El Niño and La Niña

TRACING THE DANCE OF OCEAN AND ATMOSPHERE

By now most people have heard of El Niño, if only to know the name refers to some kinds of abnormal weather. The definition of "abnormal" varies widely with geography, though. For people who live in Indonesia, Australia, or southeastern Africa, El Niño can mean severe droughts and deadly forest fires. Ecuadorians, Peruvians, or Californians, on the other hand, associate it with lashing rainstorms that can trigger devastating floods and mudslides. Severe El Niño events have resulted in a few thousand deaths worldwide, left thousands of people homeless, and caused billions of dollars in damage. Yet residents on the northeastern seaboard of the United States can credit El Niño with milder-than-normal winters (and lower heating bills) and relatively benign hurricane seasons.

Originally, the name El Niño (Spanish for "the Christ child") was coined in the late 1800s by fishermen along the coast of Peru to refer to a seasonal invasion of a warm southward ocean current that displaced the north-flowing cold current in which they normally fished; typically this would happen around Christmas. Today, the term no longer refers to the local seasonal current shift but to part of a phenomenon known as El Niño-Southern Oscillation (ENSO), a continual but irregular cycle of shifts in ocean and atmospheric conditions that affect the globe. El Niño has come to refer to the more pronounced weather effects associated with anomalously warm sea surface temperatures interacting with the air above it in the eastern and central Pacific Ocean. Its counterpart—effects associated with colder-than-usual sea surface temperatures in the region—was labeled "La Niña" (or "little girl") as recently as 1985.

The shift from El Niño conditions to La Niña and back again takes about four years. Understanding this irregular oscillation and its consequences for global climate has become possible only in recent decades as scientists began to unravel the intricate relationship between ocean and atmosphere. Although meteorologists have long been forecasting daily weather based on atmospheric measurements taken around the world, they had relatively little information about conditions in many parts of the world's oceans until the advent of arrays of fixed unmanned midocean buoys in the Pacific Ocean and orbiting satellites.

But technological advances were not the only key. As the following article recounts, atmospheric and oceanographic researchers, after years of independent inquiry into the basic workings of air and sea, at last joined forces. An elegant synthesis of these two fields of research now enables climatologists and oceanographers to construct theoretical models to simulate and predict the broad climate changes associated with ENSO. For example, scientists can now warn vulnerable populations of an impending El Niño event several months in advance, providing precious time in which to take steps to mitigate its worst effects. Invaluable as this prediction of El Niño is, it is just the first step toward the much longer-term goal of providing the climatic counterpart to the daily weather prediction that we have come to take for granted.

Of Weather and Climate

Weather has always been a significant concern to humankind, and our inability to control it has led us down through the ages to try to measure it, compare it to previous years, and predict it. Prediction, however, requires a lot of information about conditions in different locations as well as a way to convey that information between distant places. In the latter half of the nineteenth century, the telegraph made it possible for meteorological data from stations scattered over a huge area to be collected rapidly, leading to the creation of several national weather services. The

__left__: Flooded area in Lakeport, California as a result of the 1998 El Niño event. (Federal Emergency Management Agency)
__right__: Bush fire in Australia as a result of the 1998 El Niño event. (Photo courtesy of Fred Hoogervorst/Panos Pictures/London)

global observational network grew in sophistication during the twentieth century, especially after the launch of the first satellite in 1957. Today, satellites, commercial airlines, and ships at sea take measurements. Information also comes from balloons that are released twice a day into the upper atmosphere by meteorological stations around the globe, as well as by fixed buoys that record temperature several hundred meters deep in the ocean.

Even with all this high-tech help—including sophisticated computer models—we can predict the weather with reasonable accuracy only a few days in advance. How, then, has it become possible for climatologists to anticipate the onset of the El Niño phase of ENSO several months ahead? The answer has to do with how interactions between the ocean and the atmosphere play out over time.

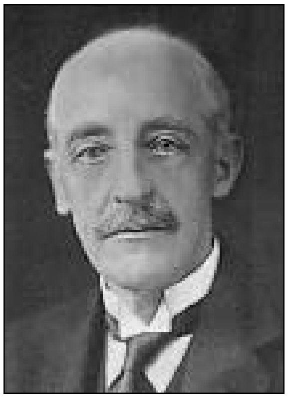
Fundamentally, many argue that the engine that drives long-term "climate" is the heating and cooling of the tropical Pacific Ocean. The sea breeze is a familiar example. On a sunny afternoon the land heats up faster than the ocean; as the air over the land warms and rises, the air over the cooler surface of the ocean flows toward the shore to take its place. Aloft, the warm air returns to the sea, then subsides over the ocean to complete the circuit. The same principles apply to the planet as a whole. Over the course of the year, the sun's rays strike more vertically in the tropical zones than at midlatitudes or at the poles; as a result, the tropical oceans absorb a great deal more heat than do waters elsewhere. As air near the ocean surface is warmed by the equatorial waters, it expands, rises (carrying heat with it), and drifts toward the poles; cooler denser air from the subtropics and the poles moves toward the equator to take its place.

In other words, the atmosphere and ocean together act like a global heat engine. This continual redistribution of heat, modified by the planet's west-to-east rotation, gives rise to the high jet streams and the prevailing westward-blowing trade winds. The winds in turn, along with Earth's rotation, drive large ocean currents such as the Gulf Stream in the North Atlantic, the Humboldt Current in the South Pacific, and the North and South Equatorial Currents. In the tropical ocean, westward-blowing trade winds harvest water vapor over the ocean, carrying it away from one part of the world and depositing it somewhere else. The result of this ocean-atmosphere dynamic is that the Pacific coast of South America, for example, is generally dry, while on the opposite side of that ocean basin, Indonesia and New Guinea contain lush jungles. The trade winds also push the warm water in the upper layer of the tropical ocean westward. As warm water piles up in the western Pacific, the cool water in the lower layers of the eastern Pacific rises to the surface.

As researchers have gradually learned, if they have information about subsurface temperatures in certain parts of the tropical Pacific Ocean, they can improve their predictions of the behavior of trade winds several months hence. Conversely, if they have information about the behavior of the trade winds, they can predict sea surface temperatures.

Starting with the Atmosphere

The first pieces to the El Niño puzzle came from atmospheric studies. In the early part of the twentieth century, British mathematician Sir Gilbert Walker, director general of meteorological observatories in India, took advantage of existing weather data to make a substantial breakthrough in atmospheric science. In 1899 the monsoon rains on which Indian farmers depend failed to come, triggering a devastating famine. Asked to find a way to predict such weather vagaries in the future, Walker began sifting through some 40 years' worth of temperature, atmospheric pressure, and rainfall data culled from a worldwide network of



Gilbert Thomas Walker (Photo courtesy of E. M. Rasmussen, University of Maryland)

weather stations. He noticed a kind of seesaw relationship between atmospheric pressure in the eastern South Pacific (east of Tahiti) and the Indian Ocean (west of Darwin, Australia)—that is, if pressure was high in one region, it was usually low in the other and vice versa.

In a 1928 paper presented to the Royal Meteorological Society, Walker named this seesaw pattern the Southern Oscillation and devised a yardstick that measured pressure differences between the two regions. He observed that, when pressure was very high in the east and low in the west, the monsoon rains in India were heavy. When the pressure difference was small, the rains failed and drought often ensued. Moreover, Walker's research showed that drought conditions hit not only Australia, Indonesia, and India but also parts of sub-Saharan Africa, and at the same time there would be mild winters in Canada. Because he had plotted certain time-lag correlations between these pressure differences at different times of the year, Walker also believed the measurements could be used for long-range forecasting for some locations.

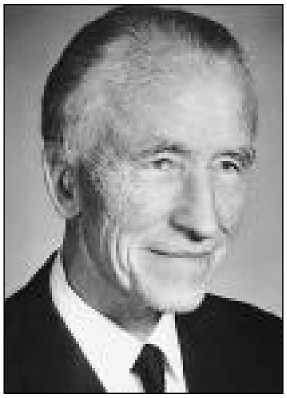
Despite his insight and vision, Walker was unable to identify the physical processes responsible for the Southern Oscillation, and for the next three decades numerous factors conspired to dampen further research on the phenomenon. Chief among them was that from 1930 to 1950 the climate signals marking the Southern Oscillation and El Niño were much less pronounced than they had been, and interest in the subject dropped off. Then in 1957 a confluence of events in climate, science, and international politics brought a resurgence of interest.

That year the Soviet Union launched *Sputnik*, the first artificial satellite, spurring a dramatic increase in support for scientific research of all kinds throughout the West. As it happened, the year also ushered in a large El Niño. Although this was a strong event, it might have passed unnoticed, except that 1957 had been designated as an International Geophysical Year, a year when scientists from all countries cooperate to improve existing understanding of the solid Earth, the oceans, and the atmosphere. As a result, scientists around the world were conducting intensive measurements of the planet. Among the data they gathered were not only atmospheric measurements but also sea surface temperatures throughout the Pacific—information that had not been available in Gilbert Walker's time. Some researchers in the 1950s noted that high sea surface temperatures off the coast of Peru seemed to correlate with a small difference in pressure across the tropical Pacific. Indeed, scientists at the Scripps Institution of Oceanography convened a group of colleagues in 1959 to discuss the phenomenon. However, it wasn't until the late 1960s that meteorologist Jacob Bjerknes, of the University of California, Los Angeles, described a mechanism that linked Walker's observations of the Southern Oscillation to El Niño.

A Meteorologist Looks at the Sea

Originally from Norway, Jacob Bjerknes had been studying the atmosphere for decades. During World War I he had worked with his father, Vilhelm Bjerknes, a pioneering meteorologist who coined the term "fronts" to describe the boundaries in the atmosphere where masses of warm and cold air meet and often spawn storms. The elder Bjerknes recognized that weather forecasting would require not only global data on atmospheric conditions but also much better knowledge of "the laws according to which one state of the atmosphere develops from another." Decades later in America his son would make an important contribution to that knowledge.

Central to Jacob Bjerknes's insight was his recognition that the interaction between the sea and air could have a major impact on winds, rain, and other aspects of weather. Bjerknes described a Pacific-wide air circulation pattern, which he called the Walker Circulation. This pattern of airflow, Bjerknes realized, hinged on the difference in sea surface temperatures in the western and eastern Pacific—a difference that creates differences in surface air pressure between the two regions.



Jacob Bjerknes. (Photo courtesy of E.M. Rasmussen, University of Maryland)

Air above the cold waters of the eastern Pacific is too dense to rise high enough for water vapor to condense to form clouds and raindrops, leaving portions of

Peru and Ecuador a desert. This desert effectively begins far offshore, where the cool dense air also creates a region of high air pressure. High pressure in the east and low pressure over warmer waters in the west (a large pressure difference in Gilbert Walker's scheme) moves air westward, generating and reinforcing the steady equatorial trade winds. The winds harvest moisture from the ocean as they blow toward the western Pacific; there the warm moist air rises, condenses, and then dumps heavy monsoon rains that nourish the jungles of New Guinea and Indonesia.

Bjerknes recognized that during El Niño conditions, when the waters off northern Peru are warmer than normal and surface air pressure is lower as a consequence, the pressure difference between east and west weakens and so do the westward trade winds. As the winds falter, warm moist air rises over the central Pacific instead of farther west, effectively stealing the monsoon rains from the region around Indonesia and spawning rainstorms that strike the west coasts of North and South America.

To determine whether Bjerknes's ideas had predictive power, atmospheric researchers now turned to computers. In the early 1950s mathematician John von Neumann, a key figure in the invention of the digital computer, led a group of scientists at the Institute for Advanced Study in Princeton, New Jersey, in some of the first efforts to use computer models to explore weather prediction. By the 1970s researchers were using computers to construct atmospheric general circulation models (AGCMs) to simulate the response of the atmosphere to a fixed sea surface temperature in the tropical Pacific. AGCMs divide an imaginary atmosphere into horizontal layers, subdivided into thousands of squares. Data on such variables as temperature, pressure, humidity, and wind are fed into a series of equations that produce new readings and outcomes for each of the grid points. The test is to see whether a model can reproduce observed real-world behavior given the same starting point, such as a certain sea surface temperature.

Oceanography's Perspective

As it happened, much-needed help was gathering in another quarter—the ocean sciences. Without something like weather prediction as a driving force in its development, oceanography lacked the sea-going equivalent of weather balloons for monitoring the oceans. For years oceanographers had to rely on studies carried out during voyages by individual vessels. In the 1970s more systematic and broader-based efforts at monitoring the world's oceans began. Some of those programs focused on the variability of the tropical oceans and on phenomena that could shed light on El Niño.

A key contribution, confirming Bjerknes's insight that the effects of El Niño were not confined along the west coast of Peru and Ecuador, came when Klaus Wyrtki of the University of Hawaii and his colleagues collected and charted tidal records and wind patterns across the Pacific basin. In 1975 Wyrtki established

Chronology of Events in the History of Understanding El Niño and La Niña

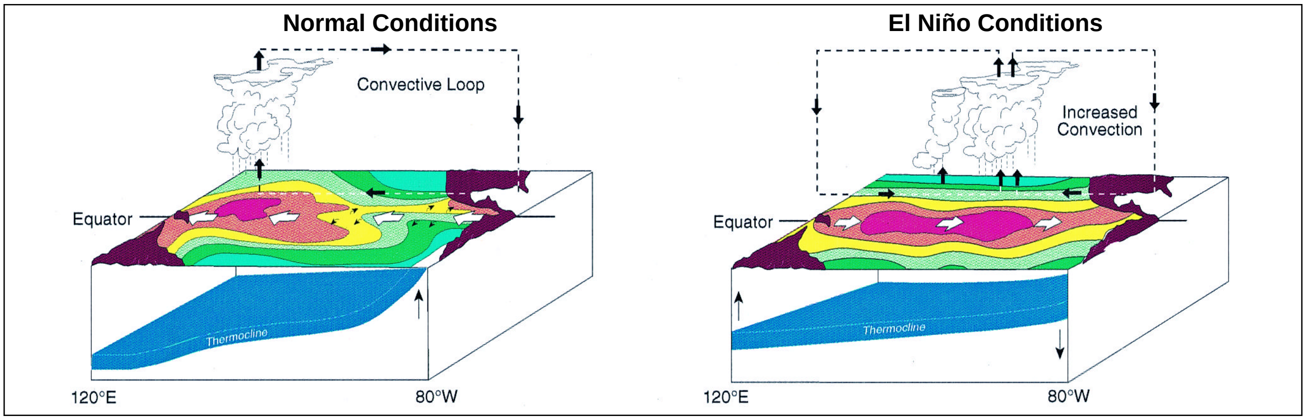
late 1800s
Fishermen coin the name El Niño to refer to the periodic warm waters that appear off the coasts of Peru and Ecuador around Christmas.

1928
Sir Walter Gilbert describes the Southern Oscillation, the seesaw pattern of atmospheric pressure readings on the eastern and western sides of the Pacific Ocean.

1957
Large El Niño occurs and is tracked by scientists participating in the International Geophysical Year . Results reveal that El Niño affects not just the coasts of Peru and Ecuador but the entire Pacific Ocean.

1969
Jacob Bjerknes, of the University of California, Los Angeles, publishes a seminal paper that links the Southern Oscillation to El Niño.

1975
Klaus Wyrtki, of the University of Hawaii, tracks sea levels across the Pacific and establishes that an eastward flow of warm surface waters from the western Pacific causes sea surface temperatures to rise in the eastern Pacific.



Under normal conditions, the steady equatorial tradewinds move air westward; there warm air rises, condenses and rains heavily in the western Pacific. In El Niño conditions, lower air pressure in the east weakens the tradewinds, thus causing abnormal rain fall along the west coasts of North and South America. Temperature gradient: red, orange, and yellow (warm); aqua, green, and blue (cool). (NOAA/Environmental Research Labs, Pacific Marine Environmental Laboratory)

that strong trade winds essentially push the warmed surface waters to the west along the equator until they pile up against the coast of Indonesia. This thickened layer of warm water, which raises the sea level in the western Pacific by as much as 18 inches, effectively depresses a layer of subsurface water called the thermocline, a kind of interface between the warm surface waters and the much colder deep ocean. In the eastern Pacific, by contrast, the warm surface layer is much thinner. As a result, the thermocline lies nearer the surface, as do cold waters welling up from the deep ocean and bringing with them the nutrients that support abundant fisheries. Wyrtki's work suggested that, when the trade winds fail, they release waves of warm water that move west to east across the Pacific Ocean, pushing the thermocline deeper in the eastern Pacific and suppressing the upwelling of cold water from the deep ocean. As a result, sea surface temperatures in the east rise, and the surface water in the eastern Pacific becomes deprived of nutrients needed to maintain certain fish populations. Because of the delayed response of the eastern Pacific to the wind changes, Wyrtki recognized the potential for predicting such events in advance.

As with everything associated with the ENSO, this redistribution of warm surface water across the Pacific displays a periodic, although irregular, character involving a complex interplay of waves, currents,

1976

Researchers use an idealized computer model of the ocean to demonstrate that winds over the far western equatorial Pacific can cause sea surface temperature changes off Peru.

1982

A severe El Niño develops in an unexpected manner, but its evolution is recorded in detail with newly deployed ocean buoys.

1985

Several nations launch the Tropical Ocean-Global Atmosphere (TOGA) program, a 10-year study of tropical oceans and the global atmosphere.

1986

Researchers design the first coupled model of ocean and atmosphere that accurately predicts an El Niño event in 1986.

1988

Researchers explain how the "memory" of the ocean—the lag between a change in the winds and the response of the ocean—influences terminations of El Niño and the onset of La Niña.

1996-1997

The array of instruments monitoring the Pacific, plus coupled ocean-atmosphere models, enable scientists to warn the public of an impending El Niño event.

and undercurrents that appear and disappear in response to changes in the winds. Oceanographers wrestling with these effects were also turning to computers for help. In the mid-1970s scientists began designing numerical models to simulate what goes on in the oceans. Using idealized computer models that treat the upper ocean as a layer of uniform temperature overlying a deep, cold ocean, they attempted to reproduce the redistribution of warm surface water. Their aim was to see what happens to the thickness of the upper layer and depth of the thermocline in response to changes in the winds. These models showed that changes in the winds over the western Pacific could indeed cause the changes in eastern Pacific sea levels associated with El Niño. In the early 1980s more realistic oceanic models were developed, in which ocean temperatures varied both horizontally and vertically. Using this model, researchers were able to reproduce the main oceanic aspects of ENSO, including sea surface temperature changes, as long as they had data about the winds for the period in question.

Any hope of documenting the actual details of the movement of warm surface water depended on continuous measurements of subsurface ocean conditions along the equator. But these measurements required maintaining moored buoys at the equator over long periods, which was considered too difficult due to the strong equatorial currents. In the early 1980s David Halpern of the National Oceanic and Atmospheric Administration (NOAA) in Seattle and like-minded colleagues determined to prove conventional wisdom wrong. They pieced together funding from various programs to set up lines of moored buoys located near the equator at longitude 110° W and 140° W. Today, measurements with improved instruments continue at these and many other locations.

Wakeup Call

By the early 1980s researchers had effectively confirmed Jacob Bjerknes's earlier insights on how an El Niño event tends to evolve. Scientists analyzing data covering six El Niños from 1950 to 1976 found that in December or January sea surface temperatures off Peru would begin to rise but, unlike in "normal times," would not drop as the Southern fall season (February-April) progressed. These anomalously warm temperatures would gradually migrate westward, growing warmer as they did so. The warm waters in the eastern Pacific would eventually lower atmospheric pressure, thereby causing the trade winds to collapse, and around the end of the year sea surface temperatures in the central and eastern Pacific would peak. This phase of El Niño would typically last into spring in the northern hemisphere, where its effects were felt most strongly. Finally, sea surface temperatures in the central Pacific would begin to cool and El Niño would bow out and be replaced either by La Niña or by average conditions.

However, when the severe El Niño struck in 1982 to 1983, its timing was unusual. This tempest did not show the typical warming of waters off Peru around April. Hindsight now shows that El Niño's signs were evident by July 1982. Unfortunately, satellites making measurements of sea surface temperature in the Pacific were confounded by the April eruption of the El Chichon volcano in Mexico, which had spewed a massive cloud of fine particles high into the atmosphere. To the satellites, sea surface temperatures appeared much colder than they actually were. Although the equatorial buoys were now in place, measurements from them were available only after the instruments were recovered months later. As a result, scientists were virtually blind to the coming threat.

Australia, already in the grip of its worst drought of the century, suffered wildfires and catastrophic agricultural and livestock losses that together cost billions of dollars of lost revenue and damage. Drought racked much of sub-Saharan Africa, forcing even normally food-exporting nations such as the Republic of South Africa and Zimbabwe to turn to the international community for help. In parts of southern Ecuador and northern Peru, up to 100 inches of rain fell during a six-month period. Swollen rivers carried a thousand times their normal flow. In all the event was blamed for nearly 2,100 deaths worldwide and forced hundreds of thousands of people to be evacuated, left thousands more homeless, and caused over $13 billion in damage worldwide.

Need for More Comprehensive Data

Underscoring the notion that not all El Niños are alike and that a multitude of factors are at work, the devastating El Niño of 1982 to 1983 served as a stringent test of the science of computer modeling. Researchers realized that a deeper understanding of El Niño—and any hope of timely prediction—would require a much more systematic and comprehensive set of observations than were available through the programs then in operation. This realization generated a groundswell of support for a major international research effort.

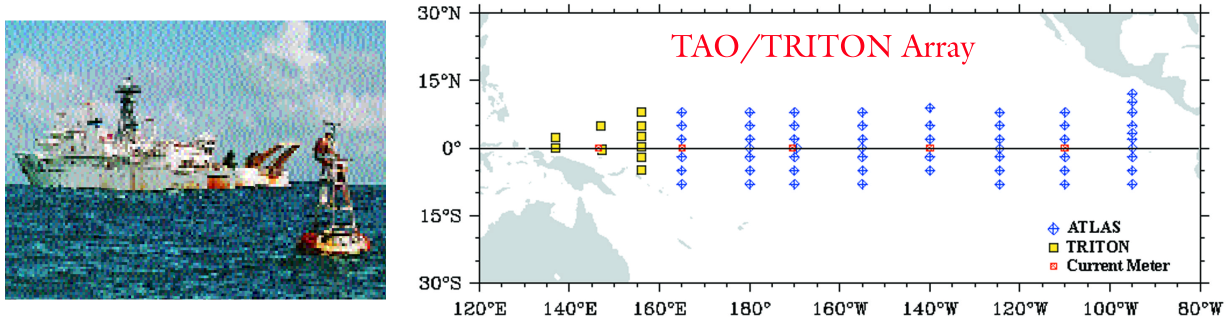
In 1985 the Tropical Ocean-Global Atmosphere (TOGA) program began looking not at the ocean or atmosphere alone but at the interactions between them, all across the Pacific. Sponsored by the United Nations World Climate Research Program, TOGA marked a major attempt to acquire reliable observational data that would support experimental forecasts. It also spurred development of a new generation of observational equipment, such as moored and satellite-tracked drifting buoys capable of taking readings and relaying them via satellites to climate researchers in real time. NOAA scientists in Seattle and collaborators at numerous institutions began monitoring the equatorial Pacific with these buoys, as well as satellites, ships, and tide and temperature gauges. The result was a wealth of data on ocean currents, sea level, and water temperatures from the surface to 500 meters underwater as well as air temperatures, humidity, and wind direction and speed. Today, an invaluable legacy of the 10-year TOGA program is a system of 70 buoys known as the Tropical Atmosphere-Ocean (TAO) Array, which continues to collect and transmit vital information on the current state of the equatorial Pacific Ocean and atmosphere.

Oceanographers seeking to understand the basic physical processes at work in the ocean welcomed the flow of data from the NOAA monitoring program. In the late 1980s researchers at the National Weather Service's National Meteorological Center in Washington, D.C., combined a realistic model of the ocean with real-time observations to provide a detailed description, on a month-by-month basis, of conditions in the Pacific, thereby allowing oceanographers to gain a more complete view of the ocean's processes.

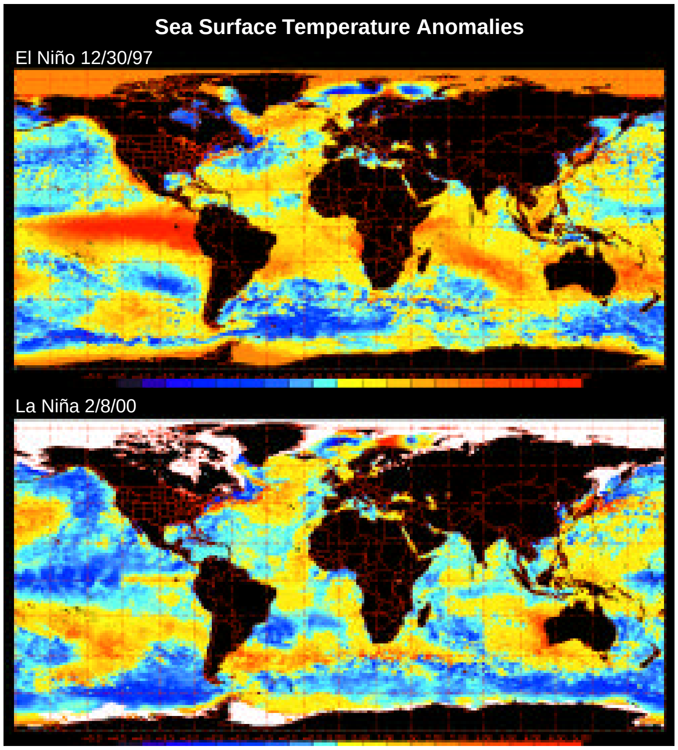
The Power of an Interdisciplinary Approach

The voluminous amount of TOGA data, together with satellite measurements of sea levels and sea surface temperatures, would have been of no avail without concurrent advances in the use of computers to model El Niño's behavior. All of these efforts, coming from ocean scientists on the one hand and atmospheric scientists on the other, paved the way for the truly powerful "coupled" models that bring together all available information to track how atmosphere and ocean changes interact. With such models it becomes possible to anticipate longer-term climate fluctuations. In the mid-1980s a statistical coupled model—based on a statistical relationship over time among selected variables such as sea level pressure over Indonesia and sea surface temperatures in the eastern equatorial Pacific—predicted the El Niño that began in late 1986. At about the same time, other researchers used a relatively simple dynamic coupled model to predict the same event. (Dynamic models differ from statistical models by solving mathematical equations on a grid that incorporates data from specified latitudes, longitudes, and depths.) Right on schedule, El Niño made an appearance in late 1986 and lasted through the first half of 1988.

A significant insight into why coupled models work—and a much-needed breakthrough in the long-standing conundrum of which partner leads in the dance of ocean and atmosphere—came in 1988. As researchers were aware, the ocean and atmosphere are inextricably linked, but they are not a perfectly balanced pair. The atmosphere is quick and agile, responding within a matter of days or weeks to altered sea surface temperatures. The vast and cumbersome ocean, by contrast, takes months to reach



***Left**: Servicing an ATLAS (Autonomous Temperature Line Acquisition System) mooring, part of the TAO Array, from the NOAA ship Ka'imimoana in the central equatorial Pacific Ocean. (Photo courtesy NOAA/Environmental Research Labs, Pacific Marine Environmental Laboratory) **Right**: Location of buoys of TAO Array in the Pacific Ocean. (TAO Project Office/NOAA/PMEL)* a new equilibrium with changes in the winds. Thus, the state of the ocean at any given time reflects a kind of memory of earlier winds—in the form of waves below the ocean surface—rather than the action of the winds in play at the moment. This lag in the ocean's response, scientists suggested, imparts certain chaotic properties that affect the timing of shifts in the cycle.



Sea Surface Temperature Anomalies show global El Niño and La Niña conditions. Temperature gradient: orange, yellow (warm); blue (cool). (NOAA/National Environmental Satellite, Data, and Information Service)

By the late 1990s, several groups around the world had devised more complex coupled general circulation models (CGCMs) to make use of the observational data from the TAO array. In early 1997 some of these models revealed telltale signs of Pacific warming on the horizon. In the spring of 1997, NOAA advisories warned the world to expect a major event. By November, at El Niño's warming peak, sea surface temperatures were up some 5 degrees Celsius over 4,500 miles of open ocean, the most dramatic ocean warming ever recorded.

The 1997 to 1998 El Niño produced societal impacts as devastating as in 1982 to 1983. Storms lashed California for months on end and damaged or destroyed more than 1,400 homes, sweeping many down soggy hillsides. Some 90 people were killed in the United States alone, including 39 in central Florida, which was ravaged by a series of seemingly random twisters, which some people blamed on El Niño's impact on the jet stream. Indonesia suffered forest and peat fires that blackened skies across southeast Asia. Off the coast of Peru, fish stocks plummeted, devastating local populations of seals, sea lions, Humboldt penguins, and seabirds such as gulls and terns. In Mexico rogue fires scorched a treasured cloud forest. In Panama drought and low water levels in lakes that feed the Panama Canal forced officials to restrict shipping through the canal for the first time in 15 years.

Disastrous as this El Niño was, it could have been much worse. The early warning allowed some farmers in drought-prone northeastern Brazil to plant heat-resistant crops. Los Angeles County, California, residents banded together to clear flood channels, bolster levees, and distribute sandbags to areas subject to flooding. The number of flood insurance policies taken out by Californians surged from fewer than 265,000 to more than 333,000. Residents of the Galápagos Islands repaved roads, installed new drainage systems, and shored up basic services such as water and communications.

Thanks to the joint efforts of oceanographers and atmospheric scientists, we now have tools that may eventually make climate fluctuations as common to predict as tomorrow's weather for some locations around the globe. From an initial inquiry into the failure of the monsoon in India and basic research into the physical processes of the ocean and atmosphere has come the invaluable ability to guide human activity in preparation for significant shifts in the planet's climatological makeup.

"El Niño and La Niña: Tracing the Dance of Ocean and Atmosphere" is an occasional article intended to explain the outcomes of basic scientific research. It was written by science writers Roberta Conlan and Robert Service for the National Academy of Sciences' Office on Public Understanding of Science. Scientific review was provided by individual members of the National Research Council's Ocean Studies Board and Board on Atmospheric Sciences and Climate, as well as other ocean and atmospheric scientists.

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Funding for this article was provided by the National Science Foundation.

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March 2000