of excellent and detailed reviews of various aspects of El Niño and La Niña.

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ELECTRICAL PROPERTIES OF SEA WATER

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Introduction

The oceans are the biggest reservoir of electrolyte solution on Earth. The electrical properties of the sea water are mainly determined by the ions dissolved in it when DC or low-frequency AC electric fields are involved. It should be noted, however, that the water plays an important role in producing the ions from the electrically inert salt crystals. For high-frequency electric fields and electromagnetic wave propagation, the properties of the water itself become more important, since the mechanism of conduction changes.

The electrical conductivity has become the most important electrical property of sea water because the definition of salinity is based on conductivity ratios. Thus, salinity in its current definition is an electrical property.

Other consequences of the sea water being an electrolyte might not be as obviously relevant to the marine scientist as is the conductivity. Whenever instruments that consist of metal parts are lowered into the sea, the galvanic potential has to be considered, either because it might influence electric