Understanding and Forecasting ENSO

BY Hayley Tritel

Introduction

El Niño and La Niña are terms that many people have heard once or twice, especially in reference to abnormal weather conditions, but many do not fully understand what these phenomena are. The purpose of this paper is to provide some background information that will define these events, to describe their effects on global climate with an emphasis on the climate of North America, and to outline how scientists recognize and attempt to predict these events.

The interaction between the global ocean and the global atmosphere is responsible for the distribution of heat on Earth. Nowhere is this interaction more evident than in the natural oscillation between warm, cold, and transitory climate episodes that originate in the tropical Pacific Ocean. Scientists generally refer to this as the El Niño/Southern Oscillation (ENSO) cycle. El Niño is the name given to warm episodes in which warm water, and, thus, tropical convection, shifts from the western tropical Pacific towards the eastern tropical Pacific. Conversely, La Nina is the name given to cold episodes in which warm water and tropical convection is shifted towards the far western Pacific.

Defining Normal, El Niño and La Niña Conditions

Under "normal" conditions, the intervening time between El Niño and La Niña episodes, there is a large area of high pressure positioned over the eastern Pacific Ocean, off the coast of South America (see Figure 1). The southern trade winds blow from this high-pressure area towards a large area of low pressure that is positioned over the western Pacific Ocean, off the coast of Indonesia. (Because air flows from higher pressure to lower pressure, the trade winds blow towards the west across the equatorial region of the Pacific Ocean.). These winds push warm water towards the west so that the sea surface is actually a half a meter lower at Ecuador than at Indonesia and the average sea surface temperature is about 8 degrees C higher in the west. This body of warm water evaporates and moist air rises, adding to rainfall in the west. Further aloft, and now drier, the air is carried by the fast-moving upper-level winds back to the east, where it cools and descends, adding to the high pressure area off South America where the cycle originated. This cycle is known as the Walker circulation in honor of Sir Gilbert Walker, who first discovered this natural oscillation of pressure (also known as the Southern Oscillation) between the eastern tropical Pacific and the western tropical Pacific.

It is also important to note that the thermocline, which is the region of sharp vertical temperature gradient separating the warm surface water from the cold deep ocean water, is pushed down in the west and elevated in the east under normal conditions. Sea level tends to mirror thermocline depth since sea water expands when heated (McPhaden 2004). Therefore, while the thermocline dips downward toward the west by 100 m along the equator, sea level stands about a half a meter higher in the western Pacific than in the eastern Pacific (as was stated previously). The resulting shallowness of the thermocline in the eastern Pacific facilitates the upwelling (i.e., upward forcing) of cold water from deep levels of the ocean by the trade winds (see Sidebar 1). As a result, a "cold tongue" develops in sea surface temperatures (SST's) from the west coast of South America to near the International Date Line.

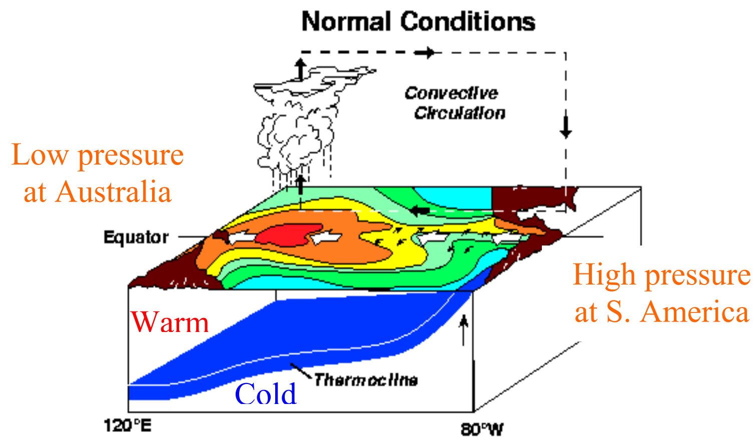
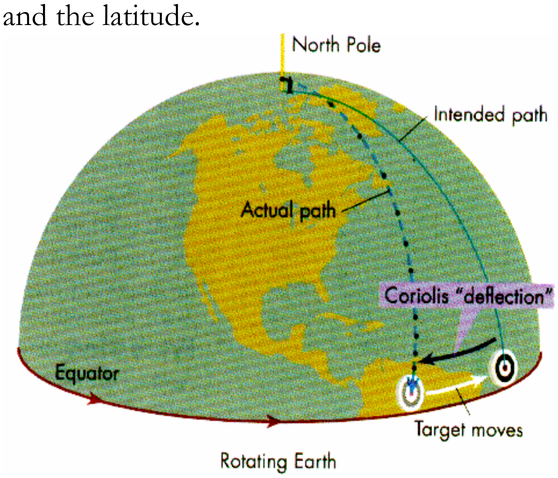


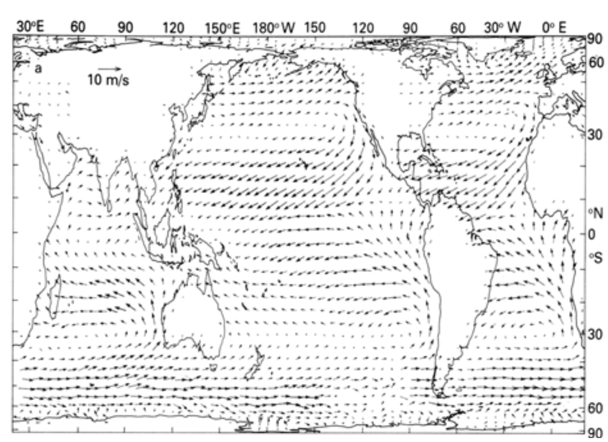
Figure 1 Schematic of normal conditions (the Walker circulation). The white arrows indicate the trade winds and the black arrows indicate the rainfall circulation pattern.

The Coriolis Effect, the Ekman Transport, and Coastal Upwelling

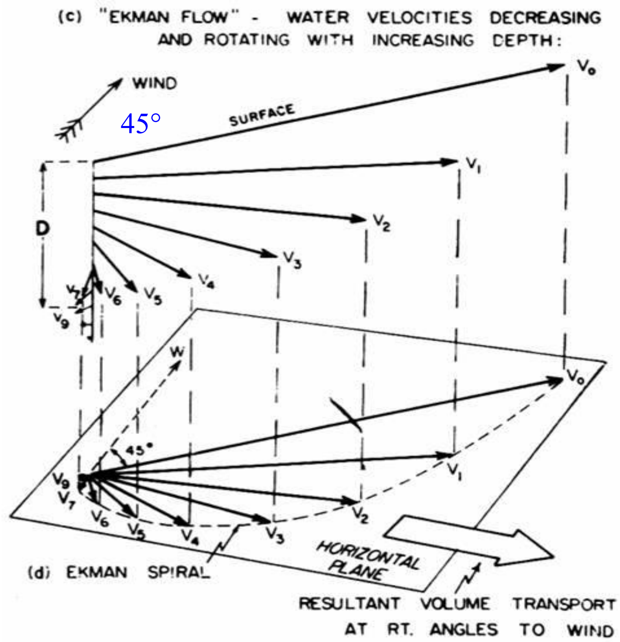
The Coriolis effect is an inertial force described by the 19th-century mathematician Gustave-Gaspard Coriolis in 1835. Coriolis showed that, if the ordinary Newtonian laws of motion of bodies are to be used in a rotating frame of reference, an inertial force – acting to the right of the direction of body motion for counterclockwise rotation of the reference frame or to the left for clockwise rotation – must be included in the equations of motion (online at http://zebu.uoregon.edu/~js/glossary/coriolis_effect.html). The effect of the Coriolis force is an apparent deflection of the path of an object that moves within a rotating coordinate system – such as the Earth. The object doesn't actually deviate from its path, but it appears to do so because of the rotation of the coordinate system.

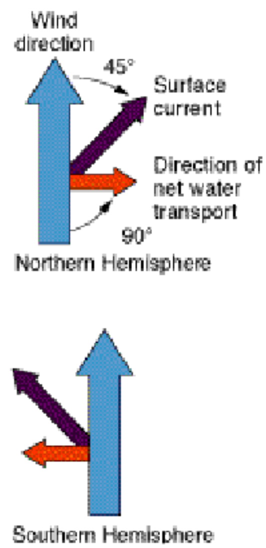
The Coriolis force is most noticeable in the path of an object moving longitudinally. For example, an object on the Earth that moves along a north-south, or longitudinal, line, will undergo apparent deflection to the right in the Northern Hemisphere and to the left in the Southern Hemisphere (see figure on the left below). (Therefore, the Coriolis effect explains the curvature of the easterly trade winds – to the right in the Northern Hemisphere and to the left in the Southern Hemisphere [see figure on the right of ocean surface winds].). There are two reasons for this phenomenon (online at http://zebu.uoregon.edu/~js/glossary/coriolis_effect.html): first, the Earth rotates eastward; and second, the tangential velocity of a point on the Earth is a function of latitude (the velocity is essentially zero at the poles and it attains a maximum value at the Equator). In other words, the Coriolis effect is related to the motion of the object, the motion of the Earth, and the latitude.





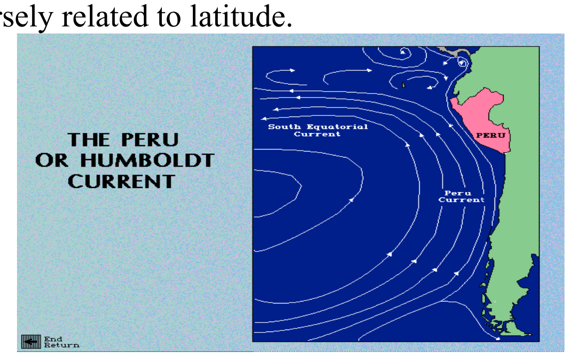
Surface ocean currents are also indirectly affected by the Coriolis effect. In 1905, Swedish oceanographer Vagn Ekman used mathematics and physics to describe the wind driven change in the surface ocean currents. He concluded that the net motion of the upper 100m of the ocean is at a right angle to the wind direction (see diagrams).

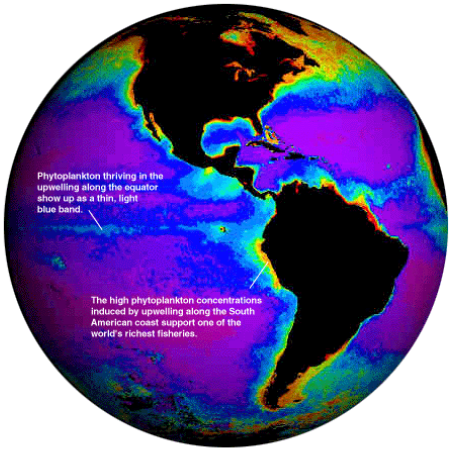




When driven by wind, the topmost layer of the ocean in the Northern Hemisphere will move to the right of the wind direction (by about 45 degrees) due to the Coriolis force (online at http://earth.usc.edu/~geol150/variability/sfcocean.html). The next "layer" down will not be affected by the wind, but will be affected by the friction caused by shear with the topmost layer. Due to the Coriolis force, this lower layer will move to the right of the topmost layer. As depth increases, successive layers will move at more extreme angles to the right of the wind direction and will also move more slowly than the overlying layers. This spiral continues until, at some depth, the movement will actually be in the opposite direction of the wind direction. However, the average movement of the column will be at a 90 degree angle to the wind direction. This net motion is known as Ekman transport.

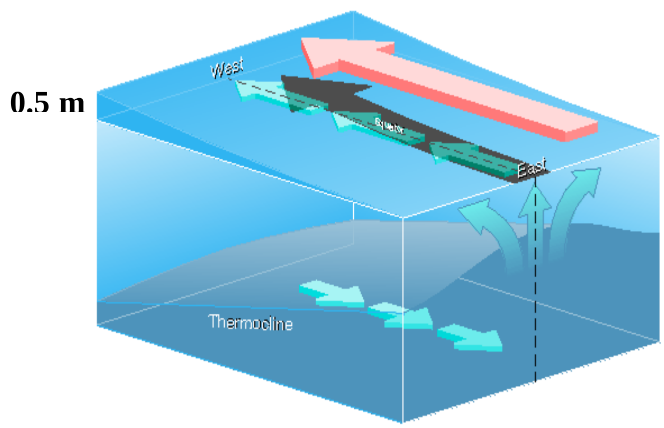
The Ekman transport will be offshore in the Southern Hemisphere due to the dominant southeasterly trade winds blowing parallel to the western edge of the continent. This will create divergence along the coast, and the diverging water will be replaced by cold water from below. Because the upwelling water is often nutrient-rich, upwelling is often associated with biological productivity. The eastern boundary current regions, where coastal upwelling occurs, are extremely productive: although their area makes up only 0.1% of the world ocean, they account for 5% of global primary production and 17% of global fish catch (Carr and Broad 2000). Among these regions, the Peruvian coast is the most productive due to a combination of a wider shelf, upwelling all year due to the Peru (or Humboldt) Current, and proximity to the equator because Ekman transport is inversely related to latitude.





This satellite image represents average conditions over a period of several years. It shows the concentration of chlorophyll in the upper layer of the ocean, with higher amounts indicated by the lighter colors and lower amounts indicated by the darker colors. Chlorophyll is produced by phytoplankton, the tiny creatures that make up the base of the food web in the marine ecosystem. As indicated in the photo, phytoplankton “boom” in the cold, nutrient-rich water that rises from the deep ocean into the sunlight (because this is where photosynthesis can take place). Phytoplankton thriving along the equator show up as a thin, light blue band. The high phytoplankton concentrations generated by upwelling along the South American coast support one of the world’s largest fisheries.

Easterly trade winds (red arrow) drag the surface water westward along the equator. The Earth’s rotation (Coriolis effect) deflects the westward current toward the right in the Northern Hemisphere and toward the left in the Southern Hemisphere, driving the surface water away from the coastline and bringing up the water from below (upward arrows). Consequently, warm surface water accumulates on the western side of the Pacific basin. Because of the lower density of the warmer water, sea level is about one half meter higher in the west than in the east when the winds are blowing at full strength. The thermocline, which marks the boundary between warm surface water and cold deep water (darker blue), is tilted (Zhang 2004). It reaches almost up to the surface in the eastern equatorial Pacific.



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 appearance of a warm, southward ocean current that replaced the north-flowing cold current in which they normally fished; typically this would happen around Christmas. Today, however, El Niño refers to a much broader basin-wide event in the equatorial Pacific. This warm phase of the ENSO cycle begins with a relaxation of the westward-flowing trade winds along the equator as atmospheric pressure rises in the western Pacific and falls in the eastern Pacific (see Figures 2-7). Weaker trade winds allow the western Pacific warm pool to migrate eastward and the thermocline to flatten out across the basin (McPhaden 2004). The usual upwelling of water along South America is not nearly as evident, which causes the sea surface temperatures to rise in this region. Tropical convection and rainfall then follows the warm water towards the east. This eastward shift in convection favors further weakening of the trade winds. Thus, weakening easterlies, eastward shifts in convection, and SST warming tendencies along the equator reinforce one another as El Niño develops (McPhaden 2004).

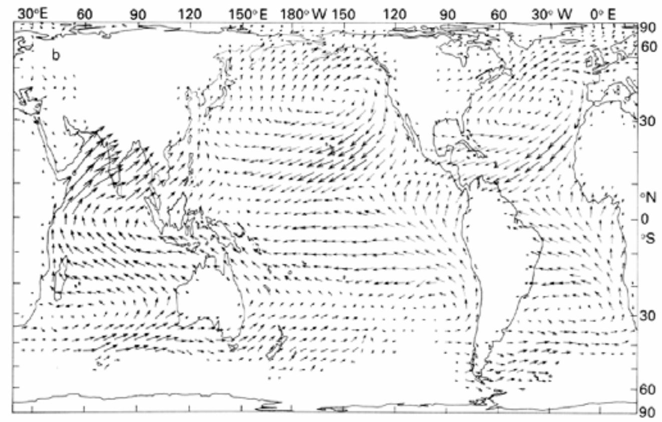
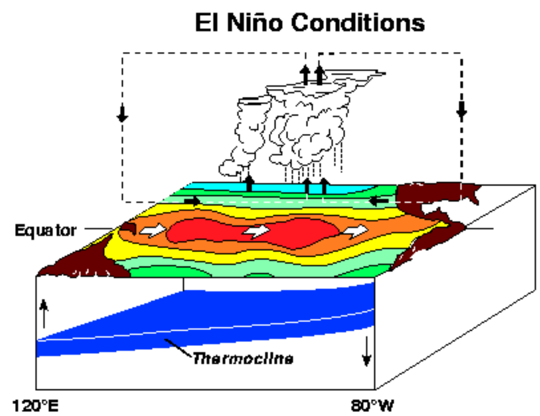


Figure 2 This map of ocean surface winds shows what happens under El Niño conditions. The easterly trade winds weaken significantly across the Pacific, as indicated by the smaller, less prominent arrows. The trades can even reverse direction completely during a particularly strong El Niño (notice the strength of the westerly arrows).

Figures 3 and 4 Schematic of El Niño conditions (right). The white arrows indicate the trade winds, which have reversed direction, and the black arrows indicate the rainfall circulation pattern, which has shifted farther to the east. The thermocline has risen in the west and dropped in the east, causing coastal upwelling to severely decline if not cease altogether (see also Figure 4, below).



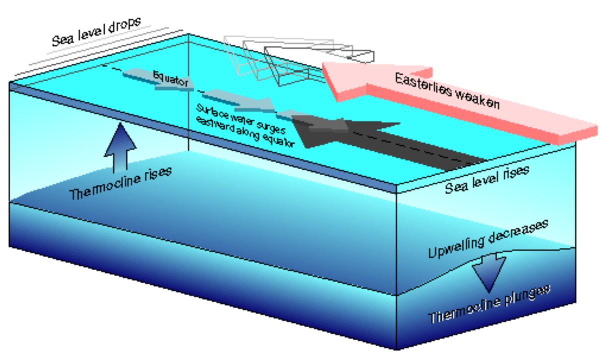
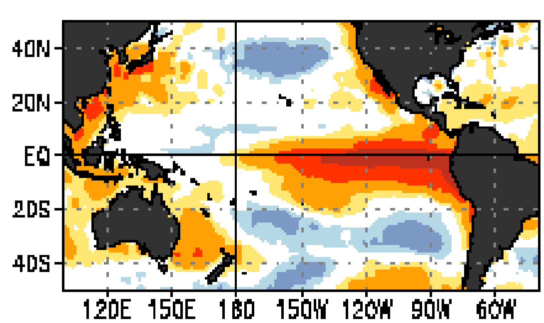


Figure 5 El Niño episodes are periods of exceptionally warm sea surface temperatures between the date line and the west coast of South America (see map below).



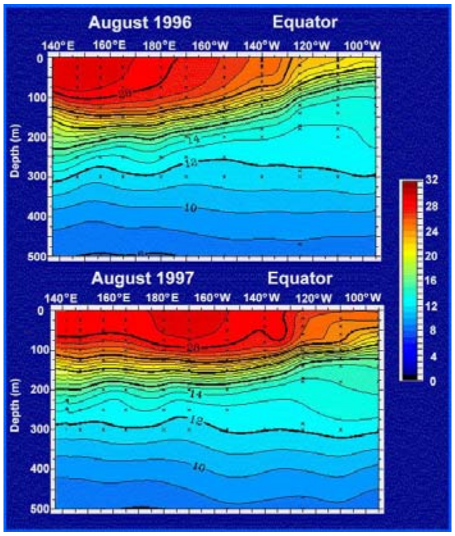
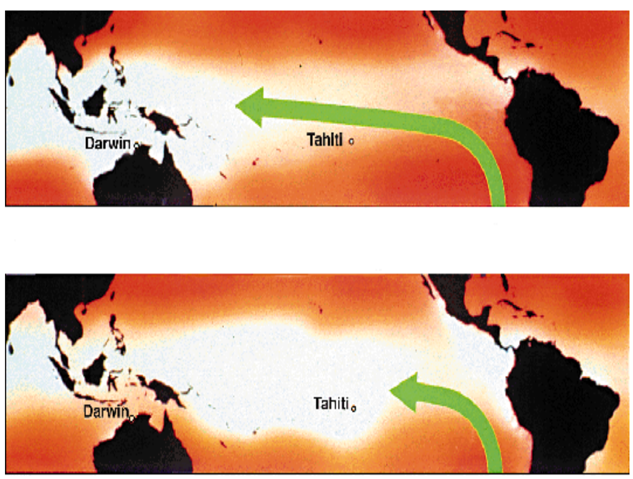


Figure 6 These graphs (left) portray the difference in the summertime ocean structure along the equator during a non-El Niño year, 1996, and 1997 which was a strong El Niño year. Notice the characteristic shift in warm water towards the central and eastern Pacific.

Figure 7 Sir Gilbert Walker discovered that air pressures at sea level in the South Pacific seesaw back and forth between two distinct patterns. In the "high index" phase of what Walker referred to as the "Southern Oscillation" (upper map for Nov. 1988) pressure is higher (darker red) near and to the east of Tahiti than near and to the west of Darwin. The east-west pressure gradient along the equator causes the air to flow westward, as indicated by the long arrow. When the atmosphere switches into the "low index" phase (lower map for Nov.1982), pressure rises in the west and falls in the east, signaling a reduction, or even a reversal of the pressure difference between Darwin and Tahiti. This causes the easterly trade winds to weaken and retreat eastward as shown. Scientists now know that the "low index" phase is El Niño.



The flip side of El Niño, known as La Niña, is characterized by stronger-than-normal trade winds, colder tropical Pacific sea surface temperatures, and a shift in heavy rainfall to the far western tropical Pacific (McPhaden 2004). The term means "the little girl" in Spanish, but is sometimes called El Viejo (anti-El Niño), or simply "a cold event" or "a cold episode". In many ways, La Niña is an exaggeration of normal conditions, accompanied by increased offshore Ekman transport and quite significant upwelling along the west coast of South America (see Figures 8-10). This is due to a steeper thermocline that is higher than normal in the eastern Pacific and lower than normal in the western Pacific. Also, the "cold tongue" of sea surface temperatures that is evident under normal conditions extends farther west than normal, usually past the International Date Line.

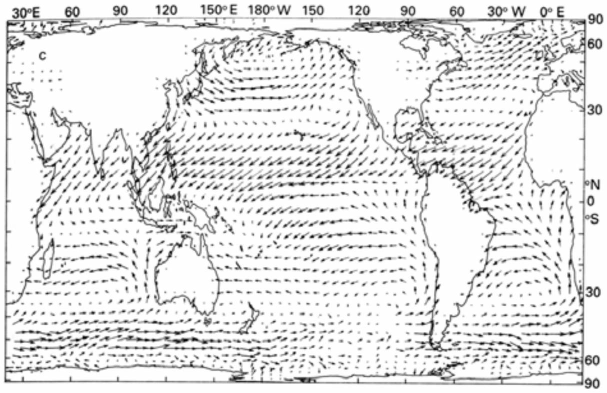


Figure 8 This map of ocean surface winds shows what happens under La Niña conditions. The easterly trade winds strengthen significantly across the Pacific, as indicated by the larger, more prominent arrows. The westerly winds can virtually disappear.

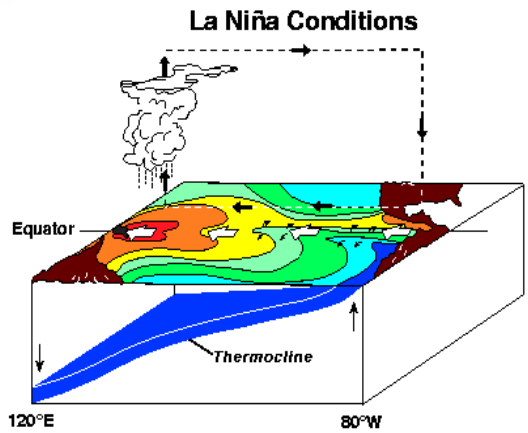


Figure 9 Schematic of La Niña conditions. The white arrows indicate the trade winds, which have strengthened, and the black arrows indicate the rainfall circulation pattern, which has shifted farther to the west. The thermocline has dropped in the west and risen in the east, causing coastal upwelling to increase.

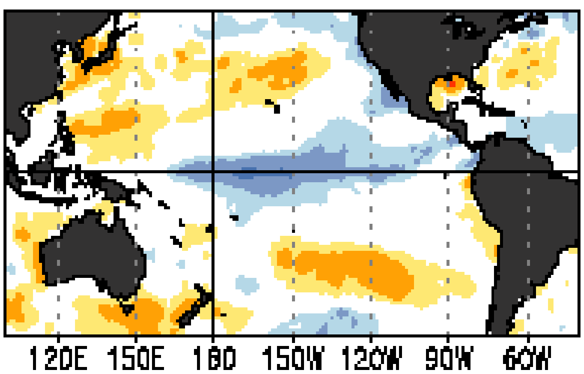


Figure 10 La Niña episodes are periods of exceptionally cold sea surface temperatures between the date line and the west coast of South America.

Localized and World-wide Impacts of ENSO Events

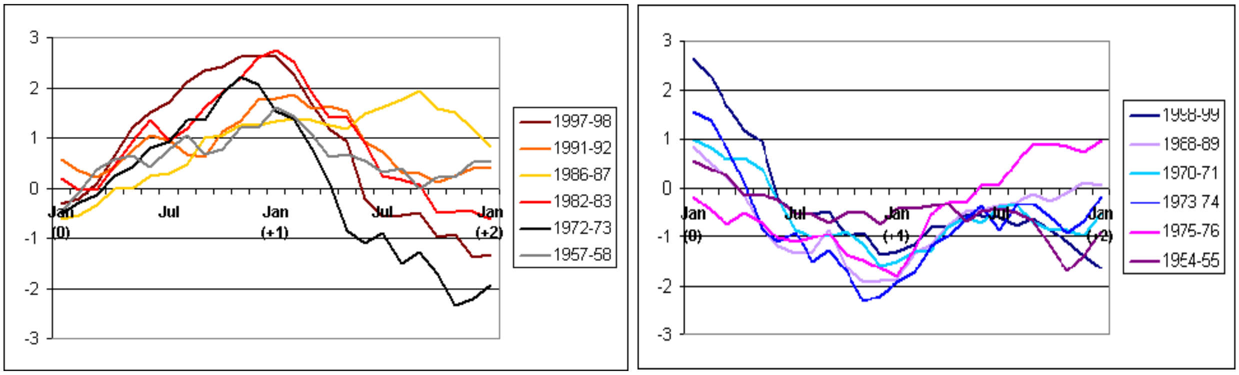
The El Niño-Southern Oscillation (ENSO) cycle is the most prominent year-to-year climate fluctuation on Earth (McPhaden 2004). Although it originates in the tropical Pacific, it extends its reach far beyond the tropical Pacific through atmospheric teleconnections that affect patterns of weather variability all over the world. The recent El Niño in 1997/98 was considered the strongest of the twentieth century, causing an estimated $36 billion worldwide in economic losses and 22,000 fatalities. The United States accounted for about $4 billion of these losses and about 200 fatalities.

For Peruvians, heavy flooding (due to the easterly shift in convection) and a severe loss in revenue for the fishing industry is associated with El Niño. Fisherman in this region rely upon the upwelling of cold, nutrient-rich water from deeper levels of the ocean to support the delicate marine ecosystem. Thus, when coastal upwelling significantly declines, the fisheries suffer greatly. For example, in 1970 (a non-El Niño year), Peru ranked as the number-one fishing nation in the world with an annual anchovy catch of 12.5 million metric tons. (The anchovy is the primary fish stock of commercial interest off the coast of Peru). When El Niño occurs and warm, nutrient-poor water invades Peru's coastal region, the anchovy population shifts to deeper water, migrates farther south in search of colder water, or fails to reproduce. In fact, this caused the collapse of the anchovy fishery in the 1972-1973 El Niño - the annual anchovy catch plummeted during these years to less than 2 million metric tons. These fish are also the main food source of the local guano bird. Therefore, in an El Niño year, these birds have great difficulty finding their prey and can starve to death by the millions. Following the 1982-1983 El Niño, the number of guano birds was estimated at 400,000, as opposed to more than 50 million in 1950.

On the other side of the globe, Australians and Indonesians endure terrible droughts and wildfires during El Niño episodes. Take, for example, the famous 1997-1998 El Niño, of which numerous forest fires in Indonesia and Malaysia were directly and indirectly related. It is estimated that 3-5 million hectares (1 ha = 2.2 acres) of rainforest were burned. (Fires are able to spread more quickly and burn larger areas during El Niño years because they are unmitigated by rainfall).

The East African country of Kenya was among the most adversely affected countries with respect to the impacts of the 1997-1998 El Niño (Glantz 2000). Kenyans were plagued by devastating flooding in cities and in rural areas, and by a major outbreak of Rift Valley Fever, which was blamed for the death of over a thousand people. Kenya's infrastructure was greatly damaged as well.

Figure 11 Flooded area in Lakeport, California as a result of the 1998 El Niño event (left).
Figure 12 Brush fire in Australia as a result of the 1998 El Niño event (right).
Figure 13a This graph shows the six strongest El Niño events that have been recorded since the 1950s. The 1982-1983 event tops the list, followed closely by the 1997-1998 event (next page; left).
Figure 13b This graph shows the six strongest La Niña events that have been recorded since the 1950s. The 1973-1974 event was the most severe, followed closely by the 1988-1989 event (next page; right).



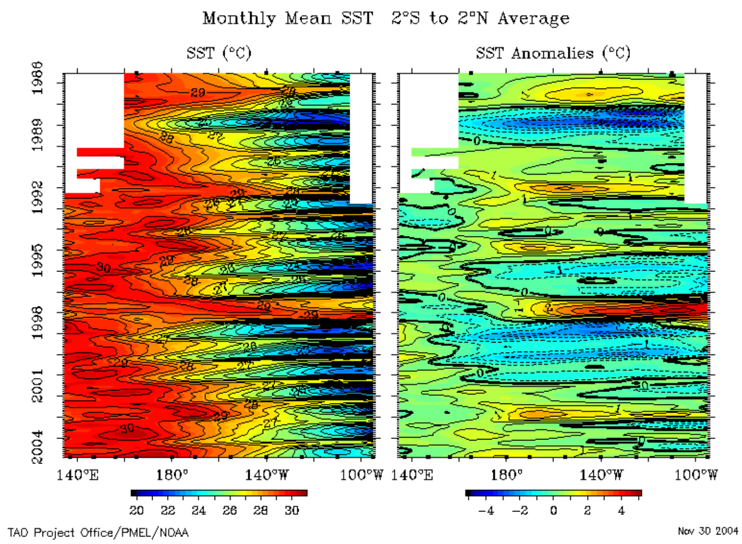


Figure 13c These graphs (left) depict every ENSO event from 1986 through this year (time is increasing downwards). The blue “scallops” on the right of the plot indicate the equatorial cold tongue of SST’s that are observed in the eastern Pacific. The strongest and most anomalous events show up most clearly. Notice the strength of the 1988-89 La Niña and the 1997-98 El Niño.

ENSO events have important impacts on hurricane and typhoon formation, as well. Hurricane formation requires fairly uniform winds throughout the atmosphere, meaning that they require low vertical wind shear. (Vertical wind shear refers to the change in wind speeds with height). El Niño episodes typically result in more eastern Pacific typhoons and fewer Atlantic hurricanes.

El Niño produces westerly wind departures at upper levels of the atmosphere and easterly wind departures at lower levels, across the eastern tropical Pacific Ocean and tropical Atlantic (Zhang 2004). These wind patterns are opposite those normally seen over the eastern Pacific, resulting in low vertical wind shear and, therefore, facilitating typhoon formation. Across the tropical Atlantic, these same wind departures increase the total vertical wind shear, often to speeds much too high for hurricane formation. There tend to be fewer Atlantic hurricanes during El Niño because of this expanded area of high vertical wind shear (Zhang 2004).

La Niña has the exact opposite effect on hurricane and typhoon activity. These cold episodes of the ENSO cycle produce easterly wind departures at upper levels of the atmosphere and westerly wind departures at lower levels, across the eastern tropical Pacific and tropical Atlantic Oceans. These wind patterns coincide with those normally seen over the eastern Pacific, resulting in high vertical wind shear and, therefore, a reduction in the number and intensity of typhoons. Across the tropical Atlantic, these same wind departures are opposite to those normally observed, resulting in lower vertical wind shear and an increase in the number and intensity of hurricanes.

El Niño and La Niña also tend to influence where hurricanes will form in the Atlantic. During El Niño, fewer hurricanes develop in the deep Tropics from African easterly waves. Conversely, during La Niña, more hurricanes form from these tropical waves. These storm systems have a much greater chance of becoming major hurricanes, and of eventually threatening the Caribbean Islands and the United States.

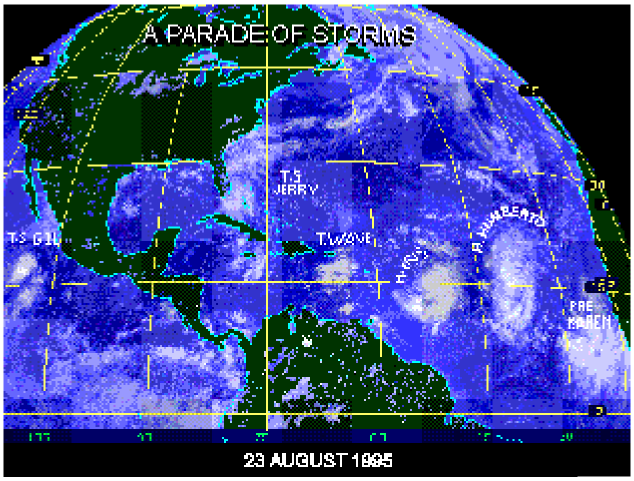


Figure 14 This satellite image shows five tropical storm systems – Tropical Storm Jerry, a Tropical Wave, Hurricane Iris, Hurricane Humberto, and pre-Karen - in the Atlantic on August 23, 1995, during La Niña. This is the largest number in many years of tropical storms recoded on a single day.

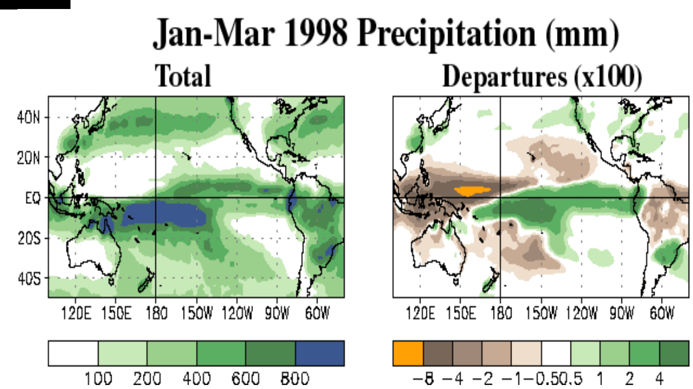


Figure 15a The left-hand panel shows the seasonal rainfall totals during the strong El Niño episode of January-March 1998 for over the Pacific basin. (The heaviest rainfall is shown by the darker green and blue colors). Since 25.4 mm is equal to one inch of rain, we see that the rainfall totals are more than 800 mm just south of the equator along the International Dateline (180° longitude), which is over 31.5 inches of rain and almost double the normal amount. The right-hand panel shows the seasonal rainfall departures from average for this year. (The areas with above average rainfall are shown by darker green colors, and the areas with below average rainfall are shown by the darker brown and orange colors). The rainfall departures are shown in units of 100 millimeters. Therefore, we see that the seasonal rainfall totals were more than 400m above normal just south of the equator along the International Date Line, which is more than 15.75 inches above normal. Conversely, the seasonal rainfall totals over the western Pacific just north of the equator were less than 100 mm (see left-hand panel), which is more than 800 mm (or 31.5 inches) below normal (see right-hand panel). This extreme drought led to several severe wildfires in Indonesia.

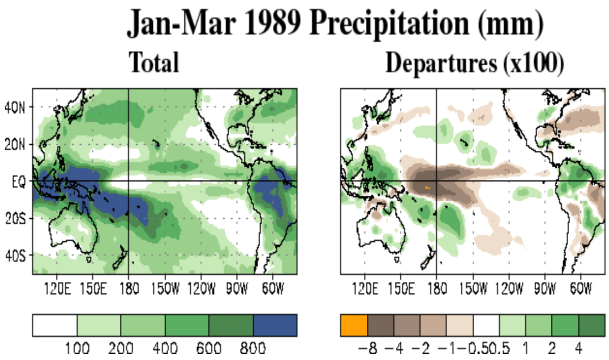
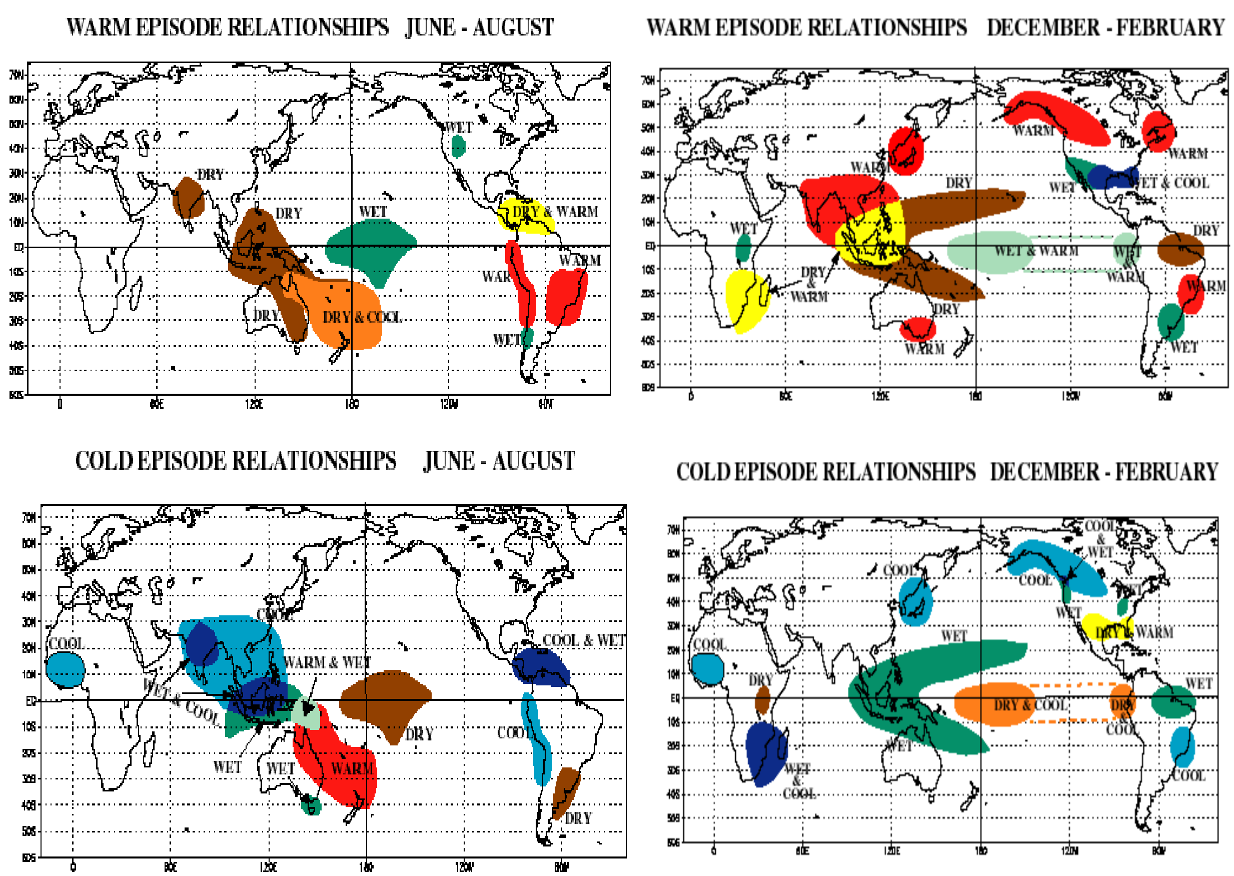


Figure 15b These diagrams show seasonal rainfall totals and departures during the strong La Niña episode of January-March 1989. In the left-hand panel, we see that the rainfall totals are more than 800 mm over the western tropical Pacific and Indonesia, which is more than 31.5 inches of rain. In the right-hand panel, we see that rainfall totals were about 200-400 mm above normal over the western tropical Pacific and Indonesia, which is about 8-16 inches above normal! We also see significantly below-average rainfall across the central tropical pacific, where totals in some areas were more than 400 mm (15.75 inches) below normal.

Figure 16a-d El Niño and La Niña episodes impact weather conditions around the globe. These four schematic diagrams (below) show the most common temperature and precipitation impacts that are associated with the two phenomena during the months of December-February and June-August.



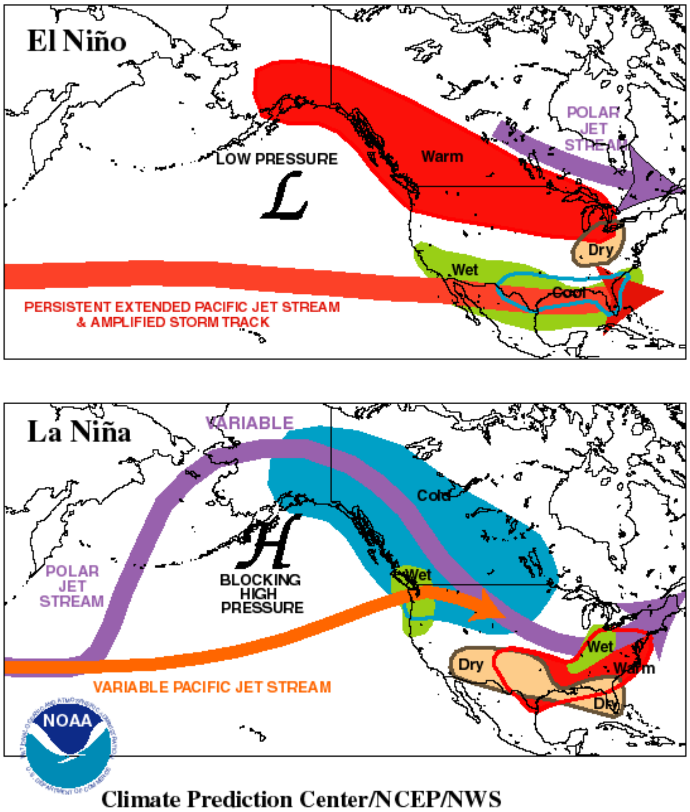
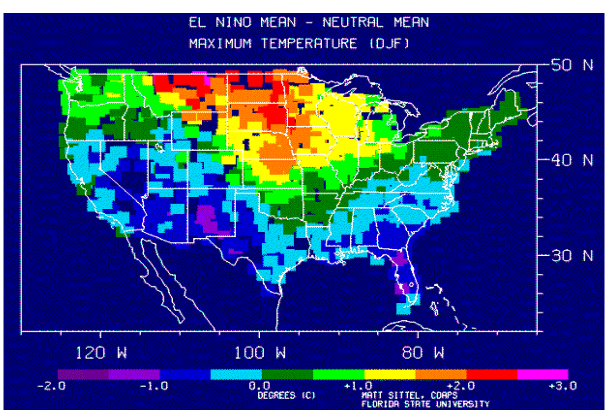


Figure 17a and b El Niño and La Niña episodes feature significant changes in the position and intensity of the wintertime jet stream. A strong jet stream and storm track with increased precipitation is characteristic of El Niño conditions across the southern part of the United States. Meanwhile, less stormy and milder-than-average conditions prevail across the northern states. A very wave-like jet stream flow over the United States and Canada is characteristic of La Niña conditions. The jet stream tends to enter North America in the northwestern United States/southwestern Canada and the strength of the jet stream is highly variable. As a result of this, colder temperatures and increased storminess persist across the northern states, while the southern states experience warmer temperatures and less storminess.

El Niño and La Niña episodes also impact tornado activity across the United States. Because a strong jet stream is an important ingredient for severe weather, the position of the jet stream often determines the regions more likely to experience tornadoes. Contrasting El Niño and La Niña winters, the jet stream over the United States is considerably different (Zhang 2004). The jet stream is oriented from west to east and shifted towards the southern portion of the United States during El Niño. Therefore, this region becomes more prone to severe weather outbreaks. Conversely, during La Niña, the jet stream and resulting severe weather is shifted farther north.



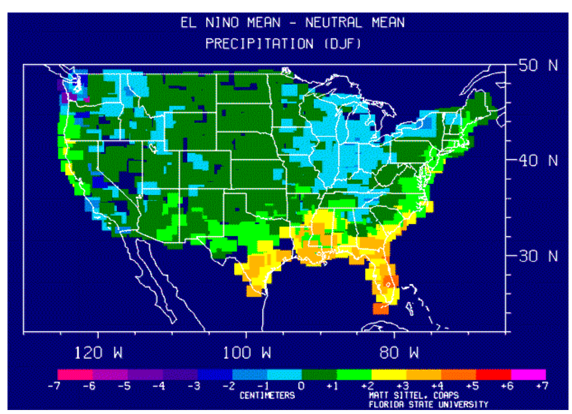


Figure 18a and b During an El Niño (left, previous page), there is a tendency for higher than normal temperatures in western Canada and the upper plains of the United States due to the low pressure system in the Pacific drawing up warm air into Canada, some of which filters into the northern United States (Zhang 2004). Another low pressure system draws cold moist air into the southern United States, bringing lower than normal temperatures to that region. We can also see that the same low pressure system in the southern United States is responsible for increases in precipitation during an El Niño, especially in those areas close to the Gulf of Mexico (right, previous page).

Figure 19 The economic consequences of an El Niño event can be astounding. Over eight billion dollars in damages can be directly attributed to the 1982 El Niño, which was the strongest El Niño event recorded in the twentieth century.

Monitoring and Forecasting ENSO Events

Accurate forecasts provide a basis for developing strategies that can be implemented to mitigate or take advantage of ENSO-related oceanic and atmospheric impacts. Much of the skill in long-range seasonal forecasts over the United States and elsewhere derives from scientist's ability to predict the evolution of sea surface temperature (SST) anomalies in the equatorial Pacific up to one year in advance.

There are two general types of prediction models that scientists currently use in order to predict SST's. A "dynamical model" consists of a series of mathematical expressions that represent the physical laws that govern the coupled ocean/atmosphere system. To make a forecast, dynamical models are given the current conditions in the ocean and atmosphere and then a computer "does the math" to determine what the future conditions (out to six months or more in advance) will be (Zhang 2004).

The second type of model, a "statistical model", uses observations of the past to make predictions for the future. To make a forecast with a statistical model requires a long history of observations, generally of the same kind that would be used as input for dynamical models, but extending far back in time, by as much as 30 to 50 years (Zhang 2004). This plethora of information is used to identify key quantitative features of the ocean and atmosphere that often occurred prior to subsequent changes in SST's in the equatorial Pacific. Examples of precursors for El Niño include (but are not limited to) 1) an increase in ocean temperatures in the western Pacific at certain depths, 2) a weakening of the easterly trade winds along the equator, 3) a strengthening of the westerly winds, and 4) a decrease in atmospheric pressure over the eastern Pacific. Statistical models are trained on the long history of these precursor events along with the resulting ENSO condition, thus they are able to predict the likelihood of various possible ENSO conditions for the next several months when given the current conditions. Statistical models range from the very simple analogs and regression analyses to the more complex nonlinear canonical correlation analyses or neurological networks.

One common statistical model that scientists use is the Southern Oscillation Index (SOI). This model calculates the surface air pressure difference between Tahiti and Darwin, Australia and shows a strong inverse correlation to sea surface temperature anomalies (see Figure 20).

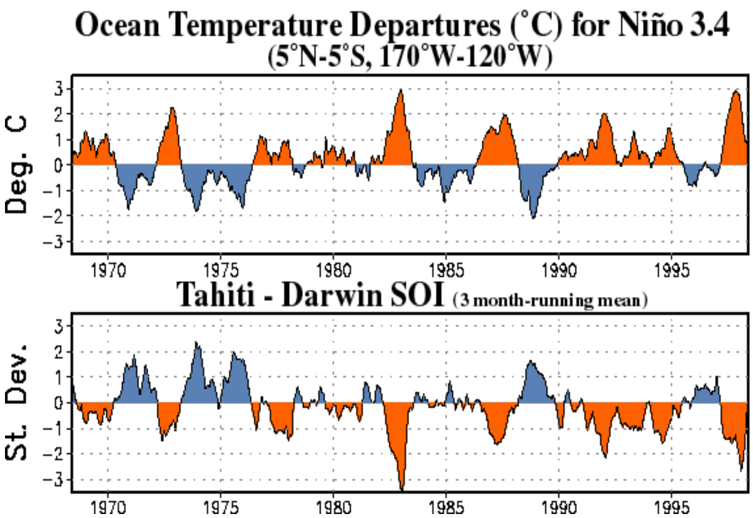
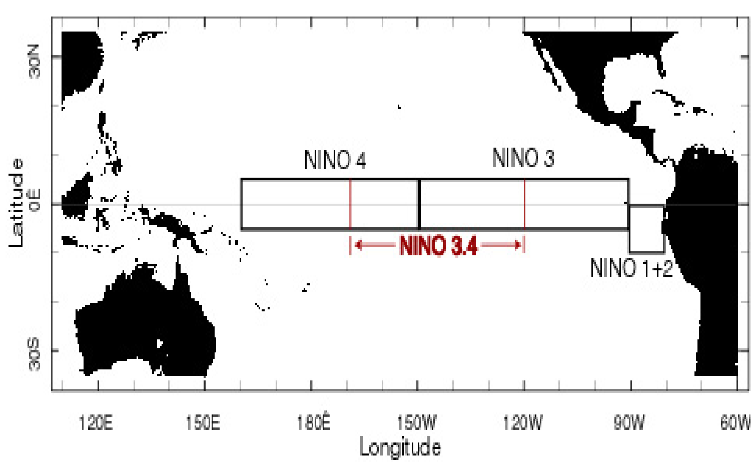


Figure 20 The negative phase of the SOI index represents lower-than-average air pressure at Tahiti and higher-than-average air pressure at Darwin. Negative SOI values that persist for several months coincide with unusually warm ocean waters across the eastern tropical Pacific typical of El Niño events. Positive SOI values that persist for several months coincide with unusually cold ocean waters across the eastern tropical Pacific typical of La Niña events. The advantage of the SOI is that records at those two locations go back a century, while there are only a few decades of SST observations in the central Pacific.

Figure 21 The central equatorial Pacific has been divided into four sections in order to monitor the evolution of SST's and, therefore, the phases of the ENSO cycle: <u>Niño 1+2</u> (0°-10° South) (90° West-80° West) <u>Niño 3</u> (5° North-5° South) (150° West-90° West) <u>Niño 4</u> (5° North-5° South) (160° East-150° West) <u>Niño 3.4</u> (5° North-5° South) (170°-120° West)



The accuracy of statistical models depends on the quality of the data entered into them. This presents a problem due to the lack of comprehensive, long-term records of many of the important quantities of interest. Prior to the mid-1950s, the ocean observations are sparse and ambiguous, making it difficult to determine the strength – or even the presence – of an El Niño or La Niña. Also, statistical models can fail because El Niño and La Niña are not exact, repeating phenomena. Scientists have observed that different events evolve in different patterns, can occur at different times of the year, etcetera. For example, the ENSO cycle has an average period of about four years, but historical records show that the period has varied between two and seven years – scientists aren't sure why. The 1980's and 1990's featured a very active ENSO cycle, with five El Niño events (1982/83, 1986/87, 1991-1993, 1994/95, and 1997/98) and three La Niña events (1984/85, 1988/89, and 1995/96) occurring during the period. This period also featured the two strongest El Niño events of the twentieth century (1982/83 and 1997/98), as well as two consecutive periods of El Niño conditions during 1991-1995 without and intervening La Niña event. So there is significant variability in the ENSO cycle from one decade, which may be relatively inactive, to the next, which may have a quite pronounced cycle. In addition, there are many climate oscillations on all timescales occurring simultaneously, and the weather at any given location is the sum of these oscillations and the interactions between them. Most of these oscillations are still poorly understood, particularly the longer-term ones, and as scientists get better and longer records more and more complexity is revealed. Thus, it is not straightforward to isolate the specific effects of ENSO by averaging over previous events. All of this results in the blurring of statistics and the reduction of confidence in such a forecast.

Dynamical models have some advantages over statistical models. For example, dynamical models are able to handle unprecedented climate events, since the basic physics would apply equally well to new situations as to familiar situations. Statistical models, on the other hand, can only see new situations as extrapolations of historically observed ones, and run the risk of missing any new discoveries.

However, dynamical models also have some significant disadvantages compared with statistical models. For example, dynamical models require much greater computer power than statistical models because the physical equations are much more complex than statistical equations. To give this some perspective, the difference is between a PC and a supercomputer! Also, dynamical models must approximate some of the oceanic and atmospheric physics because they operate on spatial scales that are too small to be represented in the model. Consider, for example, the difficulty of representing clouds in a dynamical model. The growth and precipitation of individual cumulus clouds in the tropics cannot be treated on an individual cloud basis, and must be estimated by a formula so that the results come out about right in an overall sense. This indirect treatment can compromise the accuracy of the forecast.

In modern ENSO forecasting, both dynamical and statistical models continue to be used, as the skills of both kinds of models have been found to be nearly equal. However, the general consensus among oceanographers and atmospheric scientists is that dynamical models will prove superior as computer power increases and more is learned about ENSO physics. In the meantime, as statistical models are faster and less expensive to use, their skill is often thought to represent a standard against which the skills of the more expensive dynamical models can be judged.

While forecasting of ENSO and its global consequences are far from perfect, there has nonetheless been significant progress in the development and application of ENSO forecasts over the past twenty years. As one measure of this progress, V. Kousky of the National Oceanic and Atmospheric Association (NOAA) Climate Prediction Center (CPC) attributed the success of his group in forecasting the 2002/03 El Niño to "…a combination of more experience watching El Niños develop, two decades of research, and the observation network that NOAA and NASA have invested in" (McPhaden 2004). The ENSO Observing System, inspired by the devastating impacts of the 1982/1983 El Niño, was developed as a multinational effort in support of ENSO prediction during the ten-year (1985-1994) Tropical Ocean Global Atmosphere (TOGA) Program. The key feature of the observing system is the real-time delivery, via satellite, of oceanographic and surface atmospheric data for the purpose of monitoring changing conditions, making scientific analyses, and forecasting the state of the ENSO cycle.

The system was designed with emphasis on the ocean, which was very sparsely sampled and for which no equivalent, such as the World Weather Watch, existed (McPhaden 2004). In situ components consist of the Tropical Atmosphere Ocean/Triangle Trans-Ocean Buoy Network (TAO/TRITON) array of seventy moored buoys, an array of drifting buoys, a network of volunteer observing ships, and an island and coastal tide gauge network for sea level measurements (see Figure 22, below).

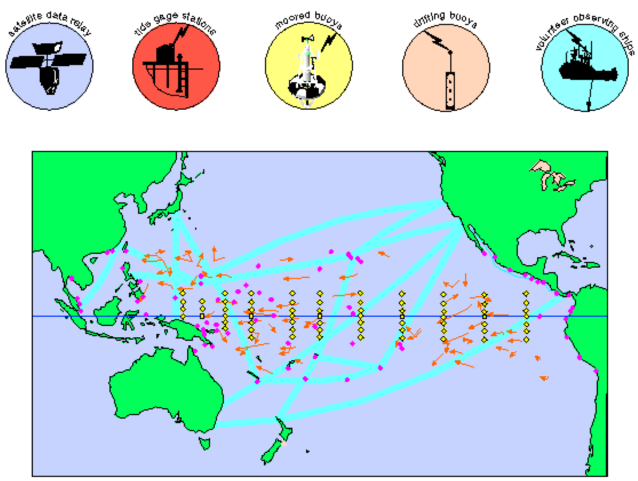


Figure 22 Shown here are the in situ components of the ENSO Observing System. The yellow squares and diamonds show the locations of moored buoys, which operate continuously for months at a time without human intervention. They monitor surface wind and other atmospheric elements, as well as water temperatures at several levels at and below the ocean surface. The pink dots are tide gauge stations. The orange arrows depict the tracks of drifting buoys. These measure water temperature and reveal the motion of the surface water. The blue lines represent the tracks of volunteer ships that make surface meteorological observations and take profiles of ocean temperatures at various depths. Not shown here are the numerous research satellites that provide critical space-based measurements. Most of the data from the in situ components are transmitted to shore within hours of collection via satellite.

Figure 23 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 (online at http://www7.nationalacademies.org/opus/elnino_7.html0).

While the ENSO Observing system has revolutionized scientist's ability to predict ENSO events, there is still much room for improvement in scientist's ability to predict the details of individual El Niño and La Niña events and their global and regional climatic consequences. We have already seen the staggering effects of El Niño and La Niña episodes and the subsequent need for scientists to continue to research and strive to understand these phenomena.

Consider, for example, that nearly twenty-five percent, or $2.7 trillion, of the Gross National Product (of the United States) is either directly or indirectly impacted by weather and climate - this gives Americans plenty of reason for concern about both extremes of the ENSO cycle. In California, prior to the 1997/98 El Niño, this state's emergency management agencies and FEMA spent about $165 million in preparation for increased rainfall. Actual storm losses during this year totaled $1.1 billion, compared to $2.2 billion in the major 1982/83 El Niño. Although portions of the $1.1 billion difference are due to different intensities and durations of storminess during each El Niño, a significant portion of the savings came from heightened preparedness (online at http://www.noaanews.noaa.gov/magazine/stories/mag24.htm). So, even though it costs nearly $5 million annually to maintain the in situ components of the ENSO Observing System, many more dollars can be saved with improved ENSO forecasts.

Peruvians consider even a short-term forecast to be valuable. In Peru, as in most developing countries, the economy (and food production in particular) is highly sensitive to climate fluctuations. La Niña years are often welcomed by fishermen, but not by farmers because these years have frequently been marked by drought and crop failures. Once a forecast is issued, farmers can decide on the appropriate combination of crops to sow in order to maximize the overall yield. Rice and cotton, two of the primary crops grown in northern Peru, are very sensitive to the amount and timing of rainfall. Rice thrives on an abundance of rain during the growing season followed by drier conditions during the ripening phase. Cotton, with its deeper root system, does best in drier weather. Therefore, a forecast of an El Niño event might induce farmers to sow more rice and less cotton than in a non-El Niño year.

For hydroelectric power production, storage and release decisions can be altered from normal use patterns in anticipation of increased rainfall (during El Niño) in the coming winter-spring season. For example, winter stream flows into the Tennessee Valley Authorities' large reservoirs can be as much as 30% above normal in El Niño years, allowing efficiency gains by switching from thermal power to hydropower. Australians can also benefit greatly from accurate and timely ENSO forecasts by taking the appropriate measures to combat severe droughts and brushfires typical of El Niño episodes. Even in the small Northwest Coho salmon fishery, annual benefits are estimated to be between $250,000 and $1 million from changing hatchery releases and harvest rates. Agriculture, energy generation, water resources, forestry, fisheries, transportation, commerce, public health – all of these industries hold the potential for millions of dollars in benefits.

The perplexing ENSO cycle will continue to challenge atmospheric and oceanic researchers and forecasters, not only because it is a fascinating scientific puzzle, but also because it is the harbinger of crippling socioeconomic impacts.

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
Gilbert Walker 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.

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 developed 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.

Timeline 1 Although scientists have a long way yet to go, this timeline provides a testament to how far scientists have come in understanding the complexity of the ENSO cycle. (Online at http://www7.nationalacademies.org/opus/elnino_9.html)

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