FAQs
(Frequently Asked Questions)
on
El Niño/La Niña/ENSO

Credit: Oman, 2014

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FAQS ON EL NIÑO/LA NIÑA/ENSO

I. HISTORY AND EXPOSURE

A. Is El Niño something new and unusual in the Earth's climate?

No. El Niño has been occurring at least since people started putting thermometers in the ocean around the middle of the nineteenth century. Moreover, archived documents left by the Spanish colonists in Peru confirm that El Niño impacts such as occur now (flooding, marine life disturbances, etc.) have been felt in Peru ever since the first conquistador (Francisco Pizarro) set foot there in the early 16th century. And, as far as we can tell from paleo-climatic indicators such as geological evidence & tree rings, El Niño has been occurring for at least thousands of years, probably much as it has during this century. It will probably continue to occur as long as our climate system works the way it has since the most recent ice sheets of the late pleistocene receded (i.e., needing to get rid of excess tropical heat as explained in the question Does El Niño play a special role in Nature?).

B. What Have we Learned from the Past?

In contrast to the march of the seasons, which is regular and therefore highly predictable, El Niño recurs at irregular intervals ranging from two years to a decade, and no two events are exactly alike. For example, the 1982-83 El Niño caught scientists by surprise because, unlike the El Niños of the previous three decades, it was not preceded by a period of stronger than normal easterlies on the equator. To further confuse scientists, this particular event also set in unusually late in the calendar year.

In order to guard against the possibility of being surprised by another "maverick" El Niño, scientists continue to document as many past events as possible by piecing together bits of historical evidence from many different sources, including:

- Sea-surface temperature records. Many millions of reports from merchant ships crossing the equator have been collected for over a century. Puerto Chicama on the Peru coast has reported water temperature regularly since the 1930s.
- Daily observations of atmospheric pressure and rainfall. Some stations, like the one at Darwin, Australia, have records extending back more than 100 years.
- Fisheries' records from South America.
- Writings of Spanish colonists in settlements along the coasts of Peru and Ecuador dating back to the late 15th century.

So-called "proxy evidence" based on coral samples from, for example, the Galapagos Islands provides information on how the frequency of El Niño events may have varied on a time scale of centuries to, potentially, thousands of years. Even data from trees, in the varying widths of their annual growth rings, provide clues to El Niños of past centuries.

C. Why has the public not heard much about La Niña before now?

For many decades, scientists have known about the oscillation in atmospheric pressure across the tropical Pacific at the heart of both El Niño and La Niña. However, La Niña's effects on fisheries along the immediate coast of South America, where El Niño was named, are benign rather than destructive, so La Niña received relatively little attention there. Research on La Niña increased after its wider impacts (often called teleconnections) were recognized in the 1980s.

D. So, did El Niño also occur during the ice ages?

We don't know yet. The global climate was very different then and the need for a heat-exporting mechanism may not have existed. As you might guess, however, scientists are anxious to know this because it will help us to understand how sensitive the features of our present climate system (such as ENSO) are to significant changes in the climatic background state. Clearly we are altering our present climate, so we need to understand what kinds of changes in weather systems might be expected as a result.

E. Could the problem of disentangling the many factors and dynamics at play in El Niño and global warming be compared to writing down the scores of many different tunes whilst they are played all at the same time. Might cacophony be a good analogy to describe circulation patterns?

That's a nice analogy. However, it could be refined in the following way: when the scores are played together, they not only become entangled, but they may actually metamorphose into a slightly different tune, one for which no score existed at the start of the piece. That is to say, that El Niño, global warming, and other climate signals are actually physically altered by their interaction in ways you would not expect by considering them in isolation. Sorting out these complex interactions is in fact one of the major challenges of climate research today.

F. Why don't you see much publicity about the causes of El Niño?

The reason that you don't see much publicity about the causes of El Niño is that we don't understand the origins of the event. We do, however, have a pretty good understanding of how it evolves once it has begun, and that gives a useful ability to make forecasts 6-9 months ahead for some regions. That is the information you see because that is the present state of reasonably secure knowledge. Of course, there are a variety of theories, and many scientists are working on various aspects of the genesis, which would presumably extend the predictive skill out another few months or even years.

The fact is, at several points over the past two decades we thought we had working theories of what causes El Niño. Unfortunately (or perhaps fortunately for those who like scientific challenges), nature has shown that those theories were at best incomplete. For example, during the mid-1980s a group at Columbia University developed a fairly simple theory and wrote a computer model to produce predictions based on it. This was successful in predicting the 1986-87 and 91-92 events almost a year in advance, and they were (figuratively?) breaking out the champagne. Then along came the event of 1993, then another in

94-95, and most prominently the present event [early 2000s], none of which developed according to the ideas in their theory.

The main reason this is so difficult is that the processes that cause El Niños involve the full complexity of ocean-atmosphere interaction on a global scale. We have developed a reasonably good understanding of how the atmosphere works (at least in theory), *once the sea surface temperature (SST) that drives the atmospheric circulation is known*. (We are somewhat further behind when it comes to the ocean, which is much harder to observe). That works pretty well to run the atmospheric models to make short-term weather forecasts because the ocean changes rather slowly. But, when you consider longer-term phenomena like El Niño, it is not enough to specify the SST; one must consider how the ocean will evolve under the winds, and then how the altered ocean will modify the winds, and so on, in many tricky and sensitive feedback loops. We are just beginning to be able to see how these fundamentally coupled disturbances work, and generally only in very idealized cases. Remember that for a long time meteorologists only talked to meteorologists, and oceanographers only to oceanographers. Now we are really at the initial stages of being able to think about these coupled problems.

II. ENSO

A. What is ENSO?

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1. ENSO stands for El Niño Southern Oscillation. The ENSO cycle refers to the coherent and sometimes very strong year-to-year variations in sea-surface temperatures, convective rainfall, surface air pressure, and atmospheric circulation that occur across the equatorial Pacific Ocean. El Niño and La Niña represent opposite extremes in the ENSO cycle.

   El Niño refers to the above-average sea-surface temperatures that periodically develop across the east-central equatorial Pacific. It represents the warm phase of the ENSO cycle, and is sometimes referred to as a Pacific warm episode.

   La Niña refers to the periodic cooling of sea-surface temperatures across the east-central equatorial Pacific. It represents the cold phase of the ENSO cycle, and is sometimes referred to as a Pacific cold episode.

2. It is the "El Niño-Southern Oscillation," the name that scientists use for what is often called El Niño. Historically, El Niño referred to warming of

ocean water in the eastern Pacific. The Southern Oscillation is a see-saw shift in surface air pressure between Darwin, Australia, and Tahiti. When pressure is high at Darwin, it's low at Tahiti and vice versa. In the 1950s scientists realized that the El Niño and the Southern Oscillation were parts of the same event. During normal times, the pressure is lower at Darwin than at Tahiti. But during the warm phase, usually called "El Niño," the pressure is lower at Tahiti.

3. “ENSO" stands for "El Niño / Southern Oscillation". The acronym arose in the climate research community, and reflects an attention bias toward the warm phase of the entire cycle.

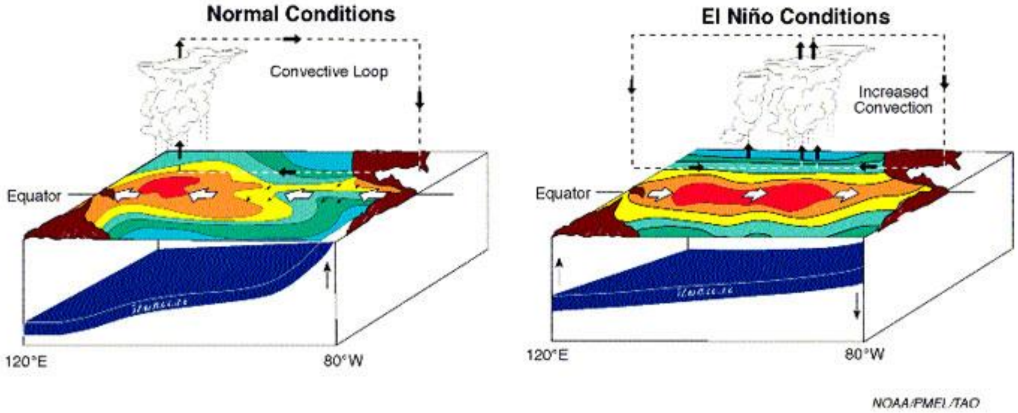
El Niño is just one phase of an irregular fluctuation between warmer than usual and colder than usual ocean temperatures in the region mentioned above. The cold phase has recently come to be known as "La Niña". The El Niño/La Niña "cycle" does not occur with strict periodicity. Historically, an El Niño usually recurs every 3-7 years, as does its (cold) La Niña counterpart.

The overlying atmosphere is tightly coupled to ocean temperatures and circulation patterns. An atmospheric pressure signal is seen throughout the tropics that is strongly linked to El Niño and La Niña. When barometric pressure is higher than usual in the western Pacific near Indonesia, pressure is lower than usual in the subtropical Pacific near Easter Island and Tahiti. This global-scale pressure signal, identified 70 years ago, is known as the "Southern Oscillation". Surface barometric pressure at Darwin, Australia and the island of Tahiti are strongly anti-correlated: when one is higher than usual, the other is lower than usual. The difference, Tahiti minus Darwin, suitably normalized, is referred to as the Southern Oscillation Index (SOI), and is frequently used as a convenient, simple and reasonably accurate tool to monitor the status of El Niño/La Niña.

Because more attention has been devoted to El Niño, and noting the association between the Southern Oscillation in the atmosphere and El Niño (and La Niña) in the ocean, the research community began to refer to the combination as ENSO (El Niño/Southern Oscillation). This moniker is somewhat asymmetric: El Niño pertains to just one of the two phases of the Southern Oscillation.

It would be perhaps more accurate to refer to El Niño as the warm phase of the Southern Oscillation, and to La Niña as the cold phase of the Southern Oscillation. The term "ENSO" is, however, firmly engrained.

III. EL NIÑO



NOAA/PMEL/TAO

A. How did El Niño receive its name?

1. El Niño originally was the name used for warmer than normal sea surface temperatures in the Pacific Ocean off the west coast of South America. It occurs when the easterly winds die down, in turn allowing for warmer waters normally kept in the western Pacific to drift eastward towards the Americas. El Niño is Spanish for 'the Christ child' and gets this name because it is known to occur during the Christmas season off the coast of South America. Now, El Niño has come to refer to a whole complex of Pacific Ocean sea-surface temperature changes and global weather events. The warming off South America is just one of these events.

2. The term El Niño (Spanish for "the Christ Child") was originally used by fishermen along the coasts of Ecuador and Peru to refer to a warm ocean current that typically appears around Christmastime and lasts for several months. Fish are less abundant during these warm intervals, so fishermen often take a break to repair their equipment and spend time with their families. In some years, however, the water is especially warm and the break in the fishing season persists into May or even June. Over the years, the term "El Niño" has come to be reserved for these exceptionally strong warm

intervals that not only disrupt the normal lives of the fishermen, but also bring heavy rains.

3. El Niño translates from Spanish as 'the boy-child'. Peruvian fisherman originally used the term – a reference to the Christ child—to describe the appearance, around Christmas, of a warm ocean current off the South American coast.

Nowadays, the term El Niño refers to the extensive warming of the central and eastern Pacific that leads to a major shift in weather patterns across the Pacific. In Australia (particularly eastern Australia), El Niño events are associated with an increased probability of drier conditions.

Changes to the atmosphere and ocean circulation during El Niño events include:

- Warmer than normal ocean temperatures across the central and eastern tropical Pacific Ocean.
- Increased convection or cloudiness in the central tropical Pacific Ocean - the focus of convection migrates from the Australian/ Indonesian region eastward towards the central tropical Pacific Ocean.
- Weaker than normal (easterly) trade winds.
- Low (negative) values of the SOI (Southern Oscillation Index).

Monitoring these changes help to detect an El Niño event and forecast its lifetime.

4. El Niños were originally recognized by fisherman off the coast of South America as the appearance of unusually warm water in the Pacific ocean, occurring near the beginning of the year. El Niño means *The Little One* in Spanish. This name was used for the tendency of the phenomenon to arrive around Christmas.

5. Our first knowledge of this came from Peruvian geographers, who at the end of the 19th century were interested in the unusual climate aberrations that occurred along the Peru coast in the odd year. They took note of what a knowledgeable ship captain said about the fishermen in northern Peru, who typically saw a switch from cold to tropical ocean conditions around Christmas of every year and attributed this to a southward setting, warm "El Niño current". The term was an obvious reference to the Christ child. We don't actually know how mythical this story might be, but that is the tale that got passed on. The geographers noted that in some years the onset of warm conditions was stronger than usual and was accompanied by unusual oceanic and climatic phenomena.

Starting with the arrival of foreign-based scientific expeditions off Peru in the early 20th century, the concept gradually spread through the world's scientific community that "El Niño" referred to the unusual events. The annual occurrence was forgotten, although one geographer (Eguiguren) lamented this inaccuracy. It was separately noted by Sir Gilbert Walker in the 1930s that notable climate anomalies occur around the world every few years. These were associated with what he called the Southern Oscillation (SO), a large fluctuation in atmospheric pressure. In the 1950's, Berlage observed that the SO-related climate anomalies generally coincided with El Niño occurrences. It wasn't until about 1960 that scientists came to realize that the warming off Peru is only part of an ocean-wide perturbation that extends westward along the equator out to the dateline. About the same time, the noted meteorologist Jacob Bjerknes proposed that El Niño was just the oceanic expression of a large-scale interaction between the ocean and the atmosphere and that the climate anomalies could be understood as atmospheric "teleconnections" emanating from the warm-water regions along the equator in the mid-Pacific. The catchy term "El Niño" is frequently abused in the popular vernacular through the tendency of people to confuse what is essentially an oceanic happening with the climate anomalies that are associated with it.

Starting in about 1975, oceanographers and meteorologists began to combine their efforts to expand and refine the Bjerknes hypothesis by systematically studying the El Niño and the Southern Oscillation together in what we now call "El Niño–Southern Oscillation", or ENSO. The advent of powerful computers and modern measurement systems has caused a rapid acceleration in our understanding of ENSO, especially since the large event of 1982/83.

6. The name El Niño (referring to the Christ child) was originally given by Peruvian fisherman to a warm current that appeared each year around Christmas. What we now call El Niño seemed to them like a stronger event of the same type, and the usage of the term changed to refer only to the irregular strong events. It wasn't until the 1960s that it was widely realized that this was not just a local Peruvian occurrence, but was associated with changes over the entire tropical Pacific and beyond.

The following quote is given in the introduction to an excellent (scholarly) book by George Philander of Princeton University ("El Niño, La Niña and the Southern Oscillation", Academic Press, 1990). These are remarks quoted from

Senor Federico Alfonso Pezet's address to the Sixth International Geographical Congress in London in 1895.

In the year 1891, Senor Dr Luis Carranza, President of the Lima Geographical Society, contributed a small article to the Bulletin of that Society, calling attention to the fact that a countercurrent flowing from north to south had been observed between the ports of Paita and Pacasmayo.

The Paita sailors, who frequently navigate along the coast in small craft, either to the north or the south of that port, name this countercurrent the current of "El Niño" (the child Jesus) because it has been observed to appear immediately after Christmas.

As this countercurrent has been noticed on different occasions, and its appearance along the Peruvian coast has been concurrent with rains in latitudes where it seldom if ever rains to any great extent, I wish, on the present occasion, to call the attention of the distinguished geographers here assembled to this phenomenon, which exercises, undoubtedly, a very great influence on the climatic conditions of that part of the world.

The name El Niño now refers to the warm phase of a large oscillation in which the surface temperature of the central/eastern part of the tropical Pacific varies by up to about 4°C, with associated changes in the winds and rainfall patterns. The complete phenomenon is known as the El Niño/Southern Oscillation, abbreviated ENSO. The warm El Niño phase typically lasts for 8-10 months or so. The entire ENSO cycle lasts usually about 3-7 years, and often includes a cold phase (known as La Niña) that may be similarly strong, as well as some years that are neither abnormally hot nor cold. However, the cycle is not a regular oscillation like the change of seasons, but can be highly variable in strength and timing. At present we do not fully understand what causes these changes in the ENSO cycle.

The Southern Oscillation was named in 1923 by Sir Gilbert Walker, who noted that "when pressure is high in the Pacific Ocean it tends to be low in the Indian Ocean from Africa to Australia". This was the first recognition that changes across the tropical Pacific and beyond were not isolated phenomena but were connected as part of a larger oscillation. Walker was Director of Observatories in India and was mostly concerned with variations in the Indian monsoon.

The first real description of El Niño/Southern Oscillation in terms of physical mechanisms was by Prof Jacob Bjerknes of the University of California, Los Angeles (UCLA) in 1969.

B. Technically speaking, what is an El Niño?

1. El Niño is an intermittent disruption of the climate system centered in the equatorial Pacific that has effects on short-term climate around the Pacific basin.

2. El Niño, or more completely, the El Niño/Southern Oscillation (ENSO) refers to the phenomenon where the normal ocean/atmosphere circulation patterns in the South Pacific Ocean are disrupted, resulting in higher than normal sea surface temperatures in the eastern South Pacific Ocean. Because this disruption, when it appears every few years, is usually strongest around Christmas time, South American fishermen (who are adversely affected by it) called it El Niño (Spanish for *the Christ child*). Scientists are not yet certain of the causes underlying the phenomenon, but it is clear that there is a good connection with anomalous weather patterns around the world.

El Niño is where the normal circulation patterns of the atmosphere and ocean in the Southern Pacific break down and may even reverse. La Niña, on the other hand, is an abnormal strengthening of that normal circulation.

3. El Niño is an unusual warming of the tropical Pacific Ocean that occurs irregularly at about 3-6 year intervals in response to a large scale weakening of the trade winds that normally blow westward from South America toward Asia. Normally, the trade winds produce cool surface water in the eastern Pacific, through evaporation and the upwelling of colder water from below the surface. Simultaneously, they "corral" warm surface waters over in the far western Pacific. As the trade winds weaken, so does the containment of the warm water in the west and the maintenance of the coolness in the east. As a result, relatively warm water becomes ubiquitous all across the Pacific from New Guinea to South America. Although the immediate cause (wind weakening) is known and scientists have made much progress in understanding the phenomenon, the exact nature of the processes that govern its repetitive cycle are still not certain.

4. El Niño is an oscillation of the ocean-atmosphere system in the tropical Pacific that has important consequences for weather around the globe.

Among these consequences are increased rainfall across the southern tier of the US and in Peru, which has caused destructive flooding, and drought in the West Pacific, like that that has sometimes been associated with devastating brush fires in Australia. Observations of conditions in the tropical Pacific are considered essential for the prediction of short-term (a few months to 1 year) climate variations. To provide necessary data, NOAA operates a network of buoys which measure temperature, currents and winds in the equatorial band. These buoys daily transmit data which are available to researchers and forecasters around the world in real time.

In normal, non-El Niño conditions, the trade winds blow towards the west across the tropical Pacific. These winds pile up warm surface water in the west Pacific, so that the sea surface is about 1/2 meter higher at Indonesia than at Ecuador.

The sea surface temperature is about 8 degrees C higher in the west, with cool temperatures off South America, due to an upwelling of cold water from deeper levels. This cold water is nutrient-rich, supporting high levels of primary productivity, diverse marine ecosystems, and major fisheries. Rainfall is found in rising air over the warmest water, and the east Pacific is relatively dry. The observations at 110 W show that the cool water (below about 17 degrees C) is within 50m of the surface.

During El Niño, the trade winds relax in the central and western Pacific leading to a depression of the thermocline in the eastern Pacific, and an elevation of the thermocline in the west. The observations at 110W show, for example, that during 1982-1983, the 17-degree isotherm dropped to about 150m depth. This reduced the efficiency of upwelling to cool the surface and cut off the supply of nutrient rich thermocline water to the euphotic zone. The result was a rise in sea surface temperature and a drastic decline in primary productivity, the latter of which adversely affected higher trophic levels of the food chain, including commercial fisheries in this region. The weakening of easterly trade winds during El Niño is also evident. Rainfall follows the warm water eastward, with associated flooding in Peru and drought in Indonesia and Australia. The eastward displacement of the atmospheric heat source overlaying the warmest water results in large changes in the global atmospheric circulation, which in turn force changes in weather in regions far removed from the tropical Pacific.

5. El Niño is a warming of the Pacific Ocean between South America and the dateline, centered directly on and typically extending several degrees of latitude to either side of the equator. Coastal waters near Peru are also warm. The warming is expressed as a departure from long-term average ocean temperatures, which are generally cool in the region due to upwelling. El Niño is thus associated with a slackening, or even cessation, of the cold upwelling conditions which typically prevail in that area.

During a typical El Niño, the ocean warms a degree or two (C) above its climatological average. A strong El Niño can warm by 3-4 degrees C over large areas, and even 5 degrees C in smaller regions.

Typically, El Niño is first noticed along the South American coast around Christmas (hence the origin from Peruvian fishermen of its Spanish name ("the child")). Farther west, in the open ocean, El Niño typically begins to appear about a month later (near the Galapagos) to about 4 months later (near the Date Line) than near the coast.

6. The term El Niño refers to the large-scale ocean-atmosphere climate phenomenon linked to a periodic warming in sea-surface temperatures across the central and east-central equatorial Pacific (between approximately the date line and 120^{o}W). El Niño represents the warm phase of the El Niño/Southern Oscillation (ENSO) cycle, and is sometimes referred to as a Pacific warm episode. El Niño originally referred to an annual warming of sea-surface temperatures along the west coast of tropical South America.

NOAA's Climate Prediction Center, which is part of the National Weather Service, declares the onset of an El Niño episode when the 3-month average sea-surface temperature departure exceeds 0.5^{o}C in the east-central equatorial Pacific [between 5^{o}N-5^{o}S and 170^{o}W-120^{o}W].

7. El Niño, or more completely, the El Niño/Southern Oscillation (ENSO), refers to the phenomenon where the normal ocean/atmosphere circulation patterns in the South Pacific Ocean are disrupted, resulting in higher than normal sea surface temperatures in the eastern South Pacific Ocean. Because this disruption, when it appears every few years, is usually strongest around Christmas time, South American fishermen (who are adversely affected by it) called it El Niño (Spanish for *the Christ child*). Scientists are not yet certain of the causes underlying the phenomenon, but it is clear that there is a good connection with anomalous weather patterns around the world.

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8. Winds, Upwelling and the Food Web

To understand how El Niño affects the ocean, we first need to learn about how surface winds move the water during normal years, and how the resulting motions affect water temperatures and amounts of chemical nutrients available to the food web. We will consider two separate regions: the equatorial Pacific extending westward from the Galapagos islands to beyond the dateline, and the coastal waters off Peru and southern Ecuador.

The easterly winds that blow along the equator and the southeasterly winds that blow along the coasts of Peru and Ecuador both tend to drag the surface water along with them. The Earth's rotation then deflects the resulting surface currents toward the right (northward) in the Northern Hemisphere and to the left (southward) in the Southern Hemisphere. The surface waters are therefore deflected away from the equator in both directions and away from the coastline. Where the surface water moves away, colder, nutrient-rich water comes up from below to replace it, a phenomenon known as *upwelling*. Both equatorial and coastal upwelling are concentrated in narrow regions less than 100 miles wide that show up clearly in satellite images.

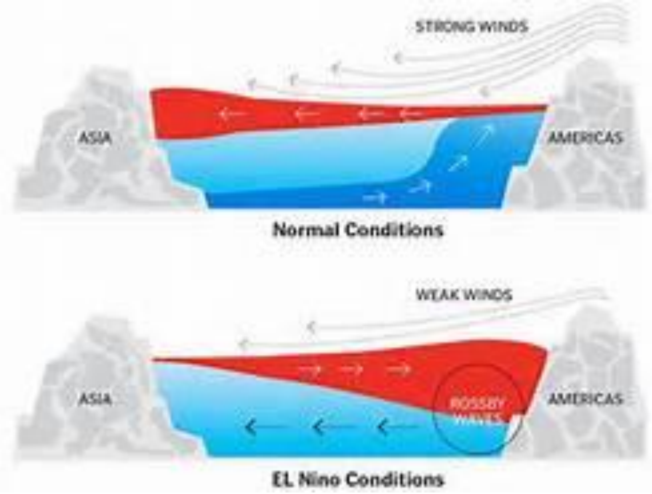
The winds that blow along the equator also affect the properties of upwelled water. In the absence of these winds, the dividing layer between the warm surface water and the deep cold water, known as the *thermocline*, would be nearly flat; but the winds drag the surface water westward, raising the thermocline nearly all the way up to the surface in the east and depressing it in the west.

The cold water below the thermocline is rich in chemical nutrients. Wherever the thermocline is shallow enough, stirring by the wind mixes the nutrient-rich water with the surface water. In the presence of sunlight, tiny plant species called *phytoplankton* use the nutrients to produce a greenish plant substance called *chlorophyll*. These explosively growing "blooms" of phytoplankton use up all the available nutrients within a week, at which time they die and sink. During their brief lifetime in the Sun they are visible in satellite images as greenish patches of water, which serve as markers for places where upwelling is bringing nutrients to the surface. The surface waters above the thermocline would soon become devoid of nutrients were they not continually being replenished by upwelling.

The newly upwelled water is colder than its surroundings. It can be tracked for several weeks using *infrared satellite imagery* that reveals the water temperature. Its signature in the infrared images takes the form of a distinctive "cold tongue" extending westward along the equator from the South American coast.

So it is that the winds control the upwelling and the upwelling controls the phytoplankton production. The phytoplankton production, in turn, affects the lives of the tiny sea animals called zooplankton, which "graze" on them and, ultimately, this affects all the creatures at higher levels of the marine food web. The winds are also responsible for the cold tongue in the sea-surface temperature pattern that is visible in satellite imagery.

When the Winds Weaken



During El Niño years, when the easterlies retreat into the eastern Pacific, the ocean responds in the following ways:

- The thermocline along the equator flattens out, rising in the west and plunging several hundred feet below the surface in the east—deep

enough so that coastal upwelling is no longer able to tap the cold, nutrient-rich waters from beneath it.
- Equatorial upwelling decreases, further reducing the supply of nutrients to the food web.
- The cold tongue in sea-surface temperature weakens or disappears.
- Sea level flattens out, dropping in the west and rising in the east. Surface water surges eastward along the equator.

When this impulse of relatively warm water reaches the eastern end of the basin, typically a few months later, it is forced to turn northward and southward along the coast, causing sardines and other species of fish to move and raising sea level as it goes. These effects have been felt as far north as Canada and as far south as central Chile.

How the Sea Affects the Winds

The oceans and the atmosphere carry on a continuous dialogue. Each listens to what the other is saying and responds. Up to now we have eavesdropped on one side of that conversation: how the winds along the equator influence the slope of the thermocline and the intensity of the upwelling. But the resulting changes in sea-surface temperature will, in turn, have an effect on the winds.

When the easterlies are blowing at full strength, the upwelling of cold water along the equatorial Pacific chills the air above it, making it too dense to rise high enough for water vapor to condense to form clouds and raindrops. As a result, this strip of the ocean stays conspicuously free of clouds during normal years and the rain in the equatorial belt is largely confined to the extreme western Pacific, near Indonesia.

But when the easterlies weaken and retreat eastward during the early stages of an El Niño event, the upwelling slows and the ocean warms. The moist air above the ocean also warms. It becomes buoyant enough to form deep clouds which produce heavy rain along the equator. The change in ocean temperatures thus causes the major rain zone over the western Pacific to shift eastward. Related adjustments in the atmosphere cause barometers to fall over the central and eastern Pacific and rise over Indonesia and Australia, resulting in a further weakening and eastward retreat of the easterlies.

In this way, the dialogue between wind and sea in the Pacific can become more and more intense as each partner sends back a stronger message. Small perturbations in the ocean and atmosphere can amplify one another until eventually a full-fledged El Niño is under way. And, just as it is often hard to say which partner was responsible for a change in the mood of a dialogue, or precisely what they said that set the conversation off in a new direction, it is often difficult to identify the subtle change in the ocean-atmosphere system that initiates a transition into or out of El Niño conditions.

Summary

We still have many uncertainties in our understanding and forecasting of El Niño Southern Oscillation (ENSO). For instance, we need to better understand and model how ENSO events are unique and how they interact with other climate and weather patterns, often leading to diverse regional and local economic impacts.

Those issues not withstanding, cost benefits studies have shown investments in El Niño forecasting to be a sound use of taxpayer dollars. Comparing forecast systems costs with anticipated benefits in just the U.S. agriculture sector yields an estimated annual rate of return on that investment of between 13 to 26 percent.

For additional reading on the impacts of El Niño, see *El Niño 1997-98: The Climate Event of the Century*, edited by Stan Changnon, Oxford Press, 2000. For additional reading on the economics of El Niño, see *Improving El Niño Forecasting: The Potential Economic Benefits*, edited by Rodney Weiher, NOAA, 2000, available at rodney.f.weiher@noaa.gov.

C. How do we Recognize an El Niño Event? / What are typical El Niño characteristics?

1. El Niño can be seen in sea surface temperatures in the Equatorial Pacific.

El Niño can be seen in measurements of the sea surface temperature, such as those shown above, which were made from the TAO Array of moored buoys. In December 1993, the sea surface temperatures and the winds were near normal, with warm water in the Western Pacific Ocean (in red on the top panel of December 1993 plot), and cool water, called the "cold tongue" in the Eastern Pacific Ocean (in green on the top panel of the December 1993 plot). The winds in the Western Pacific are very weak (see the arrows pointing in the direction the wind is blowing towards), and the winds in the Eastern Pacific are blowing towards the west (towards Indonesia). The bottom panel of the December 1993 plot shows anomalies, the way the sea surface temperature and wind differs from a normal December. In this plot, the anomalies are very small (yellow/green), indicating a normal December. December 1997 was near the peak of a strong El Niño year. In December 1997, the warm water (red in the top panel of the December 1997 plot) has spread from the western Pacific Ocean towards the east (in the direction of South America), the "cold tongue" (green color in the top panel of the December 1997 plot) has weakened, and the winds in the western Pacific, usually weak, are blowing strongly towards the east, pushing the warm water eastward. The anomalies show clearly that the water in the center of Pacific Ocean is much warmer (red) than in a normal December. **[ADD FIGURE}**

December 1998 was a strong La Niña (cold) event. The cold tongue (blue) is cooler than usual by about 3° Centigrade. The cold La Niña events sometimes (but not always) follow El Niño events.

2. El Niño- related oceanic and atmospheric conditions are generally opposite to those of La Niña?

Typical El Niño oceanic conditions include:

- A deep layer of very warm ocean water across the east-central equatorial Pacific, with sea-surface temperatures generally 1.5-2.5^{o}C above average, and subsurface ocean temperatures typically 3-6^{o}C above average at the depth of the oceanic thermocline.
- A deeper than average oceanic thermocline across the east-central equatorial Pacific, with depths typically ranging from 150-175 m.

Typical atmospheric conditions of El Niño include:

- Enhanced convective rainfall and below average air pressure across the eastern half of the equatorial Pacific.
- Suppressed convective rainfall and above-average air pressure across Indonesia, the western equatorial Pacific and northern Australia.
- Weaker than average easterly trade winds across the eastern half of the equatorial Pacific.
- Westerly winds at low levels of the atmosphere across the western equatorial Pacific.
- A strong negative value of the Southern Oscillation Index due to lower-than-average surface air pressure at Tahiti, French Polynesia and higher-than-average surface air pressure at Darwin, Australia.
- In the upper atmosphere higher than average air pressure over the subtropical eastern Pacific of both hemispheres flanking the region of enhanced equatorial convection located over the east-central equatorial Pacific.

- Items 1-6 above are associated with a weaker-than-average equatorial Walker Circulation.
- An equator-ward shift and eastward extension of the mean wintertime jet stream along the poleward flanks of these anomalous high-pressure cells (over the eastern half of the Pacific Ocean) in both hemispheres.
- In the August-October period, increased upper level westerly winds leading to higher-than-average vertical wind shear and reduced hurricane activity across the tropical North Atlantic, and to below-average vertical wind shear and increased hurricane activity over the eastern tropical North Pacific.

D. How do we detect El Niño?

In the tropical Pacific Ocean, El Niños are detected by many methods, including satellites, moored buoys, drifting buoys, sea level analysis and XBTs. Many of these *in-situ* ocean-observing systems were part of the Tropical Ocean Global Atmosphere (TOGA) program, and are now evolving into an operational El Niño/Southern Oscillation (ENSO) observing system.

Other models are used for El Niño research, such as those at NOAA's Geophysical Fluid Dynamics Laboratory, at Center for Ocean-Land-Atmosphere Studies, and other research institutions.

E. What indices are used to see if an El Niño or La Niña is occurring?

A variety of indices are used to characterize ENSO because it effects so many elements of the atmosphere-ocean climate system. Probably the two principal indices are the Southern Oscillation Index (SOI), which is given by the difference in sea-level pressure between Tahiti and Darwin, Australia, and the Niño 3 index, which refers to the anomalous SST within the region bounded by 5N-5S and 150W-90W. The measurements needed for these indices are straightforward, and we have long historical records, especially for the SOI.

Other indices are, however, effective at characterizing other aspects of ENSO. For example, the anomalous 850 mb zonal winds show how the low-level atmospheric flow is responding to low-level pressure anomalies associated with ENSO and other mechanisms. Often the 850 mb flow (about 1.5 km above sea level) exhibits a "cleaner" signal than the winds at the surface, which are subject to local effects such as terrain. An index involving the 200 mb zonal flow is used to describe the upper tropospheric winds, the anomalies of which tend to be opposite to those at 850 mb and below. The 200 mb flow is particularly important because it changes at levels in the tropics that tend to have the biggest consequences for the atmospheric circulation outside of the tropics. The 500 mb temperature represents a proxy for the anomalous heat content of the tropical troposphere. In an overall sense, there is greater heating of the troposphere, and more deep cumulus convection than normal during warm ENSO events (El Niños).

Finally, there is one more widely used index for the atmosphere, which relates to the outgoing longwave radiation, or OLR. The deeper the cumulus convection, the colder the cloud tops, which means the thermal or infrared radiation to space is reduced. It is straightforward to monitor OLR via satellite; its value in the tropical Pacific near the dateline is an effective way to gauge the frequency and magnitude of the thunderstorm activity that changes with ENSO.

F. Is there a scale for the intensity of El Niño?

The most widely used scale is known as the Southern Oscillation Index (SOI), which is based on the surface (atmospheric) pressure difference between Tahiti and Darwin, Australia. It was noted as far back as the 1920s that these two stations were anti-correlated, so that when Tahiti pressure is high, Darwin pressure is low. This reflects the very large scale of the phenomena, since one would not usually expect such a close relation between such faraway places. When Tahiti pressure is high, that indicates winds blowing towards the west (normal trade winds), and when it is low the winds blow to the east (El Niño).

We use the Southern Oscillation Index for three main reasons, despite the fact that it is only an indirect measure of El Niño and that these locations (Tahiti and Darwin) are not ideally sited for this purpose. First, the time series at Darwin and Tahiti are more than 100 years long; there is no other record that would enable us to categorize the El Niño cycle that far back. Second, the measurement of atmospheric pressure is simple (it is just the height of a column of mercury in a barometer) and not subject to calibration problems, as, for example, thermometers are. A column of mercury is just a measure of length, which is accurate and easily convertible between inches and centimeters, whereas thermometers are inherently less accurate since they rely on a carefully-made glass tube that may be subject to expansion or irregularities. Also, the placement of the thermometer (in the sun or shade or breeze, near buildings, etc) can have a large effect on its accuracy. (For example, temperature measured in cities shows a long-term rise associated with the heat generated by urban activities and the increased absorption of solar heat by pavement compared with forests, the so-called urban heat island effect. This is one of the things that makes it hard to detect the signature of greenhouse warming).For this reason, pressure measurements are highly desirable for interpreting long records. Third, pressure tends to be similar over wide regions, whereas more directly-important quantities (SST and winds) can have many local effects that make it hard to interpret single point measurements as representative of large-scale situations.

The SOI is given in normalized units of standard deviation. It can therefore be used as an intensity scale. For example SOI values for the 1982-83 El Niño were about 3.5 standard deviations, so by this measure that event was roughly twice as strong as the 1991-92 El Niño, which measured only about 1.75 in SOI units. By this standard, the 1997-98 El Niño was about as strong as the one in 1991-92. However, the sea surface temperature anomaly in November 1997 was about as large as in 1982-83, leading some to claim that this is a more important measure. More than anything, this shows that no single number can summarizes the intensity of events.

G. Are all El Niños the same? / Are big El Niños different from average El Niños?

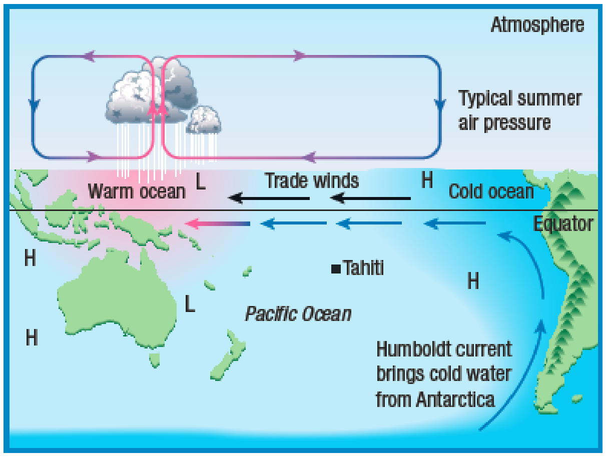
1. Every El Niño is somewhat different in magnitude and duration. Magnitude can be determined in different ways, such as variations in the Southern Oscillation Index (SOI). Plots of Sea Surface Temperature Anomalies (SSTA) from the ENSO Monitor show El Niños back to 1982, including the 1982-1983 El Niño, which, until 1997, was the largest El Niño of this century. Another comparison of different El Niños can be seen in plots of Sea Surface Temperature Anomalies from CPC for different regions (Niño 1,2,3,4) in the Pacific Ocean. The Niño 3 region, in the Eastern Equatorial Pacific Ocean, extends from 150W to 90W and 5N to 5S. The El Niño in 1982-1983 had far stronger sea surface temperatures in the Niño 3 region than El Niños in 1976, 1987 and 1991. Another comparison of El Niños is available from the CDC as plots of an El Niño index for comparison of El Niño events back to 1950.

In a plot of Sea Surface Temperature along the Equator from 1986-present, warm water (red) penetrated further to the East in the 1986 and 1997 El Niños than it did during the 1991-1993 El Niños.

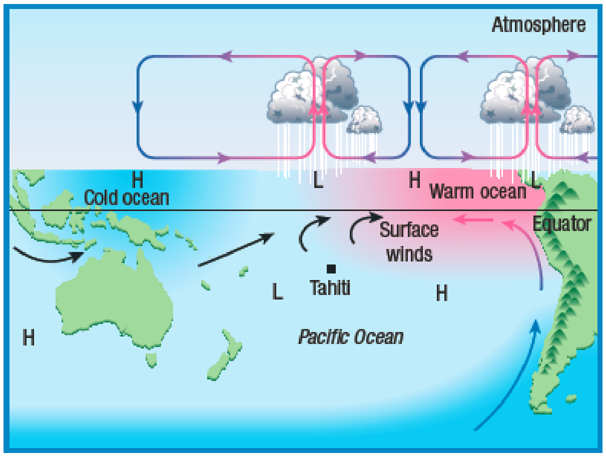
2. This is one of the strongest El Niños on record. There is some evidence that the effects of large El Niños (which constitute a small sample) may be different from those of the typical El Niño. In particular, heavier precipitation may occur farther north in Nevada and California, and especially along the coast. For example, the record El Niño of 1982-83 brought heavy precipitation as far north as Oregon and Washington, the only major exception in the last 70 years to the typical dry winter response expected in the Pacific Northwest.

IV. LA NIÑA

2.61 Normal conditions in the Pacific Ocean



2.62 El Niño conditions in the Pacific Ocean



A. What is La Niña?

1. "La Niña" refers to certain years between El Niño events in which most of the El Niño characteristics are reversed, including the tropical Pacific ocean temperatures, which are colder than average. Because it is contrary to El Niño (cold instead of warm) and its climatic effects are frequently opposite as well (droughts instead of floods, and vice versa), it is given the contrasting feminine name in opposition to the masculine "El Niño". The way we characterize ENSO anomalies is to subtract long-term averages from our data. During the intervening years between El Niño events the equatorial Pacific Ocean is somewhat cooler than that average, since together with the warm El Niño events they must sum to the average. So you might say that La Niña is an inevitable consequence of how we calculate the anomalies. However, in some years the equator is unusually cold, though never as cold as a strong El Niño is warm. This prompts some scientists to think that La Niña is a physical phenomenon in its own right, or at the very least, the opposite phase of an "ENSO cycle".

   Scientists have never accurately predicted a La Niña and it is difficult to agree on what constitutes one. La Niña events with significant impacts are fairly unusual.

2. La Niña is essentially the opposite of El Niño. La Niña exists when cooler than usual ocean temperatures occur on the equator between South America and the dateline. The name La Niña ("the girl child") was coined to deliberately represent the opposite of El Niño ("the boy child"). The terms El Viejo and anti-El Niño are also sometimes used. La Niña occurs almost as often as El Niño, but has been lesser known. La Niña and El Niño are but two faces of the same larger phenomenon.

   Stronger than usual trade winds accompany La Niña. These winds, from the east, push the ocean water away from the equator in each hemisphere. (This is caused by the rotation of the earth.) Cold water from below rises to replace the warm surface water which has moved away from the equator.

   The cool water acts as an impediment to the formation of clouds and tropical thunderstorms in the overlying air. This suppression of rain-producing clouds leads to dry conditions on the equator in the Pacific Ocean from the dateline east to South America.

3. La Niña refers to the periodic cooling of ocean surface temperatures in the central and east-central equatorial Pacific that occurs every 3 to 5 years or so. La Niña represents the cool phase of the El Niño/Southern Oscillation (ENSO) cycle, and is sometimes referred to as a Pacific cold episode. La Niña originally referred to an annual cooling of ocean waters off the west coast of Peru and Ecuador.

4. La Niña is defined as cooler than normal sea-surface temperatures in the central and eastern tropical Pacific ocean that impact global weather patterns. La Niña conditions recur every few years and can persist for as long as two years.

5. La Niña is characterized by unusually cold ocean temperatures in the equatorial Pacific, as compared to El Niño, which is characterized by unusually warm ocean temperatures in the equatorial Pacific. La Niña is also sometimes called El Viejo.

   At higher latitudes, El Niño is only one of a number of factors that influence climate. However, the impacts of El Niño and La Niña at these latitudes are most clearly seen in wintertime. In the continental US, during El Niño years, temperatures in the winter are warmer than normal in the North Central States, and cooler than normal in the Southeast and the Southwest. During a La Niña or El Viejo year, winter temperatures are warmer than normal in the Southeast and cooler than normal in the Northwest.

B. What are typical La Niña characteristics?

1. La Niña- related oceanic and atmospheric conditions are generally opposite to those of El Niño:

- A deep layer of cooler than average ocean temperatures across the east-central equatorial Pacific, with sea-surface temperatures generally 1-2°C below average, and sub-surface temperatures typically 2-4°C below average at the depth of the oceanic thermocline.
- A shallower than average oceanic thermocline across the east-central equatorial Pacific, with depths typically ranging from 50-100 m.

Typical atmospheric conditions of La Niña include:

- Suppressed convective rainfall and above average air pressure across the eastern half of the equatorial Pacific.
- Enhanced convective rainfall and below-average air pressure across Indonesia, the western equatorial Pacific and northern Australia.
- Stronger than average easterly winds across the entire equatorial Pacific.
- A strong positive value of the Southern Oscillation Index (SOI), due to higher-than-average surface air pressure at Tahiti, French Polynesia and lower-than-average surface air pressure at Darwin, Australia.
- In the upper atmosphere, lower than average air pressure over the subtropical eastern Pacific of both hemispheres flanking the region of suppressed equatorial convection located over the east-central equatorial Pacific.
- The first five bullets above reflect an enhanced equatorial Walker Circulation.
- A weaker mean wintertime jet stream along the poleward flanks of these anomalous low-pressure cells (over the eastern half of the Pacific Ocean) in both hemispheres.
- Above-average air pressure in the upper atmosphere over the subtropical Atlantic Ocean of both hemispheres, along with a stronger-than average Tropical Easterly Jet over the equatorial Atlantic Ocean.
- In August-October, the enhanced upper-level easterly winds lead to reduced vertical wind shear and increased hurricane activity across the tropical North Atlantic, and to above-average vertical wind shear and decreased hurricane activity over the eastern tropical North Pacific.

V. SOUTHERN OSCILLATION / SOUTHERN OSCILLATION INDEX

A. What are the Southern Oscillation and Southern Oscillation Index (SOI)?

1. The fluctuations in ocean temperatures during El Niño and La Niña are accompanied by even larger-scale fluctuations in air pressure, known as the Southern Oscillation, between the western and eastern tropical Pacific.

   During El Niño higher than average air pressure covers Indonesia and the western tropical Pacific and below-average air pressure covers the eastern tropical Pacific. These pressure departures are reversed during La Niña, which features below-average air pressure over Indonesia and the western tropical Pacific and above-average air pressure over the eastern tropical Pacific.

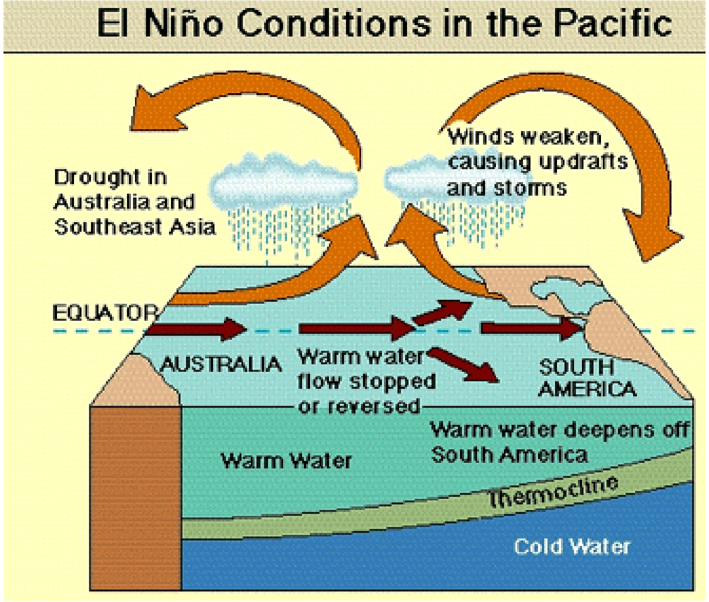
   The Southern Oscillation Index (SOI) is designed to measure the strength and phase of the Southern Oscillation. The SOI is calculated using departures from normal in the surface air pressure difference between Tahiti, French Polynesia and Darwin, Australia. These stations are used because of their long data records.

   During El Niño episodes the SOI has a large negative value due to lower-than-average air pressure at Tahiti and higher-than-average pressure at Darwin.

   During La Niña episodes the SOI has a positive value due to higher-than-average air pressure at Tahiti and lower-than-average pressure at Darwin.

2. It has been found that the cyclic warming and cooling of the eastern and central Pacific can be seen in the sea level pressure in the region. In particular, when the pressure measured at Darwin is compared with that measured at Tahiti, the differences between the two can be used to generate an "index" number. A positive number indicates La Niña (eastern tropical Pacific ocean cooling) and a negative number indicates El Niño (or ocean warming).

VI. DISTINCTIONS



A. What is the difference between El Niño, La Niña and ENSO? What is SOI?

1. El Niño and La Niña refer to different phases of ENSO. El Niño refers to a pattern characterized by the tropical Pacific's warmest water spreading eastward to the coast of South America. La Niña refers to times when waters of the tropical Pacific are colder than normal.

El Niño (EN) is characterized by a large scale weakening of the trade winds and warming of the surface layers in the eastern and central equatorial Pacific Ocean. El Niño events occur irregularly at intervals of 2-7 years, although the average is about once every 3-4 years. They typically last 12-18 months, and are accompanied by swings in the Southern Oscillation (SO), an inter-annual see-saw in tropical sea level pressure between the eastern and western hemispheres. During El Niño, unusually high atmospheric sea level pressures develop in the western tropical Pacific and Indian Ocean regions, and unusually low sea level pressures develop in the southeastern tropical Pacific. SO tendencies for unusually low pressures west of the dateline and high pressures east of the dateline have also been linked to periods of anomalously cold equatorial Pacific sea surface temperatures (SSTs), sometimes referred to as La Niña.

The Southern Oscillation Index (SOI), defined as the normalized difference in surface pressure between Tahiti, French Polynesia and Darwin, Australia, is a measure of the strength of the trade winds, which have a component of flow from regions of high to low pressure. High SOI (large pressure difference) is associated with stronger than normal trade winds and La Niña conditions, and low SOI (smaller pressure difference) is associated with weaker than normal trade winds and El Niño conditions. The terms ENSO and ENSO cycle are used to describe the full range of variability observed in the Southern Oscillation Index, including both El Niño and La Niña events.

There has been a confusing range of uses for the terms El Niño, La Niña and ENSO by both the scientific community and the general public. Originally, the term El Niño (in reference to the Christ child) denoted a warm southward flowing ocean current that occurred every year around Christmas time off the west coast of Peru and Ecuador. The term was later restricted to unusually strong warmings that disrupted local fish and bird populations every few years. However, as a result of the frequent association of South American coastal temperature anomalies with inter-annual basin scale equatorial warm events, El Niño has also become synonymous with larger scale, climatically significant, warm events. There is not, however, unanimity in the use of the term El Niño. The tendency in the scientific community though is to refer interchangeably to El Niño, ENSO warm event or the warm phase of ENSO as those times of warm eastern and central equatorial Pacific SST anomalies. Conversely, the terms La Niña, ENSO cold event or cold phase of ENSO are used interchangeably to describe those times of cold eastern and central equatorial Pacific SST anomalies.

The terms "El Viejo" and "anti-El Niño" have also been applied to the cold phase of ENSO. However, these terms are used less frequently, as the term La Niña has gained currency.

B. What are some main differences between El Niño and La Niña?

1. El Niño and La Niña represent opposite extremes in the naturally occurring climate cycle referred to as the El Niño/Southern Oscillation (ENSO). They are associated with opposite extremes in sea-surface temperature departures across the central and east-central equatorial Pacific, and with opposite extremes in convective rainfall, surface air pressure, and atmospheric circulation departures in the Tropics from Indonesia to South America (approximately ½ the distance around the globe).

   Usually, sea-surface temperatures off South America's west coast range from the 60s to 70s°F, while they exceed 80°F in the "warm pool" located in the central and western Pacific. Deep atmospheric convection over the equatorial Pacific is generally confined to this warm pool area.

During El Niño the equatorial easterly trade winds diminish, resulting in an eastward shift of the Pacific warm pool and associated area of tropical convective rainfall. During a strong El Niño the warm pool covers the entire eastern half of the equatorial Pacific.

During La Niña the easterly trade winds strengthen, colder-than-average sea surface temperatures develop over the eastern equatorial Pacific, and the Pacific warm pool and equatorial convective rainfall are confined to the extreme western part of the basin.

2. El Niño and La Niña are extreme phases of a naturally occurring climate cycle referred to as El Niño/Southern Oscillation. Both terms refer to large-scale changes in sea-surface temperature across the eastern tropical Pacific. Usually, sea-surface readings off South America's west coast range from the 60s to 70s F, while they exceed 80 degrees F in the "warm pool" located in the central and western Pacific. This warm pool expands to cover the tropics during El Niño, but during La Niña, the easterly trade winds strengthen and cold upwelling along the equator and the West coast of South America intensifies. Sea-surface temperatures along the equator can fall as much as 7 degrees F below normal.

3. Both terms refer to large-scale changes in sea-surface temperature across the central and eastern tropical Pacific. Usually, sea-surface readings off South America's west coast range from the 60s to 70s F, while they exceed 80 degrees F in the "warm pool" located in the central and western Pacific. This warm pool expands to cover the tropics during El Niño but shrinks to the west during La Niña. The El Niño/Southern Oscillation (ENSO) is the coupled ocean-atmosphere process that includes both El Niño and La Niña.

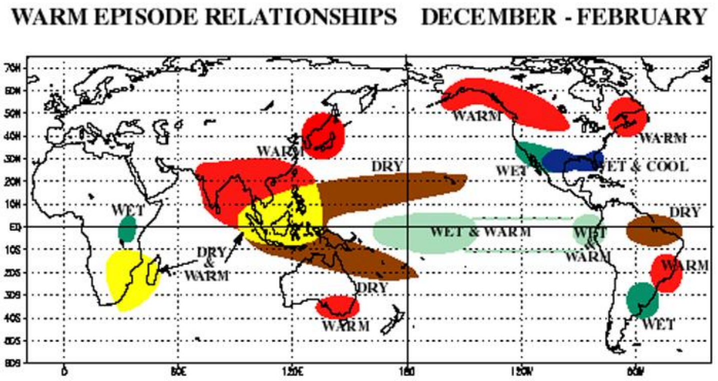
4. An El Niño has warmer than normal surface waters in the eastern Pacific and cooler than normal surface waters in the western Pacific. This is generally associated with weaker than normal winds blowing from east to west (the trade winds).

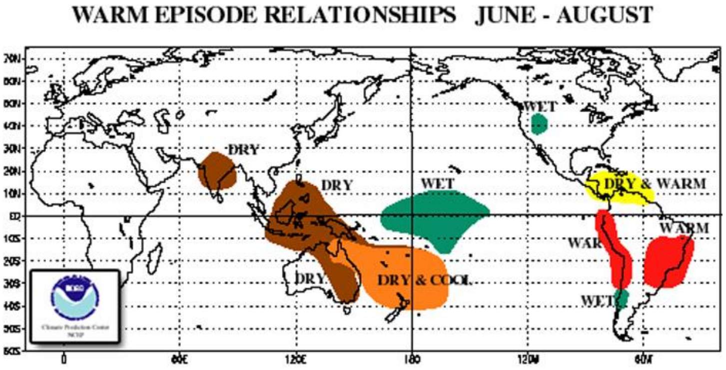
   A La Niña occurs when the waters in the eastern Pacific are much colder than normal, while the waters in the west are much warmer than normal. During a La Niña, the Trade winds are stronger than normal.

C. What is the difference between El Niño, ENSO and the Southern Oscillation?

El Niño refers to the oceanic component of the El Niño/Southern Oscillation system, the Southern Oscillation to the atmospheric component and ENSO to the coupled system. In practice, El Niño is sometimes used to refer to the entire system.

VII. El NIÑO/LA NIÑA SYSTEMS


WARM EPISODE RELATIONSHIPS DECEMBER - FEBRUARY


WARM EPISODE RELATIONSHIPS JUNE - AUGUST

A. What Happens During El Niño or La Niña?

During an El Niño or La Niña, the changes in Pacific Ocean temperatures affect the patterns of tropical rainfall from Indonesia to the west coast of South America, a distance covering approximately one-half way around the world. These changes in tropical rainfall affect weather patterns throughout the world.

B. Are there Exceptions to La Niña / El Niño Opposition?

1. The La Niña climate signal in the US West seems more reliable than the El Niño signal. This is especially true in the US Southwest. El Niño generally

brings wet weather there in winter, but there are a number of exceptions. La Niña brings dry winters to the US Southwest. There have been no exceptions to this pattern, at least during the past 65 years. That is, La Niña brings much more consistent consequences in the US Southwest.

In the Pacific Northwest, this consistency appears to be not as true. La Niña generally brings cold, snowy, wet, active winters to the northern Cascades and the northern Rockies. There are a few exceptions to this picture among La Niña years. There appear, however, to be more such exceptions in El Niño years, to the dry, mild winter pattern these regions typically experience with El Niño.

2. For both El Niño and La Niña, the north/south dividing line between the opposing effects in the Southwest and the Pacific Northwest extends as a zone from about San Francisco to Cheyenne, Wyoming. The effects of both phases of ENSO are equally nebulous in this region. The effects of larger El Niños extend farther north along the West Coast, and the effects of La Niña can extend south along the West Coast from the Pacific Northwest. Thus, northern California can be the recipient of moisture from both the northern end of El Niño's effects and the southern end of La Niña's effects.

3. In the central Sierra there are no large-scale winter floods associated with El Niño. All but one of the biggest floods have occurred in La Niña winters. However, not all La Niña winters have large floods, and many have small or average winter flood peaks. Thus, La Niña opens the door to, but does not guarantee, large scale rain-on-snow conditions associated with the biggest Sierra floods--more so than El Niño. The deep tap to abundant tropical moisture (the so-called "pineapple connection") associated with major Sierra floods has a higher likelihood of occurrence in La Niña years than in El Niño years, but in both cases is not common. These very large floods can be generated in just a few days, and the weather pattern during that time may poorly represent the overall character of the winter. Both 1996-97 and 1985-86 illustrate this point very well: without the short period of intense rains, these two years with the largest floods would likely have entered the record books as drought winters.

4. The overall atmospheric flow patterns differ substantially between La Niña and El Niño winters. El Niño winters tend to feature strong and persistent flow from the Pacific into North America, blocking the movement of cold Canadian air toward the south. La Niña winters have much more north-south movement of air masses, and alternations of temperature, particularly in the northern half of the West.

5. Although El Niño has received considerably more attention than La Niña, evidence suggests that the types of weather associated with La Niña winters have more deleterious effects to the national economy than do those of El Niño.

C. Are there combined effects that are more likely?

In some areas, combined events can interact to accentuate the effects of El Niño. For example, in the southern West, during the winter months vigorous storms are more likely, precipitation amounts are heavier, the frequency of precipitation is higher and events are more likely to persist. Thus, ground saturation is likely to be greater, and landslides are more frequent. With more frequent and vigorous storms, coupled with wet soils, trees are more likely to topple. In the northern West, by contrast, such circumstances are proportionately less likely.

VIII. IS EL NIÑO THEORY OR FACT?

El Niño as a physical occurrence is a proven fact. The way it works is a theory (actually several different theories). El Niño is as real as other weather phenomena: thunderstorms, for instance. We recognize its characteristics as similar to previous occurrences, and note that its life cycle is roughly the same each time. (Of course each one is different, as each thunderstorm is different, but the basic evolution is similar enough that we know an El Niño when we see it).

On the other hand, a difference from thunderstorms is that we have a very good idea what triggers thunderstorms, what conditions make it likely for them to occur, to the point where weather forecast models commonly pinpoint the locations and predicted severity of thunderstorms a day or so in advance. We do not have such knowledge for El Niño. Once an El Niño has started, we have reasonably good skill in predicting the subsequent evolution over the next 6-9 months, but before it has started we have very little skill in predicting the onset before the event has become obvious. There are a variety of theories for why El Niños start, but none of them has given us real skill in making a forecast in advance, the way we can for thunderstorms.

It must be said that there is still plenty of social utility in predicting the evolution of an El Niño after it starts, since that gives 6 months or so warning before the effects come to the US. For instance, a fairly weak El Niño started in 1997, and that enabled forecasters to predict that the following winter was likely to be warmer than normal across the northern states, and wetter than normal along the Gulf Coast. Such forecasts are certainly useful for farmers and water managers, but from a scientific point of view they are unsatisfying because they do not answer the fundamental question of why the event started in the first place.

One reason for this state of affairs is that El Niños only come along every 4-5 years or so, so there aren't very many to study (we've had decent instrumentation in the tropical Pacific for less than 20 years). Thunderstorms happen every day in summer, so there has been lots of opportunity to carefully observe their development.

Perhaps this is a deeper question, though, concerning the meaning of the word "theory". In science, we use the word theory somewhat differently from ordinary usage. Ordinarily, to say something is a theory means it is kind of a guess, not proven. Scientists, on the other hand, speak of the "theory of gravitation", or the "theory of evolution", and in these cases it means the precise description of the mechanism. In no way does it indicate that the phenomenon in question is less than a fact. No one doubts that gravity is a fact, but the exact way it works is still a subject of research (Einstein spent the last 40 years of his life trying to explain gravitation without simply postulating it, that is, to explain it in connection with the other atomic forces. This is still a major question of physics, and you may have heard of the search for a "unified field theory"). Similarly, no serious scientist doubts that evolution is a fact, but there is plenty of discussion about its specific mechanisms, whether it happens quickly or slowly, what size population of an organism is likely to produce new species, under what conditions a species will die out, etc. All these are part of the process of honing the theory.

In the case of El Niño, one theory is that these events are the means by which heat is drained from the equatorial oceans after a period of accumulation. Such a theory predicts that by observing the growth of heat content, it should be possible to forecast when an El Niño will occur. That seems to be at least partly true, but it was contradicted by the El Niño of 1993, which occurred immediately after one the previous year, and no accumulation had occurred. Another theory argues that El Niños are triggered by random events occurring in other parts of the climate system, and suggests that we will never be able to predict them. Some scientists argue for an opposite (cold) phase called La Niña, and see the whole thing as an oscillation swinging back and forth, while others think there is just the normal situation disturbed by occasional El Niños. However, you can see that despite the existence of competing theories for El Niño, there is no doubt that it is a real, factual occurrence.

IX. ENSO-NEUTRAL

A. Is there such a thing as "normal", aside from El Niño and La Niña?*

Over the long-term record, sea-surface temperatures in the central and eastern tropical Pacific diverge from normal in a roughly bell-curve fashion, with El Niño and La Niña at the tails of the curve. Some researchers argue there are only two states, El Niño and non-El Niño, while others believe either El Niño or La Niña is always present to a greater or lesser degree. According to one expert, NCAR's Kevin Trenberth, El Niños were present 31% of the time and La Niñas 23% of the time from 1950 to 1997, leaving about 46% of the period in a neutral state. The frequency of El Niños has increased in recent decades, a shift being studied for its possible relationship to global climate change.

B. What does ENSO-neutral mean?

ENSO-neutral refers to those periods when neither El Niño nor La Niña is present. These periods often coincide with the transition between El Niño and La Niña events. During ENSO-neutral periods the ocean temperatures, tropical rainfall patterns and atmospheric winds over the equatorial Pacific Ocean are near the long-term average.

C. How does El Niño relate to the usual situation in the tropical Pacific?

To understand El Niño, it is necessary to understand the normal trade-wind system in the tropical Pacific. The sun heats the equatorial regions more strongly than the rest of the globe, so air tends to rise from the surface there, replaced by inflow from the subtropics. The Coriolis Effect turns these inflows to the right in the northern hemisphere and to the left in the southern, resulting in the great trade-wind belts that blow equator-ward and westward over the width of the tropical Pacific. This sets up the coupled ocean-atmosphere interaction in the tropical Pacific in which the winds determine the water temperature but the water temperature also determines the winds, in a chicken and egg situation. In this system, we can start a description at any point in the cycle. For example, we observe that there is cool water in the east and warm water in the west. The winds blow towards the warm water, since that heats the atmosphere and makes the air rise, then other air flows in to fill the gap. (These are the trade winds that the Spanish used to sail from their colonies in South America to the Philippines). Because of the force of the trades, sea level at Indonesia is about 1/2 meter higher than at Peru. At the same time the trade winds act on the ocean as well. The westward winds along the equator push the warm water (heated by the sun) off to the west, drawing up the thermocline and exposing the cooler water underneath in the east. This upwelling cools the eastern surface water, which returns us to the starting place of the description.

So if you ask me, "Why are there trade winds?" I will say, "That's simple. There are trade winds because the water is cold in the east and warm in the west." But if you ask me, "Why is the water cold in the east and warm in the west?" I'll say, "That's simple, too. It's because there are trade winds." The ocean and the atmosphere are inextricably coupled together.

The thermocline is the boundary between the cold deep water (that extends to the bottom of the ocean and around the world) and the warmer upper layer. In the tropics it forms a relatively sharp boundary. The trade winds, in piling up warm water in the west, make a thick (150 meter) warm layer in the west that pushes the thermocline down there, while it rises in the east. The shallow (30 meter deep) eastern thermocline allows the winds to pull up water from below, water that is generally much richer in nutrients than the surface layer. (This is so because life lives mostly in the sunlit zone. Available nutrients there are quickly taken up by some form of life (e.g. plankton). Debris from the living creatures rains down into the lower layer, where nutrients dissolve, making the deep water rich, so that wherever there is upwelling, abundant life exists.)

Note that the rising air over the western Pacific is associated with rainfall. When air rises it cools, and can hold less evaporated water. The water comes out as rain. But in returning to a liquid state, it releases the heat that was used to evaporate it from the ocean surface (heat that came from the sun), and this middle atmosphere heating amplifies the rising motion. This is a principal mechanism for heat from the sun to warm the atmosphere (the atmosphere by itself is relatively transparent to solar radiation).

Because the warm pool pumps great amounts of heat and moisture into the upper atmosphere, this system is one of the major driving forces of world climate. The huge source of heat helps set the path of the jet streams (storm tracks) that control temperate-zone weather, much as a large rock in a stream determines the pattern of water flow, including wavy motions that extend well downstream of the rock. Therefore, when the warm pool changes shape or position, the effects ripple outward to affect much of the world's weather.

During El Niño events, this entire system relaxes. The trade winds weaken, particularly west of the dateline, and the piled-up water in the west sloshes back east, carrying the warm pool with it. The region of rising air moves east with the warm pool, and so does the pumping of heat and moisture into the upper atmosphere, distorting the usual paths of the jet streams, which eventually causes the changes in weather around the world. With weakened trade winds, the upwelling in the east correspondingly weakens; as the warm pool moves east the upwelled water is also not as cool as during normal periods. When eastern SST becomes warm the east-to-west temperature contrast is small, and so the trade winds weaken even further, leading to a complete collapse with essentially flat conditions across the entire equatorial Pacific.

We don't know what initiates El Niño. But we do see that it apparently does not take much to destabilize the strong-trade-wind/large-temperature-contrast non-El Niño state discussed in sections above. This is because of ocean-atmosphere coupling.

Suppose a relatively brief opposing wind occurs over the west Pacific warm pool. It may last for as little as one month. This starts an eastward current that pushes the warm pool a little bit east of its usual position. If the ocean and atmosphere were not coupled, then this motion would soon stop when it ran into the trade winds. But we have shown that the trade winds exist because of the temperature contrast between east and west. If the central Pacific is warmed by flow from the west, even a small amount, then the region of rising air will tend to move east with the warm water. That means the trade winds will also shrink back east a little, since those winds are caused by the rising air. But then the pressure of the trades holding up the sea surface slope to the west is weakened, and even more west Pacific water tries to slosh eastward, the central Pacific is warmed a little bit more, and the rising air moves further east, and the trades shrink more. This collapse continues until the water is warm across the Pacific, the trades are weak, and the thermocline and sea surface slope flatten out. That is El Niño. Note that this collapse extracts its energy from the background state of the Pacific (the fact that sea level is higher in the west), which is a signature of instability.

While we can describe the collapse pretty well, we don't seem to know what makes the system ready to collapse, or what exactly causes the opposing winds in the first place.

There are two main theories at present. The first is that the event is initiated by the reflection from the western boundary of the Pacific of an oceanic Rossby wave (type of low-frequency planetary wave that moves only west). The reflected wave is supposed to lower the thermocline in the west-central Pacific and thereby warm the SST by reducing the efficiency of upwelling to cool the surface. That makes winds blow towards the (slightly) warmer water and starts the event. The nice part about this theory is that the Rossby waves can be observed for months before the reflection, implying that El Niño is predictable.

The other idea is that the trigger is essentially random. The tropical convection (organized large-scale thunderstorm activity) in the rising air tends to occur in bursts that last for about a month, and these bursts propagate out of the Indian Ocean (known as the Madden-Julian Oscillation). Since the storms are geostrophic (rotating according to the turning of the earth, which means they rotate clockwise in the southern hemisphere and counter-clockwise in the north), storm winds on the equator always blow towards the east. If the storms are strong enough, or last long enough, then those eastward winds may be enough to start the sloshing. But specific Madden-Julian Oscillation events are not predictable much in advance (just as specific weather events are not predictable in advance), and so to the extent that this is the main element, then El Niño will not be predictable.

In my opinion, both of these two processes can be important in different El Niños. Some models that did not have the MJO storms were successful in predicting the events of 1986-87 and 1991-92. That suggests that the Rossby wave part was a main influence at that time. But those same models have failed to predict the events since then, and the westerlies have appeared to come from nowhere. It is also quite possible that these two general sets of ideas are incomplete, and that there are other causes entirely. The fact that we have very intermittent skill at predicting the major turns of the ENSO cycle (as opposed to the very good forecasts that can be made once an event has begun) suggests that there remain important elements that await explanation.

The most severe effects of El Niño are found close to the equator. The usual pattern of deserts in Peru and heavy rainfall over Indonesia and the west Pacific reverses. Forest and range fires can occur in Indonesia (as has been happening in recent months, exacerbated by deliberate burning) and Australia, while Peru suffers flooding, with accompanying epidemics of cholera and other sewage-borne diseases. The food chain in the rich upwelling region is also disrupted, so fish die off, with consequent hardship for the birds, mammals and people that survive on that stock. The warmer water near Central America spawns more and stronger hurricanes, which can go as far west as Hawaii. The entire sequence of the event lasts about one year, and events are usually separated by 2-7 years, in an irregular and not-well-understood pattern.

X. TELECONNECTIONS

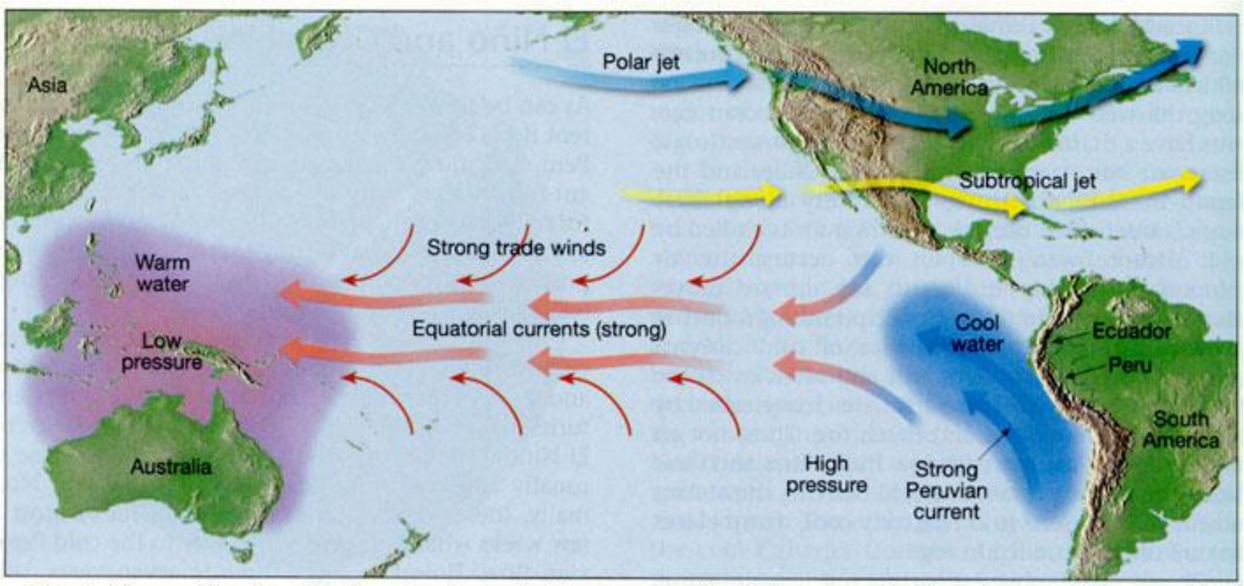


Fig.6 Normally, the trade winds and strong equatorial currents flow toward the west. At the same time, an intense Peruvian current causes upwelling of cold water along the west coast of South America.

A. What are El Niño teleconnections?

Teleconnection modes can be visualized as the preferred ways the atmosphere oscillates (in a manner roughly akin to a drum head) on time scales of weeks and longer. El Niño disturbs the atmosphere by moving the west Pacific warm pool (region of sea surface temperature greater than 28 ° C, usually found from Indonesia to the dateline) eastward. The warm pool is one of the main sources of heat driving the atmosphere, comparable to a continent during summer. The effects of the warm pool extend upward through the atmosphere because the warm water tends to produce and support extensive organized thunderstorm activity and tropical cyclones. These pump large amounts of heat and moisture to high levels. When the warm pool is displaced east during El Niño, the enhanced thunderstorm activity in the central equatorial Pacific perturbs the flow in the upper atmosphere, with a ripple effect downstream consisting of a series of alternating high and low pressure regions along a great circle route into North America. One might make an analogy to placing a large rock in a mountain stream. The disturbance spreads downstream in a series of waves, the lengths of which are determined by the size of the rock and the speed of the flow. On a planetary scale, the waves take particular forms and directions due to the sphericity and rotation of the earth, and the general westerly flow of the temperate-latitude jet streams.

The principal teleconnection mode between the tropical Pacific and the Northern Hemisphere Circulation is called the Pacific-North American pattern, or PNA. The downstream wave appears as higher pressures than normal over western Canada and lower pressures than normal over the southeastern United States.

This in turn modifies the winds and jet streams that are responsible for the temperature and precipitation anomalies over North America.

The mid-latitude jet streams occur fundamentally because of the temperature gradient between the equator and the poles. This gradient is not evenly spread over that entire distance, but tends to be concentrated in relatively narrow bands. For example, in winter it is fairly uniformly hot between the equator and, say, central Mexico, while it is fairly uniformly cold between the northern U.S. and the north pole. The whole gradient is concentrated in perhaps one quarter or less of the equator-pole distance. The jet stream flows in this region. During non-El Niño periods the eastern equatorial Pacific is cool, and the equator-pole gradient is weaker there than in the west. During El Niño periods, the eastern Pacific warms up as much as 4-5°C and the gradient is consequently larger. This contributes to strengthening the jet approaching North America.

Another element affecting North America is that when the eastern Pacific is warm, increased evaporation occurs, as well as tropical convection, and the moisture pumped into the upper atmosphere can be carried northeast by the subtropical jet stream, contributing to heavier rainfall across the southern tier of the U.S., from California to Florida.

Other important teleconnections that have been noted include droughts that often occur in Africa and northeast Brazil during El Niños. In this case the mechanism has to do with eastward displacement of the circulation in the equatorial plane. In non-El Niño years, this circulation consists of rising motion over the warm pool and sinking over the eastern Pacific, connected by surface westward winds and upper eastward winds, known as the Walker cell. (This pattern of vertical motion is why it is usually wet in Indonesia but dry in Peru). When the cell moves east, the sinking motion is correspondingly displaced, producing drought in the equatorial Atlantic region. There are also probably other effects due to the anomalous Atlantic winds changing the local SST. There may also be far-downstream effects associated with the PNA.

Other notable effects in the Atlantic include a reduction in the frequency of hurricanes that usually strike the Caribbean region and the south- eastern U.S. in late summer and fall. It is thought that this is also due to the eastward displacement of the Walker cell, as stronger winds in the upper atmosphere shear off the tops of developing tropical storms in that region, tending to prevent them from becoming hurricanes.

XI. WHERE

A. Do El Niño events occur only in the Pacific Ocean?

The great width of the Pacific Ocean is the main reason we see El Niño Southern Oscillation (ENSO) events in that ocean as compared to the Atlantic and Indian Oceans. Most current theories of ENSO involve planetary scale equatorial waves. The time it takes these waves to cross the Pacific is one of the factors that sets the time scale and amplitude of ENSO climate anomalies. The narrower width of the Atlantic and Indian Oceans means the waves can cross those basins in less time, so the ocean adjusts more quickly to wind variations. Conversely, wind variations in the Pacific Ocean excites waves that take a long time to cross the basin, so the Pacific adjusts to wind variations more slowly. This slower adjustment time allows the ocean-atmosphere system to drift further from equilibrium than in the narrower Atlantic or Indian Ocean, with the result that inter-annual climate anomalies (e.g. unusually warm or cold Sea Surface Temperatures) are larger in the Pacific.

There is another way in which the width of the Pacific enables ENSO to develop there as compared to the other basins. In the narrower Atlantic and Indian Oceans, bordering land masses influence seasonal climate more significantly than in the broader Pacific. The Indian Ocean in particular is governed by monsoon variations, under the strong influence of the Asian land mass. Seasonally changing heat sources and sinks over the land are associated with the annual migration of the sun. Heating of the land in the summer and cooling of the land in the winter sets up land-sea temperature contrasts that affect the atmospheric circulation over the neighboring ocean. This land influence competes with the ocean-atmosphere interactions that are essential for generating ENSO.

B. Does El Niño originate solely in the tropics or do the mid-latitudes play an important role?

We observe that large-amplitude climate signals occur well outside the tropics during El Niño events. The question is, are those precursors of El Niño, or are they far-field effects essentially incidental to the equatorial Pacific "main event"? Both points of view have their advocates.

On the one hand, there is no doubt that the entire ocean-atmosphere system is interconnected, and each El Niño event occurs on the background of existing conditions, which includes the positions of the mid-latitude jet streams as an important component. In addition, newly-developing theories of the slow (decadal) evolution of the equatorial circulation point to a key role for water masses that originate in the subtropics or higher latitudes. These water masses are part of a global-scale meridional overturning circulation, in which water sinks at high latitudes (due to evaporation or winter cooling making it more dense), and travel a circuitous subsurface route to the equator, where they upwell. Then the water flows poleward at the surface back to the subtropical gyres, warming under the sun to complete the cycle, which probably takes several decades or so. Now researchers have shown that the sinking water masses can have different temperature and salinity properties, and that as these reach the equator, they modify the conditions prevailing there, and it is thought that these slow changes may be the reason why some periods have many El Niños (like the 1990s) while others don't.

On the other hand, numerical models of the equatorial ocean-atmosphere system (including fairly simple to quite complex formulations) commonly develop inter-annual climate oscillations similar to El Niño. This indicates that at least the basic phenomena is intrinsic to the general situation of a wide ocean spanning the equator, and theory bears this out. Therefore I think the prevailing sentiment among climate researchers is that the mid-latitude influences referred to above can modify individual El Niños, but that fundamentally it is an instability of the equatorial ocean-atmosphere system that would occur in recognizable form regardless of what happens poleward of say 15-20 degrees latitude.

However, at present we do not know with any certainty how El Niño events are initiated. Therefore the tropical/extra-tropical debate cannot be said to be resolved. Another regional influence that is cited by some is the Asian monsoon. As with the mid-latitude situation, the fact that El Niño develops in models without an Indian Ocean again indicates that the Pacific ocean/atmosphere system is probably sufficient, but we really don't know for sure. These topics are the subject of much current research.

C. Why do El Niño and La Niña only occur in the Pacific?

This question does not have a simple or straightforward answer, since this is not a settled issue. Fundamentally we are not exactly sure why the Pacific should have an El Niño/La Niña cycle and the Atlantic not. We observe that this is the case and can think of reasons why this makes sense, but if we had no observations to tell us the answer in advance I don't think we would deduce it from theory. For example, if earth did not have an Atlantic or Pacific, and we were studying a new planet with such features for the first time, I doubt that anyone would predict such a distinction. It's always easier to come up with a theory when you know what the answer has to be! Please take my answer below in this spirit.

A principal difference between the Atlantic and Pacific is the width of the equatorial region; the Pacific is more than twice as wide. This is important in terms of their capacity to sustain an El Niño/La Niña cycle because of the peculiar dynamics of equatorial waves. Equatorial waves are not the familiar surf or swell seen on the surface, but very largescale motions that carry changes in currents and temperature over thousands of kilometers. The period of these waves is measured in months, and they take typically 3 months to more than a year to cross the Pacific. Surprisingly, these waves do not spread out equally in all directions like waves made by dropping a rock in a lake, but preferentially propagate eastward or westward. When winds blow over a large area of the ocean consistently for a month or more, equatorial waves are usually generated, and these then modify conditions over a very large region, including places far removed from where they were generated. For example winds over the far western Pacific make waves that carry the signal to the coast of South America, even though the winds in the South American region may not change at all. The subsurface changes due to the arriving waves can then cause sea surface temperature changes, entirely due to winds occurring many thousands of kilometers to the west.

With the huge distances across the Pacific, one side of the ocean can be reacting to conditions due to one set of waves, while the other can be doing something completely different. As the waves propagate back and forth, a cycle can be set up that oscillates (El Niño/La Niña). The much smaller Atlantic, on the other hand, is not large enough to sustain much of an oscillation, since the waves cross it so quickly, often in only a month or so. This does not allow a cross-ocean contrast to be created, nor an oscillation to be set up. Some indications suggest that some kind of weak oscillation may in fact occur in the Atlantic, but it never gets to the amplitude of that in the Pacific.

A second reason that the Pacific is more important in this regard is that the fundamental driver of the whole ocean-atmosphere circulation is heat. The large width across the Pacific allows the existence of a huge pool of warm water in the west. The smaller distances across the Atlantic mean that the Atlantic warm pool is very much smaller. The Pacific warm pool is a gigantic source of heat that is one of the main controls on the atmosphere. When the warm pool shifts east (during El Niño) or shrinks west (during La Niña), the effects reverberate around the world, causing the weather disruptions associated with this cycle. In the Atlantic, there is simply not enough of a warm pool to make that much difference to worldwide weather. So even if there is an analogue to El Niño in the Atlantic, it has much less power to cause weather disturbances that affect more than local conditions.

This is not to say that there aren't significant oscillations that occur in the Atlantic and Indian Oceans. These have been getting more attention lately, but in the past were ignored because the Pacific El Niño is so powerful and has such obvious effects.

XII. WHEN

A. How often do El Niño and La Niña (ENSO Events) typically occur and how long do they last?

1. El Niño and La Niña episodes typically occur every 3-5 years. However, in the historical record this interval has varied from 2 to 7 years. El Niño typically lasts 9-12 months, and La Niña typically lasts 1-3 years. They both tend to develop during March-June, reach peak intensity during December-April, and then weaken during May-July. However, prolonged El Niño episodes have lasted 2 years and even as long as 3-4 years.

2. Scientists studying El Niño this century often say its warming cycle occurs every two to seven years. The warm sea surface temperatures generally appear off the coast of Peru close to Christmas, hence the name El Niño or "the Christ child," and usually reach their peak warmth in the Eastern Pacific the following year during the late fall. Following the peak, the waters will tend to slowly cool through the winter and spring of the next year. But El Niño's effects can be felt continually around the globe for more than a year, though this is generally not the case in any one place. Since the ocean warming can affect global weather patterns, these atmospheric changes, such as drought in Indonesia and Australia, appear before the peak in some locations while the weather and climate in other places, such as in the USA, are affected after the peak warming. But scientists caution that El Niño, and the larger "Southern Oscillation" of which it is a part, occur irregularly, meaning the cycles may not occur within specific time periods. For example, nearly all of the years since 1990 have had significant warming of the Eastern Pacific sea surface, indicating weak to moderate El Niño conditions. The 1990-1995 warming was the longest El Niño on record.

3. On average El Niño occurs every 3-6 years but only irregularly and not as predictably as the astronomically controlled tides. As measured by the degree of warming, every other event tends to be stronger or weaker, with the strong ones occurring only at 8 to 15 year intervals. The intervening weak and moderate events do not typically bring such disastrous consequences. The events of 1982/83 and 1997/98 were unusually strong, equaled historically only by events in the late 1800s. Really big events like 1982/83 and 1997/98 occur only a few times in a century.

4. El Niño and La Niña occur on average every 3 to 5 years. However, in the historical record the interval between events has varied from 2 to 7 years. According to the National Centers for Environmental Prediction, this century's previous La Niñas began in 1903, 1906, 1909, 1916, 1924, 1928, 1938, 1950, 1954, 1964, 1970, 1973, 1975, 1988, and 1995. These events typically continued into the following spring. Since 1975, La Niñas have been only half as frequent as El Niños. La Niña conditions typically last approximately 9-12 months. Some episodes may persist for as long as two years.

B. What years are El Niño/La Niña years?

Definitions for what constitute an El Niño/La Niña event vary so there is not a definitive set of years.

C. Does a La Niña typically follow an El Niño?

No, a La Niña episode may, but does not always follow an El Niño.

D. Is the periodicity of El Niño events (every 2-7 years) the same as La Niñas?

No! It is wrong to think of this as an oscillation, simply swinging back and forth. There can be several El Niños in a row, as we had in the early 1990s. Many scientists are coming to the view that there may not be such a thing as La Niña, or at least that it is not just the opposite of El Niño. Perhaps there is just the normal situation that is disturbed every few years by an El Niño. In that case the swinging back to cool temperatures should not be called La Niña but just plain normal. Also that means that the word "periodic", which implies an oscillation, is not appropriate. This is a controversial subject, and there is no accepted result. But in any case it is definitely not a simple oscillation.

E. Why are El Niño and La Niña strongest during December-April?

El Niño and La Niña are typically strongest during December-April because the equatorial Pacific sea-surface temperatures are normally warmest at this time of the year. Consequently, a slight warming of the waters due to El Niño can result in a major redistribution of tropical convective rainfall, whereas a slight cooling due to La Niña can restrict the tropical convection to Indonesia.

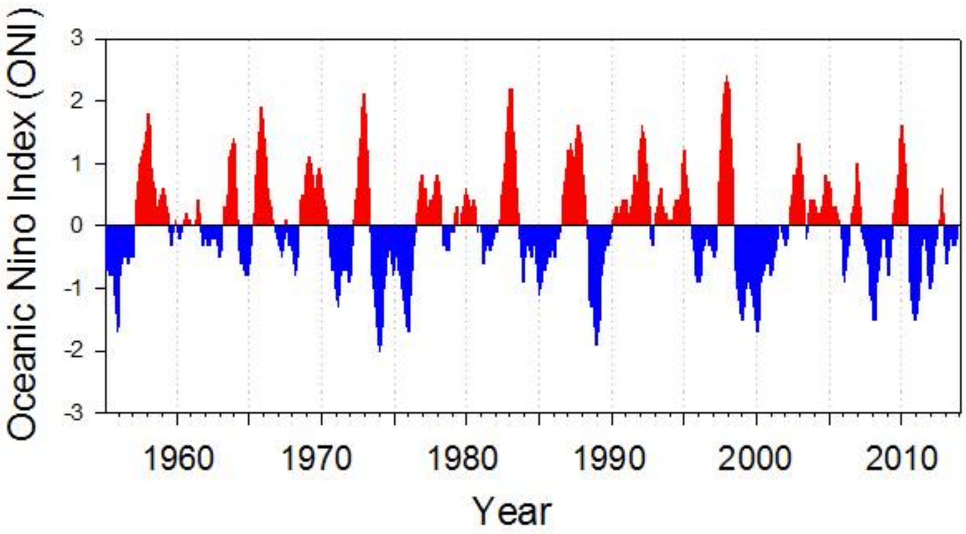
The El Niño and La Niña-related sea-surface temperature and tropical rainfall anomalies also affect the wind patterns, which in turn further amplify the sea-surface temperature anomalies. This coupling between the ocean and atmosphere is a critical aspect of the El Niño and La Niña phenomena.

In a typical December-April the Pacific warm pool is most extensive, water temperatures in the central and east-central equatorial Pacific are at their warmest levels, and tropical convection extends from Indonesia to the International dateline.

During El Niño the Pacific warm pool and associated area of deep tropical convection expand to well east of the date line during December-April, and the tropical easterly trade winds are weakest.

During La Niña the Pacific warm pool and deep tropical convection are confined to well west of the date line during December-April, and the tropical easterly trade winds are strongest.

E. Are there long term trends associated with El Niño?



Yes. A number of climate indicators were noted to have changed in 1976, especially around the Pacific Basin. Prior to 1976, El Niño and La Niña occurred with about equal frequency, each at intervals of about 3-7 years. Since 1976, there have been 9 El Niños (using a 6-month average of the Southern Oscillation Index of -0.50 as the criteria), or one every 2.2 years. There has been just one moderate La Niña in that interval (1988-89) and a rather weak La Niña (not even counted by some) in 1996-97. Longer perspectives, since 1860, indicate that the 1976-1997 period is quite unlike any other in the record. This is a source of considerable puzzlement at this time.

XIII. CAUSES

A. What initiates El Niños?

It is necessary to state outright that we do not know why El Niño events begin. It's not that the answer is obfuscated behind scientific jargon. It's that we don't know. Not only don't we know, we're not really that close to knowing. Having said that, what we DO know is how an event evolves once it has started. Although that may not be so satisfying scientifically, it is certainly useful societally, since we are usually well able to recognize the start of an event, and then the models do a reasonably good job of forecasting the subsequent changes. Since the start is typically 6-9 months before the effects start hitting the Americas, that gives us a useful forecasting ability. For example, no model (nor anyone's scientific intuition) forecast the massive 1997-98 El Niño until the first signs were already visible (say, in Dec 1996). The models then began forecasting a weakish event; after the big westerly winds in March 1997, then the model forecasts for the next year were quite realistic.

Very roughly the theories fall into two categories: that the Pacific ocean-atmosphere system has a natural frequency of oscillation which is perturbed by chaotic processes (weather) to be irregular; or that the system is stable until an event is triggered by some kind of outside forcing. Since we have only very short records relative to the timescale of the events (say we have observed only about 5 of them with decent resolution), it is not possible to make a statistical distinction, so people are free to theorize aimlessly. Personally I lean to the second (trigger) idea, but I would not bet my life savings on it, small though that is. It seems to be true that unless the Pacific is "ready" for an El Niño that even with the appropriate trigger it is not possible to get a large event. By "ready" I mean "with high sea level in the west having been built up by several years of strong trade winds". For example in early 1993 there were large westerly events that would have been a great trigger if the Pacific were built-up, but since there had been an El Niño the year before the Pacific had nothing to offer.

Perhaps I should back up. During El Niño the equatorial Pacific releases a large amount of heat (and mass) to the subtropics. This occurs as the warm water of the far west sloshes eastward and then poleward along the shores of the Americas. Before the event, the trade winds have "built up" a large thick warm pool in the west. If that build-up has not happened, then there is nothing to release. So now maybe you can understand why one can interpret this two ways. If you focus on the buildup, then that takes several years and produces the natural timescale. But the buildup by itself is not sufficient (in my opinion). The trigger is necessary, too. Which one is the "cause"?

B. Why does El Niño (La Niña) occur?

1. El Niño and La Niña result from interactions between the surface of the ocean and the atmosphere in the tropical Pacific. Changes in the ocean impact the atmosphere and climate patterns around the globe. In turn, changes in the atmosphere impact the ocean temperatures and currents. The system oscillates between warm (El Niño) to neutral (or cold La Niña) conditions with an on average every 3-4 years.

2. El Niño and La Niña are naturally occurring phenomena that result from interactions between the ocean surface and the atmosphere over the tropical Pacific. Changes in the ocean surface temperatures affect tropical rainfall patterns and atmospheric winds over the Pacific ocean, which in turn impact the ocean temperatures and currents. The El Niño- and La Niña-related patterns of tropical rainfall cause changes in the weather patterns around the globe.

3. El Niño results from interaction between the surface layers of the ocean and the overlying atmosphere in the tropical Pacific. It is the internal dynamics of the coupled ocean-atmosphere system that determine the onset and termination of El Niño events. The physical processes are complicated, but they involve unstable air-sea interaction and planetary scale oceanic waves. The system oscillates between warm (El Niño) to neutral (or cold) conditions with a natural periodicity of roughly 3-4 years. External forcing from volcanic eruptions (submarine or terrestrial) have no connection with El Niño. Nor do sunspots as far as we know.

4. Typically, a La Niña is preceded by a buildup of cooler-than-normal subsurface waters in the tropical Pacific. Eastward-moving atmospheric and oceanic waves help bring the cold water to the surface through a complex series of events still being studied. In time, the easterly trade winds strengthen, cold upwelling off Peru and Ecuador intensifies, and sea-surface temperatures (SSTs) drop below normal. During the 1988- 89 La Niña, SSTs fell to as much as 4 degrees C (7 degrees F) below normal. Both La Niña and El Niño tend to peak during the Northern Hemisphere winter.

C. Do volcanoes or sea-floor venting cause El Niño?

The idea that volcanoes cause El Niño events originally gained prominence because of the eruption of Mt Chichon in Mexico in Feb 1982 (preceding the El Niño of 1982-83), and the eruption of Mt Pinatubo in the Philippines) in June 1991 (preceding the El Niño of 1991-92). However, when the time series of El Niños is compared to the time series of volcanic eruptions it becomes clear that the relationship is coincidental. There are numerous large volcanic eruptions around the world and almost as many El Niños. In that situation there is almost always an eruption at some time preceding any El Niño. Scientists are now convinced that this relation is coincidental.

Certain experiments bear this out. For example, several computer models predicted the onset of the 1991-92 event as early as January 1991, based on the state of the ocean-atmosphere system at that time and well before Pinatubo. That indicates that the ocean-atmosphere system was already generating the El Niño, and Pinatubo occurred coincidentally. Computer models integrating the equations of fluid motion and the flow of heat routinely produce El Niño-like variability completely on their own. Of course, computer models are not reality, but these experiments suggest that El Niño is a natural mode of variability of the ocean-atmosphere system, as much as, for example, a thunderstorm. While we do not have a complete picture of how the El Niño cycle operates, these models (and a developing theoretical understanding) suggest that the fluid envelope of the earth is prone to developing various kinds of instabilities, ranging from storm systems lasting a few hours or days, to El Niño, to longer-term fluctuations that we are just beginning to explore. There is no reason to think that external processes such as volcanoes are a necessary element.

None of this is to say that volcanoes don't affect the climate. They most certainly do, and since El Niños occur against the background existing climate, there is little doubt that volcanic eruptions that eject large amounts of dust into the stratosphere must modify the frequency, character and strength of El Niño events, possibly in important ways. The distinction I make is between "slowly modify the background" and "cause" El Niño.

As far as deep-ocean vents modifying the ocean temperatures, researchers now think that this source of heat does contribute to the long-term evolution of the ocean state. The chemical signatures of undersea vents are of great interest as tracers of the slow deep circulation of the ocean, and therefore these signatures are studied carefully. (The deep circulation is so slow that its currents cannot be measured directly, so we look at tongues of chemical tracers to estimate the speed, direction and transport of the flows). Numerous scientific papers discuss these questions, studying a variety of chemical constituents. What is consistently found is that the traces spread extremely slowly through the water column and are vastly diluted. There is little doubt that over very long periods the effects of undersea venting on the ocean are large, both for their heat and for their contribution to the chemical makeup of the ocean. However, these effects occur on timescales of thousands of years, and certainly do not produce the kind of rapid signals that characterize El Niño. To trigger an El Niño event, one would look for a signal that produced surface variability on a month to month or year to year timescale, and undersea venting has never been observed to do that.

It is indeed tempting to look for nice clean causes of complex oscillations like the El Niño cycle. Unfortunately (or perhaps fortunately for those of us who like scientific challenges), it seems that the ocean-atmosphere system is well-capable of generating these oscillations on its own, and the task now is to understand how this happens. Volcanoes and sea-floor venting are part of the slowly-changing background state on which phenomena like El Niño occur, and add to the complexity of the task.

- **Addendum to Previous Response: What are instabilities?**

  Fundamentally, El Niño is an instability, which means it is a fluctuation that gains energy from the background state. It also implies a strong element of unpredictability. Instabilities are almost by definition hard to pin down, but some examples may be helpful. When two adjacent flows of water move at different speeds (for example in a small river where the center flow is faster than near the sides or where rocks disrupt the smooth flow, or where two rivers join, or where two ocean currents flow in opposite directions), then we see eddies forming and spinning. Why do such eddies grow? Why don't the two flows simply slide by each other smoothly? The answer is that when the contrasting flows are fast enough, friction at a molecular level prevents the water from sliding smoothly. So the boundary between them breaks down into tiny spinning blobs. Once the tiny blobs form, they have their own friction with the surrounding water, including the other tiny blobs, and tend to join and absorb others, growing into larger blobs. Picturing a fast creek with rocks, we see a series of spinning eddies some of which can grow fairly large, apparently from nothing, gaining their energy from the initial flow of the river. This means that the eddies slow the overall flow, so they can be seen as a kind of fluid friction. Much of the effort in computer modeling of fluid flows involves representing this friction; since it often occurs on smaller scales than the gridbox size of the models, this is done by estimating an "eddy viscosity" that parameterizes these effects, which is an important source of the uncertainty in climate modeling. A key point is that although we can predict that eddies will form behind certain rocks, we cannot know precisely where and when, or which ones will get large and which ones will remain small.

  A thunderstorm is a weather instability that gains energy from the initial state of the atmosphere. Moist air in effect "stores" the energy from the sun that originally evaporated the water ("latent heat of evaporation"). When the moisture condenses into rain, that energy is released to warm the air at the level of condensation. In a thunderstorm, an initial rising motion (perhaps over a sun-warmed field or forest), lifts air enough to condense, then the latent heat gives additional warming, and the rising is amplified. This pulls in adjacent air, and the process accelerates an initially tiny upward pulse into a full-blown thunderstorm that gains its energy from the background conditions (the stored latent heat). But like the eddy in the river, although we can predict in general that thunderstorms will occur in a particular region on a summer afternoon, most of the time we cannot predict precisely where and when they will form. Though two summer afternoons may be apparently identical, they will produce different thunderstorms. The hallmark of instability is unpredictability in detail.

El Niño has similar characteristics on an oceanic scale. There is a cascade of events that feed on the initial conditions of the ocean-atmosphere system, as in the thunderstorm, but the initial trigger, like the initial heating that started a thunderstorm, is probably unpredictable in advance (and probably also unknowable in hindsight). But the key point regarding geothermal heating is that the trigger for El Niños is probably winds, not heat.

D. Is El Niño caused by pollution or global warming?

1. Neither pollution nor global warming is causing El Niño. We have instrumental records dating back to the 1870s, and other kinds of records (e.g. tree rings, coral growth rings) going back much further, and these all suggest that El Niño has existed long before people caused pollution or global warming. El Niño is part of the natural variability of the Pacific ocean-atmosphere system.

On the other hand, it is certainly possible that global warming will modify the way the El Niño cycle behaves. In fact it would be surprising if it didn't, since everything in the climate system is connected. However, we don't know enough about how this all works to be able to say what such a modification would be. Paleoclimate records suggest that El Niños have changed somewhat in past climates. This evidence is based on things like bottom cores in lakes in the Andes Mountains that show the occurrence of severe floods. It suggests that the events were perhaps 20% stronger than today during the last glacial maximum (20 thousand years ago) and 20% weaker about 10 thousand years ago. It is not clear why this should be the case, but it shows that changing climates can be expected to change the way El Niño behaves.

2. The jury is still out on this. Are we likely to see more El Niño's because of global warming? Will they be more intense? These are questions facing the science community today. Research will help us separate the natural climate variability from any trends due to man's activities. If we cannot sort out what the natural variability does, then we cannot identify the "fingerprint" of global warming. We also need to look at the link between decadal changes in natural variability and global warming. At this time we cannot preclude the possibility of links but it is too early to say there is a definite link.

3. We don't know if global warming due to greenhouse gases (exhaust from our cars and factories) cause ENSO events to become more frequent or more severe. Some studies suggest this may be true while others cast doubt on the idea. Part of the problem is that natural changes in the frequency and intensity of ENSO events have occurred in the last five centuries for which records exist, and it is hard for us to distinguish those from recent characteristics that might otherwise be attributed to greenhouse warming. This is also a subject of great interest in research. Unfortunately, while ENSO intervals are well matched to the political time scale that governs our research funding (3-4 years), global warming is not.

4. This is a matter of considerable speculation in the climate research community. It is plausible that a warmer earth would produce more and stronger El Niños. There is some evidence that the earth has warmed over the past two decades, and there is no doubt that El Niño has been much more frequent in that time. If the evidence of a warming earth is taken at face value (not universally accepted), there still remains a wide spectrum of opinions on whether we are seeing a manifestation of human modification of global climate, or whether the natural climate system would be exhibiting this behavior anyway.

5. The reason you won't find much information connecting El Niño and global warming is that we (meaning the mainstream scientific community) don't really have too much useful to say about it at this point. While we know that El Niño occurs on the background of the large-scale climate, and assume that as the background changes that some aspects of El Niño might also change, we are nowhere near the ability to say what those changes might be. The models are inconclusive on this point, with some saying there might be a strengthening and others saying not. (Note that "global" warming is likely to be much stronger at the poles, with much less signal in the tropics.) So rather than speculate about such a politically-charged subject, we usually keep our mouths shut.

The above cautionary note does NOT, however, mean that one should discount the possibility. Since we see that El Niños in different years vary greatly in their strength it appears the process may be quite sensitive to changes in the background state.

Much of the uncertainty in the question of whether greenhouse warming is affecting the ENSO cycle revolves around the problem of how one would measure the statistical significance of changes in recent El Niños. Some say that the string of warm events during the 1990s are evidence that a general warming trend is starting to change the weather; others say that these variations are within normal limits. The fact is we have only a few events to talk about, which means there is no statistical rigor to any argument for or against this idea. It is simply shooting the breeze. We won't have good statistics about El Niño for another hundred years or so (perhaps even longer if it is truly chaotic), so I don't bother with such arguments at all. To me the interesting stuff is the dynamics and thermodynamics anyway, and on that front we stand a chance of making progress in my lifetime.

The connection could also go the other way, although this is not often considered. The forest fires in the Amazon and Indonesia, due to the El Niño of 1997-98, are contributing strongly to the increase of C02 in the atmosphere, and also reducing the forest cover that absorbs C02. Therefore El Niño appears to be part of the problem of greenhouse warming.

XIV. PURPOSE

A. Does El Niño play a special role in Nature?

1. Most definitely. El Niño may be thought of as one of Earth's standard mechanisms for getting heat from the tropics (where more comes in from the sun than goes out) to the polar regions (where more heat returns to space than comes in). Ordinary winter storms also do this. Without these poleward transports of heat, the planet would be an unbearable hothouse in the tropics or too cold for habitation toward the poles. In the years between ENSO events, excess heat accumulates in the tropics and then gets "exported" during El Niño. It's somewhat like the accumulation of winter snow on a steep mountain slope. The snow cannot accumulate indefinitely, defying gravity; inevitably it must give way to avalanches. What happens during an El Niño "avalanche" is that a lot of excess heat gets transported poleward, most frequently through winter storms. That is why places like California and Chile have rougher winters in conjunction with El Niño.

El Niño is also responsible for a good deal of diversity in plant and animal life because the periodic stress it puts on biological systems is a stimulus to the evolutionary process. Moreover, the affected biota on both land and in the sea are much more resilient as a result of the need to survive these periodic upheavals in the environment.

2. El Niño is part of the natural rhythm of the ocean-atmosphere system, as much as winter cold or summer thunderstorms or any other weather phenomenon.

In a complicated system like this, each feature fills a role in the grand scheme of things. We cannot say exactly what the role of El Niño is, but we do observe that these events drain the west Pacific of heat that is built up over several years by the trade winds. In any case El Niño does not exist in isolation, and any changes in it would reverberate around the whole system in unpredictable ways. Further, as part of the natural environment of the Pacific basin that the animals, fish, birds and plants have adapted to over the millennia (we know that El Niños have been occurring as far back as we can see), it is not clear that stopping El Niño would even be desirable. Even if it were possible to make El Niño disappear, we have no idea what the result would be. Very possibly we wouldn't like it!

Nevertheless, it seems to me that we are able to do a lot of good for society even at our present stage of ignorance, since even without knowing what drives El Niño, we can recognize it, and then know (largely from statistics of past events) what the effects will be on regions far removed from the tropical Pacific. That's what the publicity is about, and that is appropriate, although perhaps not so satisfying to those such as yourself who ask, "why?".

XV. EFFECTS

A. SPECIFIC STORMS

1. Does El Niño cause specific storms?

El Niño is not "responsible" for any particular storm. But El Niño is a vital element all the same. For example, winter is not responsible for any particular snowstorm, but winter is certainly a crucial part of why the northern hemisphere has snow in January.

There are two ways in which El Niño adds punch to the storms over North America. First, it draws the jet streams further south in the eastern Pacific. That means more storms in general across the southern tier of the U.S.

Second, El Niño adds punch to the storms because the stronger and eastward-displaced warm pool pumps additional moisture into the upper atmosphere, where it is blown towards North America and caught up in the more-southerly jet streams.

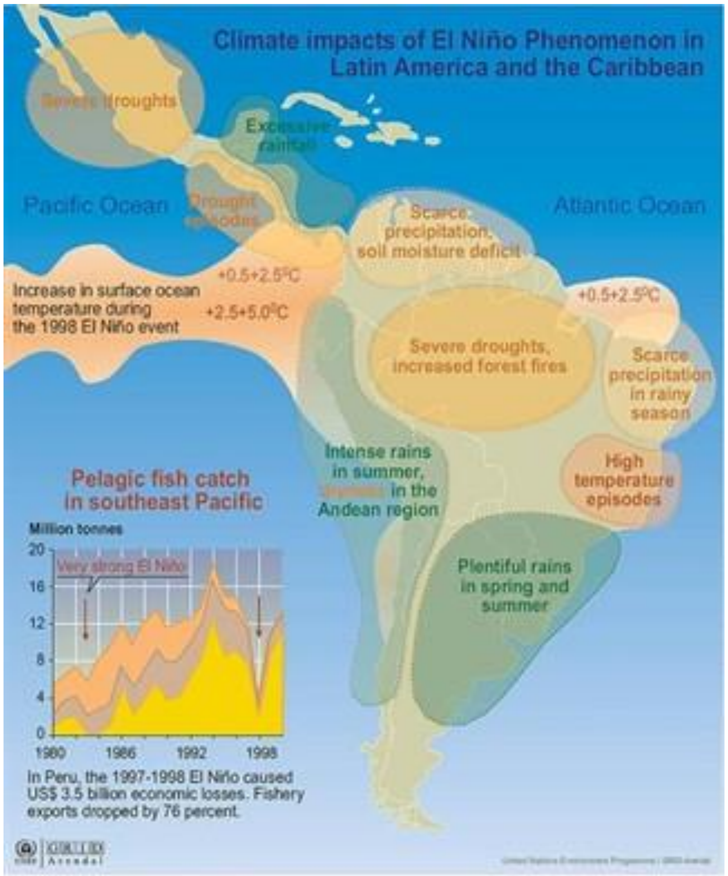
So while it is impossible to prove that El Niño caused the particular tornadoes that struck central Florida in late February, just as it is impossible to say that winter caused a particular snowstorm, it is the likely suspect. Perhaps there would have been strong tornadoes on this day in Florida without El Niño, but it appears not.

We cannot run experiments to see what a parallel earth without an El Niño this year would do. But a group at NOAA's Climate Diagnostic Center in Boulder, CO, is trying something similar using numerical forecast models. First, they run the model with the actual conditions (that is, for example, including 1997 El Niño-induced SST anomalies in the Pacific) and produce weather forecasts, just like the regular ones. Then they make another run, in which everything is the same as the first one except that they change the Pacific SST to be like a "normal" year. The difference between these forecasts gives an indication of the effect of El Niño conditions in the Pacific on the specific weather events being forecasted. The results for forecasts of Florida precipitation during the tornadoes of Feb. 23 suggest that El Niño did indeed add punch to these storms.

2. Is this a "La Niña" hurricane/tropical storm/drought/fire/flood/winter storm?

It is inaccurate to label individual storms or events as a La Niña or El Niño event. Rather, these climate extremes affect the position and intensity of the jet streams, which in turn affect the intensity and track of storms. During La Niña, the normal climate patterns are enhanced. For example, in areas that would normally experience a wet winter, conditions would likely be wetter than normal.

C. GLOBAL IMPACTS (GENERAL AND SPECIFIC)



Climate impacts of El Niño Phenomenon in Latin America and the Caribbean

In Peru, the 1997-1998 El Niño caused US$ 3.5 billion economic losses. Fishery exports dropped by 76 percent.

Sources: IPCC 2001, FAO 2002, UNEP 2003

1. **Does El Niño slow down the rotation of the earth?**

   El Niño cycles cause a correlated but small fluctuation in the "length of day" (it gets longer), so yes, this is true. The reason it happens is that the entire Earth system (solid earth, air and water) must conserve its total angular momentum (related to the speed of rotation around the earth's axis), like a spinning top, or a twirling ice skater. During El Niño, the average eastward speed of the winds around the globe increases, which is related to the reason California and Chile get more and stronger winter storms. Since the angular momentum of the air increases, the rotational speed of the solid earth must decrease, in compensation. Of course, the resulting increase in the length of the day is very small, so don't worry about arriving early for your next appointment.

2. What is the relationship between the Earth's rotation, the Coriolis force, and El Niño and La Niña?

El Niño results in a decrease in the earth's rotation rate, an increase in the length of day, and therefore a decrease in the strength of the Coriolis force. La Niña tends to have the opposite effect.

El Niño is associated with a weakening of the tropical Pacific trade winds, and also with a strengthening of the mid-latitude westerlies both at the surface and aloft. To balance these changes in atmospheric winds, the earth's rotation rate decreases in order to conserve total angular momentum of the earth/atmosphere system. Conservation of angular momentum is a basic physical principal that operates, for example, when a ballerina brings her arms closer to her body to spin faster.

The change, however, is only about 1 millisecond at the peak of a strong El Niño. There are 86400 seconds in a day, so this change represents one part in 100 million. Such a change will have little effect on normal activities on a human scale, such as flying an airplane.

3. What are the global impacts of La Niña?

Both El Niño and La Niña impact global and U.S. climate patterns. In many locations, especially in the tropics, La Niña (or a cold episode) produces the opposite climate variations from El Niño. For instance, parts of Australia and Indonesia are prone to drought during El Niño, but are typically wetter than normal during La Niña.

4. What are the Global Consequences of El Niño?

The twists and turns in the ongoing dialogue between ocean and atmosphere in the Pacific can have a ripple effect on climatic conditions in far-flung regions of the globe. This worldwide message is conveyed by shifts in tropical rainfall, which affect wind patterns over much of the globe. Imagine a rushing stream flowing over and around a series of large boulders. The boulders create a train of waves that extend downstream, with crests and troughs that show up in fixed positions. If one of the boulders were to shift, the shape of the wave train would also change and the crests and troughs might occur in different places.

Dense tropical rain clouds distort the air flow aloft (5-10 miles above sea level) much as rocks distort the flow of a stream, or islands distort the winds that blow over them, but on a horizontal scale of thousands of miles. The waves in the air flow, in turn, determine the positions of the monsoons, and the storm tracks and belts of strong winds aloft (commonly referred to as *jet streams*) that separate warm and cold regions at the Earth's surface. In El Niño years, when the rain area that is usually centered over Indonesia and the far western Pacific moves eastward into the central Pacific, the waves in the flow aloft are affected, causing unseasonable weather over many regions of the globe.

The impacts of El Niño upon climate in temperate latitudes show up most clearly during wintertime. For example, most El Niño winters are mild over western Canada and parts of the northern United States, and wet over the southern United States from Texas to Florida. El Niño affects temperate climates in other seasons as well. But even during wintertime, El Niño is only one of a number of factors that influence temperate climates. El Niño years, therefore, are not always marked by "typical" El Niño conditions the way they are in parts of the tropics.

5. Are the effects of El Niño all bad?

No. During El Niño winters, for example, Florida receives significantly more rain than normal, which reduces the risk of wildfires in the spring and early summer. Reservoirs fill and skiers and sport fisherman are happy in many places. The formation of desert lakes in northern Peru form a temporary habitat for vegetation, freshwater fish and farmers.

6. How will El Niño impact a particular region?

There has been a lot research investigating the effects of El Niño/Southern Oscillation on climate (temperature, rainfall, snowpack, climate extremes etc.) throughout the world. Note that there are very few regions where the effects of El Niño/La Niña are consistent every year due to both the varying nature of El Niño and the inherent variance of the atmosphere/ocean system. As such, the research that has been carried out is best utilized to indicate the probability of what the effects will be.

7. What effects does El Niño have in South America?

During the past 40 years, nine El Niños have affected the South American coast. Most of them raised water temperatures not only along the coast, but also at the Galapagos islands and in a belt stretching 5000 miles across the equatorial Pacific. The weaker events raised sea temperatures only one to two degrees Fahrenheit and had only minor impacts on South American fisheries.

But the strong ones, like the El Niño of 1982-83, left an imprint, not only upon the local weather and marine life, but also on climatic conditions around the globe.

8. Does El Niño affect Australia more than other areas of the world?

El Niño can be a major influence on Australia's weather. For example, it is often linked to droughts there. Northern Australia is in the tropics, which are affected more than mid-latitude regions. Also, the normally warm part of the Pacific is close to Australia and this warm water helps encourage thunderstorms. During the warm phase of an El Niño some of this warm water moves eastward, reducing the amount of rain in a large area of the western Pacific, including parts of Australia.

9. Is the occurrence of a strong "El Niño" always synonymous with disaster and Armageddon?

No. Again, a word of caution from NOAA/CPC is appropriate here:

> "When interpreting the climate information linked to El Niño it is important to note that while abnormal temperature and rainfall patterns can and sometimes do result in severe climate conditions, they do not imply calamitous conditions in many instances. For example, the above-normal precipitation expected in the Southwest and southern plains states implies a reduced chance for wintertime drought such as occurred during November 1995 - May 1996. In Florida the above-normal rainfall expected this winter indicates reduced chances of wildfires. In California, the potential impacts from El Niño can be severe. However, the above-normal rainfall across the state during the 1992-93 El Niño resulted in an end to severe long-term drought conditions that had persisted since 1986/87, and to a much-needed replenishment of water reserves."

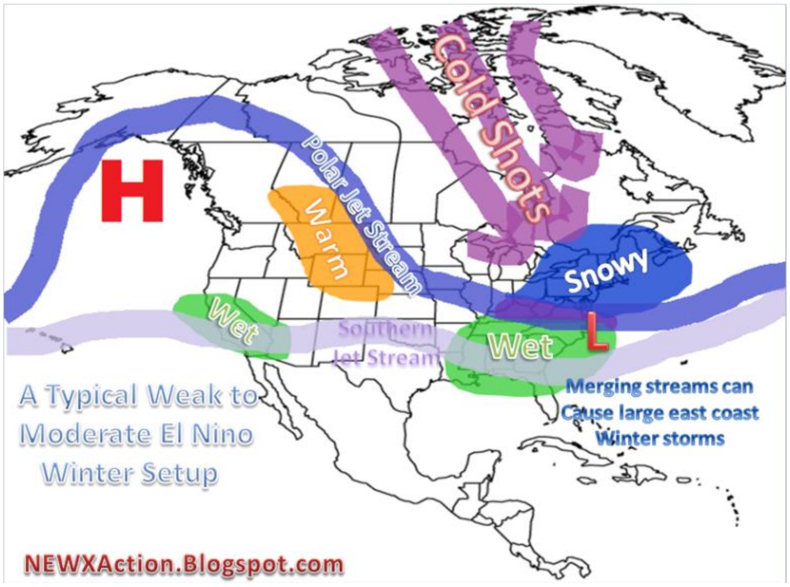
10. What about other regions of the world?

El Niño impacts are typically quite severe over southeast Asia, including Malaysia, Indonesia, New Guinea, Borneo and northern Australia. Throughout much of that region drought is common, agriculture is affected and tropical forest fires become a problem. Although western Pacific typhoons (overall) are no more frequent than normal, they tend to affect areas farther to the east, as far as Tahiti, that are otherwise less affected. To the west there is typically a failure of the summer (wet) monsoon over the Indian subcontinent, whose populations depend critically on the monsoon rains. Finally, droughts are known to occur in southern Africa and northeastern Africa.

11. Do El Niño and La Niña affect a location uniformly over the course of a season as indicated by analog forecasts?

Many atmospheric processes are involved in shaping seasonal weather. During the course of an entire season, the weather can be quite tumultuous, with enormous month to month fluctuations. For example, in 1999, Pittsburgh registered its 10th warmest February, only to be followed by the 7th coldest March in the last 47 years. Generic qualitative forecasts for full seasons obviously mask these crucial mid-season pattern shifts. Our forecasts and reports have 30-day incremental resolution, allowing you to visualize the forecast of each month.

D. GENERAL U.S. IMPACTS OF EL NIÑO



1. What are the U.S. impacts of La Niña?

La Niña often features drier than normal conditions in the Southwest in late summer through the subsequent winter. Drier than normal conditions also typically occur in the Central Plains in the fall and in the Southeast in the winter. In contrast, the Pacific Northwest is more likely to be wetter than normal in the late fall and early winter with the presence of a well-established La Niña. Additionally, on average La Niña winters are warmer than normal in the Southeast and colder than normal in the Northwest.

2. **How does La Niña affect climate in the West?**

   To a first approximation, it appears that the consequences of La Niña are nearly the opposite of El Niño in much of the U.S., including the West. In the previous discussion of El Niño effects, simply substituting the opposite words yields an approximately correct description.

3. **Do El Niños/La Niñas really affect the weather for my town?**

   The ENSO phenomena (e.g. El Niño and La Niña), causes many atmospheric and oceanic circulation changes that can affect global weather patterns. Although ENSO might indirectly affect the weather in your region, it is **only one of many** atmospheric processes, from hemispheric to the micro-scale, that determine the weather for your town. The processes must be examined collectively before conclusions can be drawn.

   Qualitative ENSO forecasts for geographic regions (i.e. the Northeast) or climate divisions are often not representative of cities within that region. Large weather differences can occur from city to city, and even within a single metropolitan location. For example, for the winter of 1995-96, Central Park, NY recorded its 4th coldest winter in 32 years, while La Guardia Airport, right across the East River, experienced a much warmer 10th placed ranking.

4. **During an El Niño event, when do the weather problems hit California, and how long do they last?**

   Off and on throughout the winter, if El Niño is strong then. Then it snows a lot in the mountains and it rains a lot elsewhere in California. Some of that is actually good, such as for skiers. In both 1982/83 and 1997/98, the worst effects were felt after the new year. Possibly the worst thing that can happen is in the spring if El Niño is still going strong as occurred in 1983. Then you can get a rapid wetting and melting of the large snowpack in the western mountains, producing severe flooding in some areas. This can be very bad. It's something the folks who manage water supplies (dams and such) have to watch out for.

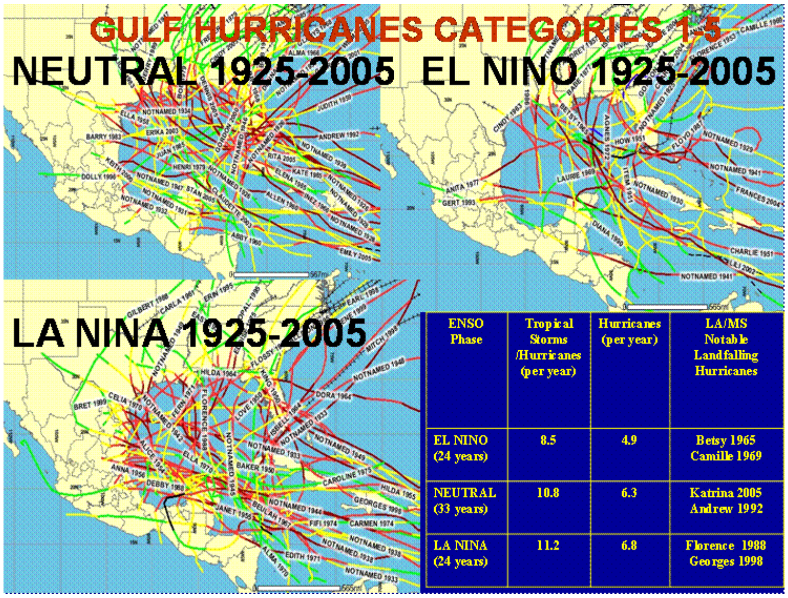
5. **Where else in the Americas are severe effects felt?**

Best known, of course, are the coastal regions of Ecuador and northern Peru, where so much rain falls that flooding, landslides, erosion and consequent property destruction reach disastrous proportions. The moisture causes explosive infestations of insects and associated problems with public hygiene that favor the development of water-born and mosquito-vectored diseases (cholera, malaria, dengue, etc.). In the deserts of Peru and Chile, entire "pampas" bloom with flowers where nothing but a barren expanse is normally found. In the far north of Peru, shallow lakes appear on the desert, with ecologies of plants and fishes that temporarily sustain migrant human populations. Farther south, both Chile and Argentina, and even southern Brazil, experience severe storms during the austral winter (June-August). Northeastern Brazil goes through severe drought in March-May, with consequences for its agriculture. Dry conditions over much of Central America and northern South America also affect agriculture and additionally cause deficits of hydroelectric energy and drinking water.

6. How can I find out the likely effects of El Niño and La Niña on the U.S. and other parts of the world?

Florida State University's Center For Ocean-Atmospheric Prediction Studies has maps showing the general effects during the four seasons of both phases of ENSO. Long-term forecasts are made by the National Weather Service. These are for three-month "seasons" for a year ahead. Finally, the National Oceanic and Atmospheric Administration (NOAA) has links to more detailed information about the effects of El Niño.

E. HURRICANES AND EL NIÑO



ENSO Phase	Tropical Storms /Hurricanes (per year)	Hurricanes (per year)	LA/MS Notable Landfalling Hurricanes
EL NINO (24 years)	8.5	4.9	Betsy 1965 Camille 1969
NEUTRAL (33 years)	10.8	6.3	Katrina 2005 Andrew 1992
LA NINA (24 years)	11.2	6.8	Florence 1988 Georges 1998

1. How do El Niño and La Niña influence the Atlantic and Pacific hurricane seasons?

The change in winds with height is referred to as vertical wind shear. Hurricane formation requires the winds to be fairly uniform throughout the atmosphere, meaning that they require low vertical wind shear. Hurricanes cannot form if the vertical wind shear is too high (above about 8 ms-1).

Dr. William Gray at Colorado State University has pioneered research efforts leading to the discovery of El Niño and La Niña impacts on Atlantic hurricane activity.

El Niño contributes to more eastern Pacific hurricanes and fewer Atlantic hurricanes. La Niña contributes to fewer eastern Pacific hurricanes and more 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. Over the eastern Pacific these wind patterns are opposite those normally seen in the region, and results in lower vertical wind shear. The eastern Pacific hurricane season is typically more active during El Niño because of the expanded area of low vertical wind shear in which hurricanes can form.

Across the tropical Atlantic, these same wind departures increase the total vertical wind shear, often to levels far too high for hurricanes to form. There tend to be fewer Atlantic hurricanes during El Niño because of this expanded area of high vertical wind shear.

La Niña produces easterly wind departures at upper levels of the atmosphere and westerly wind departures at lower levels, across the eastern tropical Pacific Ocean and tropical Atlantic. Over the eastern Pacific these wind patterns are in phase with those normally seen in the region, resulting in higher vertical wind shear. The eastern Pacific hurricane season is typically less active during La Niña because of the expanded area of high vertical wind shear.

Across the tropical Atlantic these same wind patterns are opposite to those normally observed, and result in lower vertical wind shear. There tend to be more Atlantic hurricanes during La Niña because of this expanded area of low vertical wind shear.

El Niño and La Niña also influence where Atlantic hurricanes form. During El Niño fewer hurricanes and major hurricanes develop in the deep Tropics from African easterly waves. During La Niña more hurricanes form in the deep Tropics from African easterly waves. These systems have a much greater likelihood of becoming major hurricanes, and of eventually threatening the U.S. and Caribbean Islands.

The chances for the continental U.S. and the Caribbean Islands to experience a hurricane increase substantially during La Niña, and decrease during El Niño.

2. What is the relationship between hurricanes and El Niño?

In general, warm ENSO episodes are characterized by an increased number of tropical storms and hurricanes in the eastern Pacific and a decrease in the Gulf of Mexico and the Caribbean Sea. Tropical weather products pages are available on the Web from the University of Michigan and from the University of Hawaii. A Tropical Storm and Hurricane Watch Information web page is also maintained by the Federal Emergency Management Agency (FEMA).

Atlantic Ocean

It is believed that El Niño conditions suppress the development of tropical storms and hurricanes in the Atlantic; and that La Niña (cold conditions in the equatorial Pacific) favor hurricane formation. The world expert in this area of study is Prof. Bill Gray of Colorado State University..

Pacific Ocean

El Niño tends to increase the numbers of tropical storms in the Pacific Ocean. For details, see the information about the location and numbers of tropical cyclones in the Eastern Pacific for El Niño and non-El Niño years from the Pacific ENSO Applications Center in Hawaii.

3. How is La Niña influencing the Atlantic and Pacific hurricane seasons?

Dr. William Gray at the Colorado State University has pioneered research efforts leading to the discovery of La Niña impacts on Atlantic hurricane activity, and to the first and, presently only, operational long-range forecasts of Atlantic basin hurricane activity. According to this research, the chances for the continental U.S. and the Caribbean Islands to experience hurricane activity increases substantially during La Niña.

4. In the summer of 1997 a Pacific hurricane threatened California and there were predictions that increased hurricane frequency and intensity could spell disaster, that monsoons would hit northern California, etcetera.

For the most part, such talk was unwarranted. First of all, monsoons are not hurricanes; they are periods of significant seasonal change in tropical weather and wind direction. All major continents are affected by monsoons, and they may be stronger or weaker in association with El Niño. However, a hurricane in California is only remotely possible, even during an El Niño. The possibility that a major hurricane could hit California is very small, especially during the period that El Niño is expected to produce its strongest impacts (California's winter).

5. Why is the idea of a California hurricane so implausible?

The ocean temperatures off California – including during a strong El Niño – are so cold that they would grind down a hurricane to nothing more than a strong, rainy windstorm. Historical statistics indicate that a major California hurricane is no more likely in an El Niño year than in a normal year. Such an event has never occurred since hurricane records began, so we can only guess that such a thing might happen once in a millennium or so.

6. **OK, but amid all this talk of California hurricanes, we also heard TV forecasters saying that El Niño had knocked down the chance of hurricanes. This confused me!**

   You have to keep your oceans straight. In the Pacific, El Niño has little discernible effect on hurricanes close to the continent. Atlantic hurricanes are an entirely different matter. There, you see, El Niño almost always *reduces* the frequency of storm maturation from what it would otherwise be, just as the TV weathercasters say. This is because El Niño produces increased *wind shear* ("scissors effect") over the tropical North Atlantic in the region where storms born off northwest Africa try to mature into hurricanes. This shear, or wind difference between the high and low levels of the atmosphere, tears many of the developing storms apart before they can become serious threats.

E. TORNADOES IN THE U.S. AND EL NIÑO?

What impacts do El Niño and La Niña have on tornado activity across the country?

Since a strong jet stream is an important ingredient for severe weather, the position of the jet stream 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. During El Niño the jet stream is oriented from west to east over the northern Gulf of Mexico and northern Florida. Thus this region is most susceptible to severe weather. During La Niña the jet stream extends from the central Rockies east- northeastward to the eastern Great Lakes. Thus severe weather is likely to be further north and west during La Niña than El Niño.

F. EL NIÑO AND THE OCEANS

1. **Why do the east-west differences in sea level height initially exist and what happens to reduce them?**

   Because the upper layer of warm water is so much warmer and thicker in the west, the density of a column of water there is less than in the east, where the water is colder and denser. The volume in the west must therefore be greater and the column height is higher. Under strong trade winds, characteristic ocean circulations exist that maintain these density and volume differences. As the winds fail the ocean circulations change so as to distribute the upper layer water more evenly across the Pacific. The upper layer in the west becomes thinner and in the east it becomes warmer and thicker. With the volumes and densities being more equal the sea level difference is lessened or eliminated.

2. **Does this mean that the warm water initially found off New Guinea in the western Pacific winds up off the coasts of Peru and Ecuador?**

   No. The process of adjustment is wavelike — more like a slosh in a bathtub or a lava lamp. Parcels of water do not have to travel great distances in order to reduce the upper layer thickness in the western Pacific or to expand the layer in the east. Drifting buoys released by research vessels show that eastward setting currents on the equator do move parcels toward South America but only over a fraction of the basin width. If this seems strange, consider the familiar experience of a person swimming just beyond the surf at a beach. As a swell overtakes the swimmer, a surge of water carries the person only a short distance toward the beach, yet the deformation of the water column and sea surface (the wave crest) travels a comparatively immense distance.

3. **Then how does the water off South America become so warm if not by importing warm water all the way from the western Pacific warm pool?**

   The eastern Pacific warms because El Niño suspends the local process normally responsible for its extraordinary coolness. Because the upper layer in the eastern Pacific is normally so thin, the colder water of the deep ocean is much closer to the surface. The processes of mixing and upwelling due to wind action then bring this available colder water to the surface, producing an impressive 10°C (20°F) cooling compared to elsewhere in the tropics. When El Niño causes the upper layer (in the east) to thicken considerably, the underlying cool water is depressed to greater depths and becomes unavailable to the upwelling and mixing, which are comparatively shallow processes. The normal cooling fails to occur and we are left with a warm anomaly.

4. **What are the principal changes that take place in the equatorial Pacific Ocean when El Niño occurs?**

   Before El Niño occurs the Pacific trade winds blow steadily from east to west across the Pacific. To maintain its balance the ocean must "lean into" the wind by being higher in the west than in the east (like a person leaning windward in a gale), thus creating a "pressure gradient force" toward the east in opposition to the westward wind stress. Under these normal conditions the height of the ocean surface in the western equatorial Pacific is greater than in the eastern Pacific by a few tens of centimeters. The near surface temperature in the west is about 10°C (20°F) greater than in the east and the thickness of the upper warm layer of the ocean is about 120 meters in the west as opposed to only 30-40 meters in the east.

At the onset of El Niño conditions the trade winds slacken across much of the basin. The eastward tilt of the sea surface is then unbalanced and a series of ocean responses occur over a half-year period that lead to a more nearly flattened sea surface with less east-west contrast in temperatures and upper layer depths. The most noticeable change to an observer is the remarkable increase in the equatorial sea surface temperatures over the eastern half of the basin, which is normally much cooler.

5. What effect would a well-placed tsunami have on El Niño?

It would have no effect. The time and space scales are completely different. El Niño represents the large-scale, but slow, redistribution of heat across the tropical Pacific. A tsunami is a short-lived pulse in which the entire thickness of the ocean shifts position a small distance. The actual horizontal motion of each water particle in a tsunami is very small, probably less than 30 meters in the open ocean (it can become much greater when the wave runs up on the continental shelf, of course, but that does not affect the open-ocean temperatures). El Niño, on the other hand, involves the transport of water masses over thousands of kilometers, but over a period of months.

For a possible analogy, consider a bathtub filled with cool water. If you turn on the hot water tap, the heat spreads around the bathtub over a period of a few minutes (assuming it goes in gently and you don't stir it). That's like El Niño. But if you drop a pebble into the tub, the wave it generates crosses the tub in a couple of seconds. That would be like the tsunami. That wave would have little influence on the mixing of heat, though. Nor would any differences in temperature have much influence on the wave propagation. The two processes should be considered independent.

6. Is there an El Niño in the Atlantic Ocean?

There are two kinds of El Niño phenomena in the Atlantic. One is a spin-off from the Pacific El Niño, due to transmission through atmospheric fluctuations. This atmospheric signal from the Pacific El Niño is the same phenomenon that causes the Atlantic to experience fewer hurricanes during El Niño years. The result of that "teleconnection" is that the tropical Atlantic usually experiences a smaller but anomalous warming several seasons after the maximum warming in the Pacific (which usually occurs in December).

The other "Atlantic El Niño" effect is a non-synchronous and aperiodic warming that occurs along the equator, entirely due to internal Atlantic dynamics. It is only "El Niño-like" in the sense that those dynamics are similar to the Pacific case, but it has no correlation with Pacific events. Moreover, the magnitude of the warming is much smaller, as is the typical period between events. Hence, it is not of much consequence and should probably not be called "El Niño", as this would create unnecessary confusion.

7. **My mom is going to Antarctica in January 1998. Will El Niño affect the tides and ferocity of the water in Drake Passage?**

As you probably know, Drake Passage has some of the worst weather on the planet. Anyone going there should be prepared for severe conditions at any time of year, even the height of summer. However, one goes to Antarctica to experience the majesty of wild nature, and I'm sure it will be rewarding and beautiful nonetheless.

As far as I know there are no reported effects of El Niño on Drake Passage. That doesn't mean there aren't any, but they haven't made it into the mainstream scientific literature, at least the part that I've read. Despite all the present media hype, it is important to remember that El Niño is not the only game in town. El Niño is only one fluctuation among many, and all these things are overlaid and interacting. That's one of the main reasons why we can't produce reliable forecasts for all regions. In some places, such as the U.S. Gulf Coast, the correlation of cool, rainy winters with El Niño is well established, and we can give a forecast with some confidence. In others, such as the U.S. northeast, the correlations are weak and may be coincidental. Perhaps some of the year-to-year variations we see in such regions are due to El Niño, but perhaps not. There have only been 10 or so El Niños since the 1950s, so we really have a weak basis on which to compute statistics, unless the signal is very clear.

The tides are controlled by the sun-moon-earth geometry. El Niño has little effect on this and so has little or no effect on the tides anywhere. (Of course, El Niño *does* affect sea level, by perhaps 20-30 cm, as seen in satellite altimetry data, but these changes happen over a period of months and are completely different than the tides). Perhaps surprisingly, during the largest El Niño in 1982-83, it was noted that the anomalous eastward motion of the atmosphere (due to weaker trade winds) actually did cause the earth's rotation to slow measurably, increasing the length of a day by almost 1 millisecond. This occurred because the rotation (more precisely the angular momentum) of the entire mass of the earth/ocean/atmosphere system remains constant, so when the atmosphere "went faster" in the direction of rotation (towards the east), the solid earth slowed down! This presumably had a tiny effect on the tides.

I have seen nothing to indicate that El Niño might pose an extra danger to travellers in Drake Passage, who presumably are going on well-maintained ships with well-trained crews prepared for weather. Your Mom should enjoy her trip. I always wanted to go there myself and would not let El Niño change my plans.

F. SEA FAUNA AND EL NIÑO?

1. What is the relationship between coral bleaching and El Niño / La Niña ?

Coral bleaching results when sea temperature rises above a threshold (about 28 degrees C) beyond which corals expel colorful symbiotic algae (hence the bleaching). Deprived of metabolic by-products generated by algae for extended periods, corals die. Coral bleaching was particularly pronounced during 1997-98 because a very strong El Niño occurred that year, and the El Niño related rises in sea temperature were superimposed on a slow upward sea temperature warming trend in some parts of the Pacific and Indian Oceans that may be linked to global warming.

2. How does El Niño affect sea life and birds?

El Niño cuts off the upwelling of cold water from lower-levels of the ocean off the Pacific Coast of South America. This upwelling, colder water brings many of the nutrients that keep the food chain going. When this happens, the fish either die or migrate north or south into areas where they'll find more to eat. With the fish gone, the sea birds that depend on them either die or go elsewhere. While the effects are most striking off the South American Coast, other areas are also affected.

3. **What are the known effects of El Niño on marine life?**

   El Niño affects marine life mainly through the drastic changes that occur in the Pacific ocean, especially along the equator and the Pacific coasts of North and South America. The two principal factors are (1) the intense warming in regions of normally cool, upwelled water, and (2) the reduction in the supply of high, subsurface nutrients that normally upwell in the same regions. During El Niño, changes occur in the distribution and abundance of many species. During milder El Niño events, the cold-loving Peruvian anchovy becomes scarce off Peru and more prevalent in the cooler Chilean waters to the south. In some instances the anchovy has been replaced by population increases of pelagic species that do better in warmer water, such as sardine and Spanish mackerel. Not only does the anchovy not like the warmer water, but the associated decrease in nutrients has a negative impact on the abundance of its principal food source, the microscopic algae (phytoplankton) that are normally so plentiful along the productive Peruvian coast. During strong events many other species are also affected and changes in species distribution can be seen as far away as the Gulf of Alaska.

4. **So, what happens to marine fauna during the stronger events?**

   In general, species that like warmer water become more prevalent in the cool-water regions off the coasts of North and South America. Both coasts frequently see increases in certain near-shore benthic (bottom) fauna, such as shrimp and scallops, which reproduce and survive better in the warm water (they are not great migrators). Migrating species of offshore pelagic (mid-water) fish, such as dolphinfish (also known as dorado, or mahi-mahi) typically invade the normally cool coastal waters in greater numbers; other tropical species, including popular sportfish like yellowtail, may be found far poleward of their normal distribution (much to the liking of deep sea fishermen in California). Cold-water fish such as salmon may be found closer to the poles, migrating from Oregon-Washington to the Gulf of Alaska. The marine ecosystems of both continents, from the microscopic phyto- and zooplankton to the largest predator fish, may be altered for up to a year during a strong event such as the one in 1997/98.

5. **What happens to species that can't migrate, such as corals?**

   Corals have a hard time during the more intense events. In 1982/83 (a very strong event) many of the coral species of the Galapagos Islands were killed in large numbers. Fifteen years later in 1997/98 many of the previous survivors perished as well. Many coral species depend on a symbiotic relationship they have with algae-like species (called zooxanthellae) that live in the gastrodermal tissues of the corals and increase the availability of food. When the water warms too much, the zooxanthellae disappear; the white color of the coral skeleton ceases to be obscured by the darker zooxanthellae and the corals are said to "bleach". If the waters remain warm for too long, the prolonged bleaching stresses the coral metabolism to the breaking point and they die. The good news is that corals are capable of re-establishing themselves in decimated areas, possibly after several years, by means of immigrating larvae from distant surviving populations.

6. **Does El Niño create dangerous conditions for marine life, and will it have a lasting effect on marine animals?**

   It should be remembered that El Niño is part of the normal rhythm of our earth, and of the environment that marine life has evolved to face. A plant or creature will not last long in a place in which it can only handle the easy conditions. In the natural variability, some winters are colder than others, some years drier, etc. El Niño is part of this normal climate, along with other influences that are less known. Living things may have varied success in these natural fluctuations, but "That's life". So El Niño may cause a temporary die-back of some forms of marine life in some regions, or reduce the survival rate of young, but it probably does not have a lasting effect. For example, El Niño devastates the population of seabirds off Peru by reducing the fish stock on which they live. But those birds will bounce back soon after El Niño is gone. If, however, El Niños became more frequent, then one might find the overall composition of marine life changing in that region. But the individual events themselves probably do not cause a permanent change.

   Since normal variations can have large swings, such as occur during El Niño, the boundaries of where particular forms of life can survive are somewhat smaller than they would be if the climate were more constant. For example, palm trees can survive in Seattle during most years, since we have generally mild winters. But ,every 10 years or so we'll have a killing frost, so natural palms do not occur here. But many people grow them in gardens and find that they thrive with only occasional extra protections.

H. THE INLAND WATER CYCLE AND EL NIÑO?

1. **How does El Niño affect seasonal rain patterns?**

Complaints often come from people when a severe El Niño winter extends into spring. In 1998, for instance, starting at the beginning of February, a seemingly endless series of storms, one after another, assaulted the California coast with flooding, erosion and misery. Some were stronger than others but all were significant in comparison with those of a normal winter. Instead of tracking across the Pacific south of the Aleutians and into the Gulf of Alaska, they crossed Hawaii straight into California, picking up moisture and energy from the heat-laden tropical Pacific (El Niño). From there they continued across the desert southwest, dropping rain and snow from Arizona to Texas, where they picked up new moisture from the nearby Caribbean and Gulf of Mexico, finally continuing eastward to drench the southeastern states, frequently spawning tornadoes as they passed. During the 1982-83 event, a series of 13 storms followed a similar pattern starting at the beginning of January and did not let up until early April.

2. How is the Snowpack in the Pacific Northwest (PNW) affected?

With El Niño conditions, precipitation and temperature effects combine to accentuate the effect on snowfall. In the Southwest, there is a slight tendency toward cooler winters, and a strong tendency toward wet winters, which makes higher elevation snowpacks deeper. In the PNW, El Niño winters are warmer and drier than usual, so that at a given elevation 1) less precipitation occurs, and 2) the freezing level is higher, so the type of precipitation is more likely to be rain, and 3) the accumulation season is shorter. All three conspire to produce a smaller snowpack accumulation by the end of winter in the Pacific Northwest.

a. How is streamflow affected?

Most streamflow in the West is produced by melting snow in the spring (in general, about 75 percent). At lower elevations rain can be an important component of streamflow. El Niño effects on streamflow are magnified versions of the effects on the climate elements. Because of hydrologic lags (snow does not usually begin to melt until spring), the effects of El Niño are typically delayed, in some cases for several months. Thus, the effects of El Niño on streamflow may not be manifest until late spring or summer. Usually, El Niño results in less streamflow to the Pacific Northwest and greater streamflow in the Southwest.

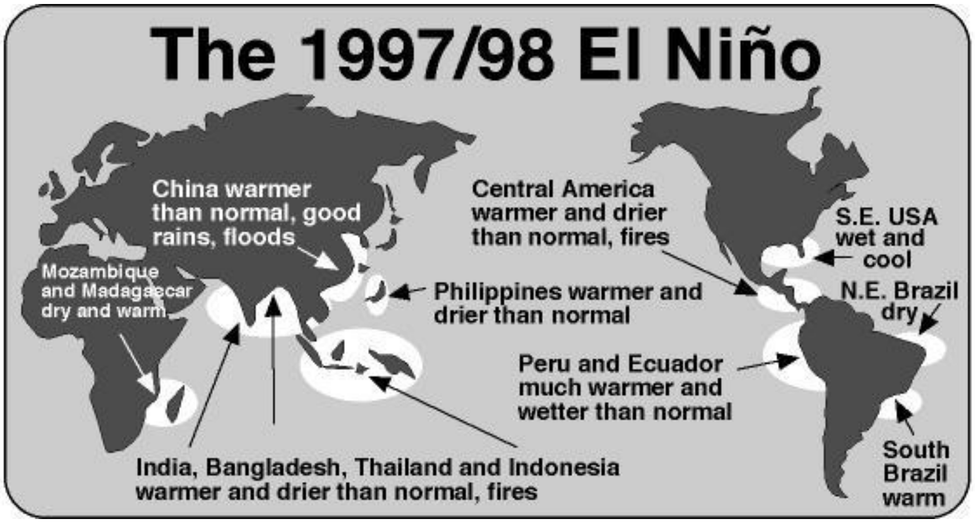
b. Is flood likelihood changed?

In southern California, Arizona, southern Nevada, New Mexico and southern Utah, almost all of the major flood episodes on mainstem rivers have occurred during El Niño winters. None have occurred during La Niña winters. The likelihood of flooding is considerably increased, but flooding is not a guaranteed outcome.

3. Why is there flooding in Peru and drought in Australia during El Niño?

Normally the Pacific's warmest water is found on the western side of the ocean, where it helps create thunderstorms. During an El Niño, this warm water shifts eastward. As the water moves east, the thunderstorms, which help supply rain to Australia, die down in that part of the Pacific. Meanwhile, the warmer water helps feed rain that falls on Peru and other areas on the east side of the Pacific.

H. ECONOMIC IMPACTS OF EL NIÑO



1. What are the economic implications of an EL NIÑO?

NOAA has the primary responsibility within the federal government to routinely provide climate forecasts and products to the nation. Most parts of NOAA are in some way involved in El Niño research, monitoring and prediction. For example, NOAA monitors the developing (and, in time, decreasing pool of) warm waters in the tropical Pacific with state-of-the-art satellites; launches new research initiatives; improves future climate forecasts; monitors the impact of the climate event on the fish population in U.S. coastal waters; operates research ships to study the world's vast oceans; and provides critical ocean data to users.

NOAA's El Niño forecasts have become much more reliable in recent years. The new Operational Climate Forecast System (which is composed of a state-of-the-art ocean analysis system that uses relevant satellite observations, all available oceanic observations, and coupled ocean/atmosphere prediction models) provides NOAA and the nation a longer lead-time for developing strategies to deal with expected impacts—including economic impacts. For example, NOAA successfully predicted the major El Niño of 1997-1998—six months in advance—and is now forecasting an El Niño for 2002-2003.

NOAA's definition of El Niño includes persistent enhanced precipitation along the equator near the international dateline and warmer-than-normal sea-surface temperatures (exceeding +0.5° C) extending from the international date line to the South American coast. El Niño episodes occur roughly every four-to-five years and can last up to 12-to-18 months. It has been nearly four years since the end of the 1997-1998 El Niño, which was followed by three years of La Niña. El Niño means little boy in Spanish. The effect was named by Peruvian fishermen who would notice its impact on their catch around Christmastime and, as a result, named the phenomenon after the infant Jesus.

2. What are the implications of El Niño for the Nation's Economy?

Weather and climate sensitive industries **directly** impacted by weather (such as agriculture, construction, energy distribution, and outdoor recreation) account for nearly 10 percent of GDP. Further, weather and climate **indirectly** impacts an even larger portion of the nation's economy, extending to parts of finance and insurance, services, retail and wholesale trade, as well as manufacturing. Some analysts estimate that nearly 25 percent of GDP, or $2.7 trillion, is either **directly or indirectly** impacted by weather and climate.

El Niño impacts important business variables like sales, revenues and employment in a wide range of climate-sensitive industries and sectors. Overall, total **U.S. economic impacts** of the 1997-1998 El Niño were estimated to be on the order of $25 billion.

- These economic impacts lead to both gains and losses among regions and within industries. For example, department store sales were up by 5 to 15 percent during the abnormally warm winter in the Midwest, but sales of snow equipment like snowmobiles were down by nearly 35 percent. Skiing was up in the West but down in the Midwest. In the highly weather-sensitive energy sector, households and businesses saved $2-7 billion in heating costs, while energy production and distribution businesses suffered from reduced sales.

- In fact, on balance, the effect of the 1997-98 El Niño in the U.S. could well have been an overall economic benefit, despite their having been both gains and losses across different regions and industries.

While economic impacts tend to cancel each other out at the national level, **El Niño does cause real economic losses** such as storm damage or crop losses, which are not offset by gains elsewhere. These are losses that can't be prevented or reduced by a better forecast or mitigation. For example, on average, El Niños result in agricultural losses approaching $2 billion, or nearly 1-2 percent of total crop output. In the 1997-98 El Niño, property losses were estimated at nearly $2.6 billion. Fortunately, these real losses are generally a small fraction of the economic impacts of El Niño.

3. What are the Economic Benefits of Better El Niño Forecasts Improving Economic Decisions?

Although all losses cannot be avoided, NOAA's El Niño forecasts produce economic value by allowing individuals, industries and public officials to take timely actions based on the forecast to mitigate and reduce losses or to capitalize on the information to improve economic outcomes. For example:

- **In California,** prior to the 1997-1998 El Niño, this state's emergency management agencies and FEMA spent an estimated $165 million preparing for storms and heavy rain. Actual storm losses in the 1997-1998 El Niño were $1.1 billion, compared to $2.2 billion in the large 1982-1983 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.
- **Within agriculture,** crop planting decisions, seed selection, fertilizer application, etc. can be adjusted to reduce vulnerability to abnormal weather conditions, making both producers and consumers better off. It also may be possible to adjust storage of crop inventories in anticipation of changed yields due to El Niño.
- **In water management,** for hydroelectric power production and competing water uses, storage and release decisions can be altered from normal use patterns in anticipation of above normal rains in the coming winter-spring seasons. For instance, winter stream flows in El Niño years into the Tennessee Valley Authorities' large reservoirs can be as much as 30 percent above normal, allowing efficiency gains by switching from thermal and hydro power.
- **In natural gas and heating oil production and distribution,** normal patterns of crude oil refining, inventories and distribution may be

adjusted to reduce losses to producers and sellers when warmer winter weather conditions are anticipated.
- **In some fisheries,** management practices can be changed to partially offset the negative effects of El Niño on recruitment.
- **Property owners** can accelerate plans to repair or improve structures to make them less vulnerable to winter storms. In California, an estimated $125 million was spent on home and business improvements and repairs to mitigate the anticipated effects of El Niño storms.

4. How do we measure the Economic Benefits of El Niño Forecasts

Economists have quantified the benefits of improved El Niño forecasts in various sectors:

- Benefits to U.S. agriculture by altering planting decisions have been estimated at $265-300 million annually, throughout El Niño, normal and La Niña years. Similarly, benefits to Mexican agriculture range from $10 to $25 million annually.
- Benefits in U.S. corn storage from optimizing inventory storage costs could approach $200 million annually.
- Even in the small Northwest Coho salmon fishery, annual benefits are estimated at $250,000 to $1 million from changing hatchery releases and harvest rates.

Further, better forecasts reduce uncertainty and improve new insurance systems like the $7+ billion weather derivatives market by improving price risk projection.

5. How can I use knowledge of ENSO as an Australian farmer?

For most of Queensland the presence of El Niño conditions have resulted in below average rainfall in winter and spring, and the presence of La Niña conditions in above average rainfall. The presence of either El Niño or La Niña conditions are usually evident by early winter, and usually persist for around 9-12 months. This allows farmers to adjust management for either below or above average rainfall in winter and spring, and usually through summer.

Not all El Niños are associated with drought, but in the last 30 years the droughts that have had the greatest impact were associated with El Niño events.

6. Is it true that El Niño years are good wine years in Europe?

Not convincingly so. There is some statistical evidence that European winters may be slightly more severe during El Niño. However, the consistency of this is fairly low and there are numerous historical exceptions to the pattern. The effects during the summer growing season are even harder to document.

J. CO_2 LEVELS AND EL NIÑO

Why is the annual increase in atmospheric CO2 concentrations smaller during El Niño years than La Niña years?

The equatorial Pacific is the largest oceanic source of CO2 to the atmosphere. Much of the ocean absorbs CO2 from the atmosphere, and this tends to slow down the increase due to fossil fuels. However, the equatorial Pacific is the site of extensive upwelling of waters from the lower layers in the east Pacific cold tongue. The upwelled water is nutrient rich, and also CO2 rich. This is because organic matter sinks below the surface throughout the ocean, decomposes and releases its nutrients and carbon into the water. In locations where there is upwelling, this water comes into contact with the atmosphere again and some of its CO2 can be released.

During El Niño, the upper layer becomes very thick. While there may still be some upwelling, it no longer can reach down to the lower levels where the nutrients and CO2 are. Thus, we see extensive die-offs of plankton, fish that feed on the plankton, and birds and mammals that feed on the fish. The CO2-rich waters are covered up, and as a result the CO2 release to the atmosphere is reduced during El Niño periods. During La Niñas, the lower layers come even closer to the surface than usual, and the CO2 release is enhanced.

K. 1997-1998 EL NIÑO

1. Was the strong 1998-1999 La Niña related to severe winter weather in the northern hemisphere?

The 1998-1999 La Niña made itself felt in the US. The seasonal forecast for wintertime conditions, based in large part on the evolving temperatures in the tropical Pacific, captured many of the large scale patterns of temperature and precipitation of the continental US. In the Pacific Northwest, for example, the three month period November 1998 - January 1999 was the wettest on record. Also, this winter was warmer and drier over large portions of the southern US, from California to Florida. One forecast "miss" was that the upper mid-west was predicted to be colder than normal that winter, but was a little warmer than normal, at least initially.

2. Why was El Niño such a big deal in 1998?

It is an interesting question to ask why El Niño suddenly became headline news in 1998. The scientific community has known about El Niño and its impacts on global weather, Pacific marine ecosystems and fisheries for about 35 years. The regional impacts of El Niño along the coast of South America have been known for hundreds of years by the people living in that area. There are three factors though that made reporting of the 1997-98 El Niño different from other recent El Niño events.

The 1997-98 El Niño was the strongest on record, and it developed more rapidly than any El Niño of the past 40 years. As a result, we started to see its impacts on weather, marine ecosystems and fisheries very quickly, and these impacts were spectacular. Early effects in August-October 1997 included record flooding in Chile, Marlin caught off the coast of Washington, the extensive smog cloud over Indonesia and a quiet Atlantic hurricane season. The press is geared towards reporting sensational stories, and this El Niño provided high drama through natural disasters and other unusual events.

In the fifteen years preceding the 1998 event, scientists had developed new observational tools that enabled them to track the development of the 1998 El Niño in greater detail than ever before. The new observations, from satellites and from sensors in the ocean itself, provided a day by day account of events as they unfolded in the tropical Pacific. These technological advances, providing high definition information on the tropical ocean and atmosphere system like never before, fueled a lot of interest in the press about El Niño, how we track it and how it affects people's lives.

Another technological advance before the 1998 event was the development of long-range forecasting capabilities for predicting the evolution of El Niño sea surface temperatures, and the consequences of those temperatures on global weather. The effects of El Niño on North American climate are most pronounced in the winter season. Because the El Niño developed so rapidly, with record high sea surface temperatures in the equatorial Pacific by July 1997, forecasters could predict a full six months in advance with some reliability that the winter over the US would be very unusual. The credibility of these forecasts was high because of the clearly identifiable impacts of El Niño earlier in the year. The anticipation of an unusual winter motivated a lot of disaster preparedness efforts by local and state governments, by the federal government, by businesses and by individuals. This mobilization of people and resources based on a climate forecast was unprecedented, and therefore caught the attention of the press. Once winter arrived, the predicted unusual weather set in, and that was also newsworthy. It turns out that the forecasts for heavy rains over the southern part of the US for the winter of 1997-98 and for an unusually mild winter in the Midwest proved to be largely correct. Record rains occurred in particular in California and Florida, two of the most populous states in the nation.

3. Both 1998 and 1997 had record-setting global mean temperatures and also El Niño. What influences what?

El Niño clearly influences globally averaged temperatures which go up a few tenths of a degree C a few months following the peak warming in the tropical Pacific. This is because the tropical Pacific loses large amounts of heat to the overlying atmosphere during El Niño. So some of the extreme warming observed in global temperatures in 1997-98 can be traced back to the occurrence of El Niño in the tropical Pacific. However, underlying the El Niño effect, which diminished in the next year, is a long-term global trend towards warmer temperatures. Two questions arise, for which we do not have answers at this point: 1) Exactly how much of the extreme rise in global temperatures during 1997-98 was due to the 1997-98 El Niño, versus the contribution from the underlying long-term trend? and 2) Did the extreme El Niño occur in response to global warming trends? This second question ties into your first question above. In fact, how global warming projects onto natural modes of climate variability like El Niño, the Pacific Decadal Oscillation and the North Atlantic Oscillation (all of which can have an affect on global air temperatures) is a very compelling research problem.

XVI. CLIMATE & WEATHER

A. DEFINITIONS

1. What is the distinction between climate and weather, and how does it help us to understand the effects of El Niño?

> "Climate is what we EXPECT,
> weather is what we GET."
> -Robert A. Heinlein

To understand the twin concepts of climate and weather and why they should be affected by El Niño, think of the atmosphere as a huge pot of fluid (our atmosphere is a mixture of gaseous fluids, after all) on a stove with heating elements (hot spots of warm tropical ocean temperatures) located under certain portions of the pot. This creates a characteristic circulation (climate) in the pot, with warm fluid rising over the hot spots and moving away toward the cooler regions where it sinks (the Earth's higher latitudes). The circulation has embedded turbulence, or eddies (weather), that are inherently less predictable than the average circulation itself, but nevertheless conform to a statistically expected behavior (again, climate). As thermal anomalies develop in ocean temperatures during El Niño, displacing cold water in certain regions, the distribution and intensity of the hot spots under the pot are changed; naturally, so too does the circulation pattern in the pot change, along with the statistical expectations for the turbulence (i.e. the weather). Although we cannot predict the precise nature of the altered weather far in advance, we do know more or less how different it will be on average.

2. What is climate variability?

A prominent aspect of our weather and climate is its variability. This variability ranges over many time and space scales such as localized thunderstorms and tornadoes, to larger-scale storms, to droughts, to multi-year, multi-decade and even multi-century time scales.

Some examples of this longer time-scale variability might include a series of abnormally mild or exceptionally severe winters, and even a mild winter followed by a severe winter. Such year-to-year variations in the weather patterns are often associated with changes in the wind, air pressure, storm tracks and jet streams that encompass areas far larger than that of your particular region. At times, the year-to-year changes in weather patterns are linked to specific weather, temperature and rainfall patterns occurring throughout the world due to the naturally occurring phenomena known as El Niño and La Niña.

B. WEATHER PATTERNS

1. **Are weather patterns variable from one El Niño to the next, & why?**

   They do indeed vary to some extent. Here's the accurate, if somewhat technical explanation from NOAA/Climate Prediction Center:

   > "In response to the more uniform pattern of heating in the tropics during an El Niño the winter time jet streams in each hemisphere tend to be more uniform from east to west and extend farther east than normal. However, the timing, location and magnitude of the ocean warming varies from one El Niño to the next, which results in variations in the patterns of tropical rainfall and deep tropical heating. These conditions contribute to variations in the precise location, strength and structure of the mid-latitude jet streams over both the North and South Pacific from one El Niño to the next, and thus to the variability in weather patterns and storm tracks over North and South America.
   >
   > "A second major reason for the variability in weather patterns from one El Niño to the next is simply that El Niño is not the only factor influencing the weather and climate. In particular, the atmosphere exhibits considerable variability on time scales ranging from days to seasons to years, and this variability often reflects nothing more than the normal chaotic behavior of the atmosphere. This description is particularly applicable to areas such as eastern North America, the North Atlantic, Europe, etc., which are heavily influenced by features such as the North Atlantic jet stream. "

There will continue to be surprises associated with future El Niño events. Scientists have really only focused on ENSO as a large-scale phenomenon since the mid 1970s. We have not witnessed all the forms these events can take nor have we recognized all the ways they can affect societies and ecosystems.

2. **Do weather patterns change during El Niño?**

   Absolutely, and rather drastically in the case of the stronger events, such as 1997-98 "El Nino of the Century.". If all that occurred during an El Niño were a warming of the equatorial ocean where nobody lives, El Niño would not occupy the public awareness as it now does.

3. **Are regional temperature changes due to human activities?**

   Global average temperature increases in recent decades are primarily due to increasing greenhouse gas concentrations in the atmosphere resulting from human activities, such as the burning of fossil fuels. Yet the magnitude of the anthropogenic influence on regional climate remains uncertain. A principal reason is because the effects of human activities are superimposed on the background "noise" of natural climate variability, which can be very large regionally.

   Global warming does not mean that temperature increases are spatially uniform or monotonic: some places warm more than the average and some places cool. Regional changes in temperature are often associated with changes natural patterns (or modes) of the atmospheric and oceanic circulation, such as the El Niño/Southern Oscillation (ENSO) phenomenon. Changes in the climate system from human activities may affect these modes, however, so quantifying the anthropogenic and natural components of the observed warming on regional scales remains a difficult and critical research question.

   Many global climate models, for instance, project changes in the statistics of ENSO variability with global warming, specifically of greater ENSO activity marked by larger inter-annual variations relative to the warmer mean state. More El Niño events would increase the probability of weather regimes that favor, for instance, regional cooling over the North Pacific Ocean with warming over much of northwest North America. Yet the details of ENSO are not well enough simulated in climate models to have full confidence in these projected changes, in part because the positive atmosphere-ocean feedbacks involved with ENSO mean that small errors in simulating the relevant processes can be amplified.

   Thus, while it is likely that changes in ENSO and other natural modes of climate variability will occur as a result of anthropogenic climate change, their nature, their size and velocity, and their implications for regional climate change around the world remain uncertain.

C. EFFECTS

1. How does El Niño affect climate in the West?

Winter versus summer

The most unambiguous signal is seen in the winter half-year, typically from October through March or April. A weaker signal may be seen in some parts of the West in summer or early autumn. Most of this discussion concentrates on winter.

Tropical storms

Eastern Pacific autumn tropical storms, west of Mexico, appear to be less frequent in El Niño years, a tendency which is well established in the Atlantic. However, those tropical storms that do occur have a greater than usual tendency to re-curve into Mexico or the southwest U.S. Higher than usual water temperatures off the Mexican coast in El Niño years can help maintain their strength, or cause them to be stronger than they would otherwise be. Hurricanes need water temperatures of about 27°C (81°F) or more to sustain themselves.

Winter circulation

During El Niño years, the storm track more frequently splits into two preferred branches. The Aleutian Low, in the Gulf of Alaska, is deeper than usual, and one branch of the jet stream departing from its vicinity heads toward the Queen Charlotte Islands and the southern coast of the main part of Alaska, bringing mildly increased storminess to those areas. A second branch of the jet stream is seen across the southern tier of the U.S. and northern Mexico, and with higher speeds than usual. Storms approaching the Pacific Northwest and southwest Canada are often split and weakened as they approach the shore, as their energy is shunted toward the north and/or the south.

Winter precipitation

With El Niño, the period October through March tends to be wetter than usual in a swath extending from southern California eastward across Arizona, southern Nevada, Utah, New Mexico, and Texas. There are more rainy days, and there is more rain per rainy day. El Niño winters can be two to three times wetter than La Niña winters in this region.

In the Pacific Northwest, El Niño tends to bring drier winters. The area affected in this manner includes Washington, Oregon, and the more mountainous portions of Idaho, western Montana and northwest Wyoming. This area of influence extends well up into Canada, and coincides very well with the Columbia River Basin on both sides of the U.S./Canada border.

In between these regions, including central and northern California, northern Nevada, southern Oregon, northern Utah, southern Wyoming, and much of Colorado, the effects of El Niño are ambiguous. No strong association in either direction (toward wet or dry) can be discerned.

Farther north, from the Queen Charlotte Islands to Kodiak Island, the relationship again switches, and southern Alaska tends to have wetter winters with El Niño.

In Hawaii, El Niño tends to bring dry winters. Drought is more likely during El Niño years, especially during the October-March period. This association is well-known in the Hawaiian Islands.

In general, in all of these regions, La Niña climate effects are approximately but not exactly opposite to El Niño effects.

Winter Temperature

Winter temperatures with El Niño conditions tend to be warmer than usual from Washington and northern Oregon across the northern tier to Montana, and also along the West Coast. Conversely, cooler than normal temperatures are seen in the far southeastern portion of the West, especially in southeastern New Mexico.

2. **There is a lot of confusion in the public about the interrelations connecting climate phenomena such as El Niño, La Niña and greenhouse effect. Is it true that a warmer atmosphere is likely to produce stronger or more frequent El Niños?**

We don't know the answer to this question. It is certainly a plausible hypothesis that global warming may affect El Niño, since both phenomena involve large changes in the earth's heat balance. However, computer climate models, one of the primary research tools for studies of global warming, are hampered by inadequate representation of many key physical processes (such as the effects of clouds on climate and the role of the ocean). Also, no computer model yet can reliably simulate BOTH El Niño AND greenhouse gas warming together. So, depending on which model you choose to believe, you can get different answers. For example, some scientists have speculated that a warmer atmosphere is likely to produce stronger or more frequent El Niños, based on trends observed over the past 25 years. However, some computer models indicate El Niños may actually be weaker in a warmer climate. This is a very complicated (but very important!) issue that will require further research to arrive at a convincing answer.

3. What are the impacts of El Niño on weather and climate?

El Niño events can have important effects on U.S. and global weather and climate. The first signs of an El Niño are an unusual warming of the water in the tropical Pacific Ocean. In turn, this warming results in increases in rising warm air, changes in the air pressure patterns and shifts in the high-level winds that direct the movement of weather. Therefore, when the 2002-2003 El Niño developed, as expected the first impacts were confined to the tropical Pacific, where Indonesia began to experience drier-than-normal conditions. Mature El Niño conditions develop over a period of several months. Typical impacts on the United States and the Atlantic basin include the following:

- **Hurricanes:** Below normal development of tropical storms/hurricanes in the Atlantic, although this does not imply any limits on the strength or location of any given tropical system.
- **Monsoons:** A drier-than-normal North American Monsoon, especially for Mexico, Arizona and New Mexico.
- **Drought:** A drier-than-normal fall and winter in the U.S. Pacific Northwest.
- **Wintertime Storms:** A wetter-than-normal winter in the Gulf Coast states from Louisiana to Florida, and in central and southern California if El Niño is strong.

Warmer Temperatures: A warmer than normal late fall and winter in the northern Great Plains and upper Midwest.

4. What are the effects of El Niño on climate?

The link between these climatic effects in distant parts of the globe and El Niño is now well-established. Yet it has taken some time for scientists to understand how the various pieces of the puzzle—from ocean currents to winds and heavy rains—fit together. Decades ago, the British scientist Sir Gilbert Walker provided the first clue.

During the 1920s, while scientists in South America were busy documenting the local effects of El Niño, Walker was on assignment in India, trying to find a way to predict the Asian monsoon. As he sorted through world weather records, he discovered a remarkable connection between barometer readings at stations on the eastern and western sides of the Pacific. He noticed that when pressure rises in the east, it usually falls in the west, and vice versa. Walker coined the term Southern Oscillation to dramatize the ups and downs in this east-west seesaw in Southern Pacific barometers.

When the seesaw is in its "high-index" (i.e. strongly tilted) state, pressure is high on the eastern side of the Pacific and low on the western side. Along the equator, the east-west pressure contrast drives the easterly (east to west) surface winds that extend from the Galapagos Islands nearly all the way to Indonesia. When the seesaw switches into its "low-index" (i.e. weakly tilted) state, the easterly surface winds weaken. The biggest changes in the slope of the seesaw and in the strength of the easterlies occur over the western Pacific. West of the dateline the easterlies usually disappear altogether during low-index years, whereas east of the dateline they usually only weaken.

Walker noticed that monsoon seasons with low-index conditions are often marked by drought in Australia, Indonesia, India and parts of Africa. He also claimed that low-index winters tend to be unusually mild in western Canada. One of his British colleagues chided him in print for suggesting that climatic conditions over such widely separated regions of the globe could be linked. In his reply Walker predicted, correctly, that an explanation would be forthcoming, but that it would require a knowledge of wind patterns above ground level, which were not routinely being observed at that time.

In the following decades, researchers added new pieces to the emerging picture of the Southern Oscillation. One such piece came from a remote part of the world for which Walker had no information: the desert islands of the central equatorial Pacific. According to standard climate statistics, these islands receive as much rainfall as many islands with much more luxuriant vegetation. One might wonder, then, "Why are they so barren?" The answer becomes apparent when one examines the rainfall records year by year. Most years, in fact, the islands receive little or no rainfall. But during "low-index" years, they experience torrential rains, day after day, month after month. Hence, Walker's pressure seesaw is linked to dramatic changes in the distribution of rainfall in the tropics.

In the late 1960s, University of California professor Jacob Bjerknes put another important piece of the puzzle into place. As a young scientist in Norway, Bjerknes had gained fame by publishing the first clearly understandable description of the life cycle of storms in temperate latitudes. Now, fifty years later, he was the first to see a connection between unusually warm sea-surface temperatures and the weak easterlies and heavy rainfall that accompany low-index conditions. Ultimately, Bjerknes' discovery led to the recognition that the warm waters of El Niño and the pressure seesaw of Walker's Southern Oscillation are part and parcel of the same phenomenon, sometimes referred to by the acronym ENSO.

5. **Does our knowledge that an ENSO is occurring enable us to predict when and where things like winter mudslides will occur?**

   No, no more than we can with earthquakes. We can say their likelihood is greater, over a season, and if summer brush fires have occurred in a particular hilly location (making it more susceptible to mudslides), we can put out a danger alert and perhaps take measures to offset that probability of occurrence. Climate prediction is a game of likelihood, a way of rigging the coin toss so that our call comes up better than 50:50. But there are no guarantees.

   Nevertheless, once the event is underway and we have the observation to tell us how strong it is, we can then make some intelligent guesses about how it will develop, and based on past experience we can make some fairly good projections about impacts for the coming season. To whom those projections will prove useful will depend on where they live and what time of year it is.

XVII. PREDICTION AND MONITORING

A. Do you have some words of caution on El Niño forecasts?

It is important to remember that El Niño is not the only effect on weather. It is but one fluctuation among many, and the weather we experience is the sum of all of these overlaid and interacting fluctuations. Most of these interactions are poorly understood, particularly the longer-term ones, and as we get longer and longer records we become aware of more and more complexity. The different El Niños occur on different background states at different times of year, and therefore have different total effects. As such, one cannot simply speak of the isolated effects of El Niño on weather in San Diego. There is only the ever-changing combination of influences. That is the main reason why we cannot produce reliable long-term forecasts.

Scientists study El Niño partly for its own effects, but also partly as an example of how this kind of climate oscillation interacts with the rest of the climate system. We know there are many such oscillations, and we would like to be able to fit the whole picture together. We hope that what we learn about the climate system from studying El Niño will help us understand other, less obvious, variability.

B. GENERAL FORECASTING

1. What is the current El Niño Forecast or Advisory?

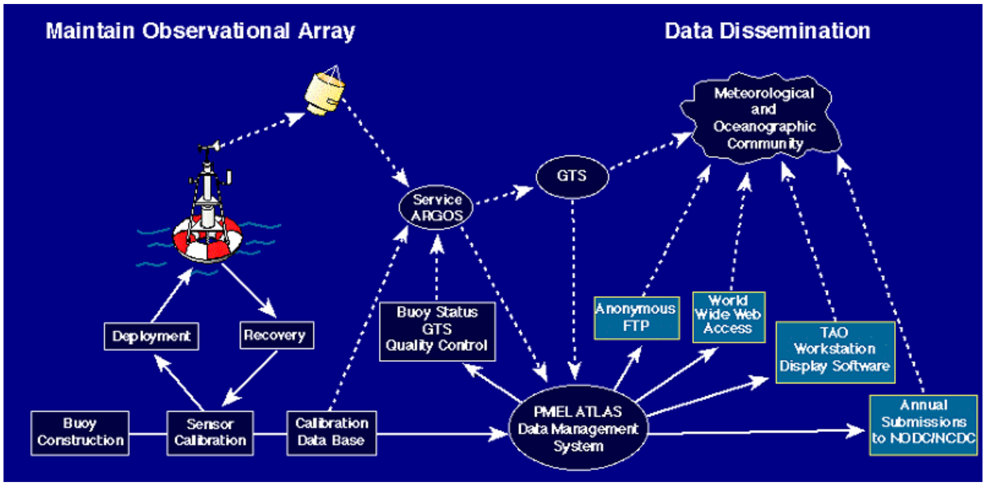
The Climate Prediction Center of the National Center for Environmental Prediction provides an El Niño Advisory, which is updated every month. They also publish a monthly Climate Diagnostics Bulletin. See http://www.pmel.noaa.gov/tao/elNiño/forecasts.html for links to El Niño advisories from several forecasting centers located throughout the world.

Real-time Pacific Ocean data from the NOAA network of moored buoys is updated daily to show the current conditions in the Equatorial Pacific Ocean.

2. If the winter of 2002-03 was an El Niño winter, why was it not as warm as most seasonal forecasts predicted?

There really is no ***typical*** El Niño or La Niña weather, in that events do not behave the same way each time. With the exception of certain locations in the tropics, El Niño and La Niña weather is quite variable, so generalizations can often be misleading. For example, while the upper mid-west of the United States is on average colder than normal during a La Niña winter and warmer than normal during an El Niño winter, the 1998-99 winter season displayed abundant warmth, while the 2002-03 winter season displayed widespread cooling. There are really only a handful of well-documented ENSO events, and a sample size of dozens will be needed to draw any type of decisive conclusions. The intensity, timing, and interaction of the ENSO Event with many other ocean-atmosphere processes ultimately determine the weather.

3. How do scientists detect La Niña and El Niño and predict their evolution?



Scientists from NOAA and other agencies use a variety of tools and techniques to monitor and forecast changes in the Pacific Ocean and the impact of those changes on global weather patterns. In the tropical Pacific Ocean, El Niño is detected by many methods, including satellites, moored buoys, drifting buoys, sea level analysis, and expendable buoys. Many of these ocean observing systems were part of the Tropical Ocean Global Atmosphere (TOGA) program, and are now evolving into an operational El Niño/Southern Oscillation (ENSO) observing system.

NOAA also operates a research ship, the KA'IMIMOANA, which is dedicated to servicing the Tropical Ocean Atmosphere (TAO) buoy network component of the observing system. Large computer models of the global ocean and atmosphere, such as those at the National Centers for Environmental Prediction, use data from the ENSO observing system as input to predict El Niño. Other models are used for El Niño research, such as those at NOAA's Geophysical Fluid Dynamics Laboratory, at the Center for Ocean-Land-Atmosphere Studies and at other research institutions.

4. **Why is predicting these types of events so important?**

Better predictions of the potential for extreme climate episodes like floods and droughts could save the United States billions of dollars in damage costs. Predicting the onset of a warm or cold phase is critical in helping water, energy and transportation managers as well as farmers plan for, avoid or mitigate potential losses. Advances in improved climate predictions also result in significantly enhanced economic opportunities, particularly for the national agriculture, fishing, forestry and energy sectors. They also provide numerous social benefits.

5. **What was the forecast for U.S. weather patterns for the remainder of the big 1998 El Niño year and into 1999?**

NOAA's Climate Prediction Center issues monthly long-lead climate outlooks that extend for 13 months at a time. The forecast issued on July 16, 1998, called for continued above normal temperatures throughout most of the Southwest U.S. and southern Florida in the late summer and fall. Into the fall, warmer than normal temperatures were forecasted for much of the Southwest, including Texas, New Mexico, Arizona and portions of Colorado. These conditions were forecasted to extend across the Southeast during the winter months. Cooler than normal temperatures were expected for the Pacific Northwest in the winter. Temperatures were also expected to be cooler than normal across the Great Lakes and Northeast later in the winter into spring. Drier-than-normal conditions were forecasted to persist in west Texas, New Mexico and Arizona through August and into October.

The late fall and early winter forecasts indicated continued dry conditions throughout much of the southern United States and into portions of the Midwest. Greater than normal precipitation was predicted for the Pacific Northwest throughout the fall and into the winter months and for the Ohio and Tennessee River Valley in the winter. Temperature and precipitation patterns in areas not specifically addressed by the forecast were not predictable at the time of the July forecast.

6. **How can the conflicting El Niño forecasts found on the web for California for the winter of 1997-98 be understood?**

There was a lot of confusion about what El Niño would do that winter. It is true that the media gave it a lot of play, perhaps more than was justified by the uncertainty of the forecasts. Please remember that weather forecasting is not an exact science, particularly when we are forecasting months ahead. However, some things were certain at the time:

* There was a strong El Niño in the tropical Pacific in 1997-98.
* Such events "often" lead to heavy winter rains in southern California.

The hard fact is that we could not know very well what would actually happen in California. We could be more confident about some areas (like the Gulf Coast), where the response to El Niño tends to be pretty robust, but California can go either way so no forecast could be taken too seriously, particularly more than about three months in advance. There definitely was a good possibility of flooding over the winter months in 1997-98; that was more than a roll of the dice, but it was certainly not certainty. What action you should have taken based on the forecasts depended on how you would be affected. It's similar to earthquake preparedness. It makes sense to have your earthquake supplies up to date and handy, but you can't spend your whole life preparing for disaster. One thing could (and can) be said reliably, however: if the 1997-98 El Niño did not produce major flooding in Southern California, such flooding will occur with another El Niño event at some point in the not-too-distant future.

One of the best forecasts is what we call "persistence." That is, when a pattern is established it tends to remain. If the winter begins rainy, then probably it will continue as such. Lots of rain in November tends to provide a good indication that an El Niño has set up the jet stream to direct moisture in California (as opposed to further east), and such a pattern would then be more likely to persist.

One of the hardest things for non-specialists to get good information on is the basis behind the various forecasts. A lot of what you hear is based on statistics of past events. But remember, there haven't been very many El Niños since we started being aware that it was a global phenomenon (not just a bunch of unconnected anomalies). There have been 10 since 1950 and only 6 since 1970. That's not a very good basis for statistics, particularly when we observe that different events evolve in different ways. It would be like measuring five kids in a classroom. Would that give you a good estimate of the average height of the kids? Maybe you'd happen to get the five shortest. So statistical forecasts (noting that El Niño "usually" brings rain to California) are not on a good foundation. How many of those 10 events means "usually"? Then you find that if you just look at the ones since 1970 (observations were extremely spotty before that), then your statistics are probably going to be different. So when you surf websites looking for information, you can easily find statistics telling you different things. It doesn't mean they're wrong, or trying to mislead, it just means that we have a very small sample of a highly variable phenomenon.

Another type of forecast is based on a dynamical model of the ocean-atmosphere system. Such a model uses a computer to solve the equations that govern fluid motion and is initialized with the present conditions and then run forward. It has the advantage of being based on the actual present conditions, not a statistical average, but it has the problem that those conditions are not known with great accuracy. Also, such models are necessarily crude since we can't simulate every molecule. In particular, we can't simulate every cloud, but have a grid structure in which the average cloud amount is estimated at each grid point (say 20-50km apart). That's a tricky business, since some effects of clouds are not well simulated by an average cloud. For example, thunderstorms and tropical convection, in addition to dumping a lot of rain, pump a huge amount of heat and moisture into the upper atmosphere in their rising motion. (That is one of the main ways that El Niño affects North America, since that heat and moisture can be carried great distances on the upper winds). But the dynamics of a thunderstorm cloud are specific, and can't be well resolved with a coarse grid point model. Scientists spend a lot of effort trying to make these things approximately right, but the wide spacing between grid points is an inherent flaw. (The way we work on these things is to make fine-grid models of single storms, then try to extrapolate those properties to the global models). That is the weakness of the dynamical forecasts. As computers get faster these will improve.

A final thing to remember is that El Niño is not the entire story. Many other oscillations are going on at the same time, so whatever the effects of El Niño, we see them all jumbled up with many other signals. Since we really have only a relatively few years of decent observations, picking these signals apart is a matter of guesswork.

7. What are the implications of our observations of the 1997-1998 El Niño on prediction? Is ENSO more difficult to predict than we had thought?

The scientific community has made tremendous advances in forecasting El Niño in the past decades. For example, we had NO forecasting capability at all prior to the 1982-83 El Niño. Many computer models correctly forecast that 1997 would be unusually warm in the tropical Pacific. That is a major advance by any measure, because just knowing that the tropical Pacific will be warm (or cold) a season or two in advance provides great leverage in making more reliable long-range weather forecasts around the globe. (This is a VERY OPTIMISTIC message). On the other hand, the forecast models missed the rapid onset, the great magnitude and the sudden demise of the 1997-98 El Niño, possibly due to weather noise that is inherently unpredictable more than about 2 weeks in advance. What that means is that there may be some inherent limits to how accurately we can hope to predict El Niño (admittedly a somewhat pessimistic message). However, the 1997-98 El Niño served as a stimulus for improving forecast models because forecast skill is not only limited by climate noise, but also by imperfect model physics and incomplete and imperfect data for initializing forecasts. These are areas where we can certainly expect to see progress in the coming years (again, an OPTIMISTIC message).

8. **How do scientists predict the evolutions of El Niño and La Niña?**

   Scientists from NOAA and other agencies use a variety of tools and techniques to monitor and forecast changes in the Pacific Ocean and the impact of those changes on global weather patterns. In the tropical Pacific Ocean, El Niño is detected by many methods, including satellites, moored buoys, drifting buoys, sea level analysis and expendable buoys. Many of these ocean observing systems were part of the Tropical Ocean Global Atmosphere (TOGA) program, and are now evolving into an operational El Niño/Southern Oscillation (ENSO) observing system. NOAA also operates a research ship, the KA'IMIMOANA, which is dedicated to servicing the Tropical Ocean Atmosphere (TAO) buoy network component of the observing system.

   Large computer models of the global ocean and atmosphere, such as those at NOAA's National Centers for Environmental Prediction, part of the National Weather Service, use data from the ENSO observing system as input to predict El Niño. Other models are used for El Niño research, such as those at NOAA's Geophysical Fluid Dynamics Laboratory and other non-government research institutions.

9. **How much confidence can we place in the predictions?**

   All forecasts are fallible (!). In the Southwest, not all El Niños bring wet winters, and in the Northwest, not all El Niños bring dry winters. The most appropriate way to use these forecasts is to "hedge one's bets" in the indicated direction. In the Southwest, the likelihood of a wet winter is typically increased from 50 percent (a coin toss) to about 65-75 percent. In the Pacific Northwest and northern Rockies, for a typical El Niño the likelihood of a dry winter is increased to 65-75 percent. For the 1997-1998 El Niño, these likelihoods were even higher than usual in the most affected areas, as much as 80 percent for a dry or wet winter, in the two respective areas.

10. **What exactly is being predicted?**

    Two kinds of prediction are being made: (1) prediction of "equatorial warm events" in the Pacific and (2) predictions of the impacts of those events. The term "warm event" refers to a large scale warming in the tropical Pacific and is frequently a euphemistic way of saying El Niño event or "El Niño-like" without actually saying "El Niño". Sometimes these events are too weak to be called "El Niño" in any universally agreed- upon way, and to call it such in advance (given our poor ability to predict its magnitude) would be to irresponsibly encourage unwarranted speculation about its impacts, which are typically minimal for the marginal cases. These predictions are done routinely once or several times a year by a number of scientific groups around the world, utilizing various kinds of numerical and/or statistical models of how the oceans and atmosphere interact with each other. Many of these predictions may be found on the Internet. NOAA/CPC provides the U.S. "official" predictions, while the International Research Institute for Climate Prediction (IRI) disseminates predictions with a global scope.

The predictions of impacts are done more empirically and more informally, and usually only in connection with a warm event that is already known to exist and is strong enough to be called El Niño without controversy. A prediction of impacts is typically based on what we know historically about climate responses to (or correlations with) El Niño occurrences. It is a probabilistic statement that certain climatic conditions can be expected more or less frequently than normal due to the existence of El Niño conditions. Sometimes these predictions are nothing more than the response of a scientist to a reporter or an interviewer. The U. S. National Oceanic and Atmospheric Administration (NOAA) routinely publishes formal climate outlooks and advisories for the coming season (available via the Internet and elsewhere). These are based on applied research by NOAA and others. When a strong El Niño is in progress, these outlooks typically warn about the unusual conditions that are expected from El Niño.

11. **How far in advance can we predict the existence and the intensity of an El Niño event?**

Accurately? In terms of timing and magnitude, hardly at all. In terms of saying that an "equatorial warm event" (only vaguely defined in magnitude) will start within a particular six-month time frame, we can typically foresee that up to a year in advance. Some prediction models succeed in doing this for one event and then go bust with the next. There was a good example of this in 1997. Accordingly, we have come to rely more on a "consensus forecast" of many models rather than on any one model. But the long-lead accuracy still leaves a lot to be desired. Most models correctly anticipated a "warm event" for the 1997/98 winter as early as one year earlier. However, none of the predictions anticipated that strong anomalies would already be in place by June, 1997, while their predicted magnitudes were small compared with what actually occurred.

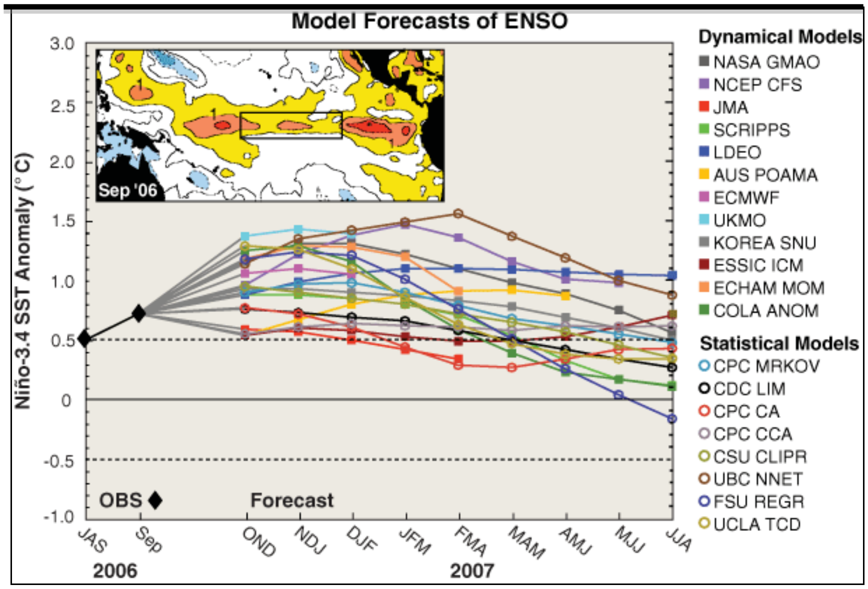
12. **Some have suggested that the dire predictions we heard during the 1997 summer (once the El Niño was underway) were premature. Is that true?**

There was a lot of misinformation and unfounded speculation, especially early in the event when we had no accurate way of knowing how strong it would be. Although the event indeed proved to be very strong, there was little basis at the time for making those dire projections. But even within the parameters of those projections the interpretations in the media were inaccurate, misleading and unnecessarily alarming. The misinformation included things like the *NY Times* saying (in July) that sea temperatures (not their anomalies) were as large or larger than ever recorded. In fact, the measured temperatures on the equator were well below previous El Niño highs; it was the difference between the measured temperatures and what is normal for that time of year that was extraordinary. The distinction, in terms of climate impacts, is crucial. The prediction (in June 1997) that Californians would see a winter with several times their normal rainfall did prove accurate, but no attempt was made to prevent that projection from unnecessarily alarming people in places where no danger was likely. When *Reuters* carried these news releases to places like Ecuador and Panama (where strong El Niños really ARE disastrous), it caused a general panic. Banks closed credits for crop planting and insurance companies refused to offer crop insurance, even though under the direst scenario the severe agricultural impacts could not occur until much later. Clearly, we have a long way to go in terms of how we handle the diffusion of ENSO-related information.

13. If the predictions of a watery grave are not reliable, can we make any predictions at all?

Certainly. We can say that "a warm event will occur" with enough advance notice to be useful and that will probably prove to be correct in most instances. The projections of climate impacts, given that an event will probably occur, are more tenuous. Such projections are probabilistic, aimed at the center of our expectations, not at the fringes of what is remotely possible, and they are still not terribly accurate, though they are much better than anything we could do 30 years ago. If regional ENSO climate outlooks are correct three or four times out of every five, then people who use them are ahead of the game over the long term.

C. TECHNICAL FORECASTING



1. What are the differences between statistical and dynamical forecast models of El Niño?

There are two main types of forecast. First are statistical forecasts, based on historical records. Second are dynamical forecasts, based on forward integration of numerical models of the coupled ocean/atmosphere system. Each has its strengths and weaknesses, and their results can be quite different.

Statistical forecasts correlate observed weather conditions with indices of the occurrence of El Niño. Typically sea surface temperature (SST) in key regions of the equatorial Pacific are used to define "El Niño periods". Alternatively, an index known as the "Southern Oscillation Index" (SOI) is used, based on the surface pressure difference between Tahiti and Darwin, Australia. The advantage of the SOI is that records at those two locations go back a century, while we have only a few decades of SST observations in mid-ocean. The correlation of one of these indices with, say, rainfall in California, can be the basis of a forecast of the likelihood of reoccurrence of heavy rains in that region during an El Niño winter. These are probably the most common type of forecast reported in the media. In some regions, such as the U.S. Gulf Coast, these correlations are quite robust and the statistical forecast is fairly reliable. In others, the correlations are weak or marginal.

The strength of statistical forecasts is that they are based on events that actually did occur, but they can fail because El Niño is not an exact, repeating phenomenon. We observe that different events evolve in different patterns, can occur at different times of year, etc. In addition, there are many climate oscillations on all timescales occurring simultaneously, and the weather we experience in any location is the sum of these oscillations and the interactions among them. Most of these are as yet poorly understood, particularly the longer-term ones, and as we get better and longer records we become aware of more and more complexity. Therefore, it is not straightforward to isolate the specific effects of El Niño by averaging over previous events. All these things result in blurring the statistics and reducing the confidence in such forecasts.

Another problem with statistical forecasts is that we do not have good, long-term records for many of the important quantities of interest. Once you go back further than the mid-1950s, the ocean records are sparse and ambiguous, making it hard to determine which are strong El Niño years and which are weak (or even whether or not there is really an El Niño at all). But if attention is limited to the period of good data, then there are really only a handful of events, and the statistics become quite unreliable. (If you measured 5 children from a classroom of 30, you might not get a good estimate of the mean height of the class). Many of the differences among statistical forecasts reported in the media are due to the choice of different averaging periods.

Dynamical forecasts are based on the hydro-dynamical equations numerically integrated forward from present observed conditions. These computer models range from relatively simple representations to complex models such as are used in weather forecasting. The simple models are useful in that specific processes can be analyzed and dissected. For a while during the 1980s it appeared that much of the El Niño cycle could be understood in terms of planetary waves bouncing around the Pacific, and this could be reasonably well simulated in a simple model. However, this theory failed to predict the series of El Niño events during the 1990s, and it appears that we must simulate the full complexity of ocean-atmosphere interaction. This is a task of utmost difficulty, compounding the problems of ordinary weather forecasting by the addition of numerous interactions between the ocean and atmosphere.

One of the major difficulties of dynamical forecasting is that we cannot simulate every molecule of air and water, but must reduce the various phenomena to a relatively crude grid mesh representation of the world. Such grids have spacing of typically tens to hundreds of kilometers, due to limitations of computer speed and storage. Consider, for example, the problem of representing clouds in such a model. The grid is far too coarse to resolve individual clouds, and therefore parameterizations are sought to simulate the processes within clouds as an aggregation. But it is the motions and thermodynamics within the individual clouds that actually produce precipitation. In general, rising air produces precipitation, and then condensation of water vapor releases heat, which accelerates the rising. To correctly estimate the amount of water and heat released by a cloud one must know the actual speed and humidity of rising air. Therefore the amount of precipitation produced by a group of individual clouds is not the same as that which would be produced by a cloud that had the average properties of the whole region, which includes both cloudy and cloud-free areas. Making an analogy to economics, the total business activity in a society is the sum of the initiatives of the individuals living there, but the net result is not the same as it would be if the society was composed of many identically-behaving "average" individuals. Much current research is devoted to figuring out how to represent complex interactions like these in a way that computers can work with.

Nevertheless, it is my belief that as computers become faster and as our understanding of the physical processes becomes better, we will rely more and more on the dynamical forecasts. They have the tremendous advantage of working forward from the actual present observed conditions, and so avoid the problem of statistically averaging over a number of events that differ in important details. In addition, for low-frequency events like El Niño, it will take decades or centuries to accumulate sufficient realizations to really improve statistical confidence. I suppose I have a personal bias towards this point of view in that this field offers the opportunity for scientists to make significant progress by advancing the understanding of physical processes within the coupled system, as we have already seen over the past several years.

2. **What climate forecast products does the NWS produce?**

CPC produces outlooks for temperature and precipitation in the U.S. for time periods of 6-10 days, 8-14 days, one month, three months (seasonal) and out to one year in advance. Other products are available for these time periods, including 8-14-day excessive heat outlooks, seasonal drought outlooks, and heating and cooling degree-day outlooks. CPC also issues special outlooks for U.S. winter weather, African seasonal rainfall, and hurricane activity in the

Atlantic and Eastern & Central Pacific Oceans. Finally, CPC provides expert assessments, including the hazards assessment and drought assessment.

3. **Has a reasonable, scientific body come up with any meaningful conclusions and/or predictions in the field of physical oceanography regarding forecasting of the ocean?**

   Regarding forecasting of the ocean, you may want to check out the following web page: http://www.pmel.noaa.gov/tao/elNiño/forecasts.html, which summarizes a number of current El Niño/Southern Oscillation (ENSO) forecasts. These forecasts rely on predicting tropical Pacific sea surface temperatures (SST) months to seasons in advance. Various kinds of forecast schemes have been developed. Some are based on the statistics of previous ENSO variations, while others are based on actually simulating future changes in ocean currents and subsurface thermal structures.

   ENSO forecasts are not perfect; however, they are sufficiently skillful at this point that individuals, corporations, municipalities, states and national governments have used them to prepare for El Niño and La Niña events. We know that unusually warm or cold tropical Pacific sea surface temperatures have major consequences for global climate and for Pacific marine ecosystems. Forecasting Pacific SSTs can therefore provide society with an opportunity to mitigate against adverse consequences or to take advantage of some of the positive aspects of ENSO-related environmental change. The 1997-98 El Niño is a good example of success in ENSO forecasting.

   The advances in ENSO forecasting over the past 15 years have come about because of a major coordinated and ongoing international research effort, and there is a vast technical literature that describes this progress. If you want to learn more, a user friendly web gateway to El Niño and related information can be found at http://www.pmel.noaa.gov/tao/elNiño/Niño-home.html

   There are other examples where ocean forecasting has been carried out successfully, but this El Niño example illustrates how one segment of the oceanographic community (in collaboration with meteorologists) has developed practical predictive applications of its research.

4. **How do models used to predict El Niño work? How accurate are they?**

   Computer models of the climate system are a sophisticated way of evaluating ideas that are too complicated for the human mind to think through. Perhaps a simple example (that the mind *can* think through) would help. We know that ocean surface water is heated by the sun during the day and that it cools off at night. Say the amount of heating is determined just by the length of the day. That means the water would heat more in the summer, since the days are long and the nights short, and cool off more during the winter. We could write these ideas down in equations, specifying the values of heating due to various amounts of sunlight, and use a computer to solve them and give us a plot of what the predicted water temperature would be at any time in the future. That's an (overly-simple) computer model of climate.

In reality, of course, we have much more complicated ideas of how the climate system works. For example, there are clouds, and the clouds not only block the sun during the day, cooling off the water, but also tend to insulate it at night, preventing cooling. Do these balance out? The answer is that it depends on how the amounts of cooling and insulating are specified. Parameters that describe these relationships have to be estimated from observations then programmed into the model. In addition, clouds are not independent of the water temperature; for example, very warm water tends to produce a lot of evaporation and rising air, setting up the conditions that consequently result in tropical rainstorms (similar to the thunderstorms we find occurring over warm summer land). But if there is wind, the clouds may be blown somewhere other than where they were formed, so the pattern of where clouds occur can quickly become extremely complicated. Since we have already specified in our model that the clouds affect the water temperature, that, in turn, means the pattern of water temperature gets more complicated, which feeds back on the cloud pattern, and so on.

But things continue to get more complicated. When air rises over warm water, other air must flow in from the sides to make up the deficit. Therefore if water temperatures are not uniform, there will be wind. Wind causes ocean currents, which move water of various temperatures around. If the winds move the warmer surface water away from a region, colder water from below may be pulled up. This is called “upwelling.” Because cold water weighs more than warm water, the difference in their densities also causes currents to flow.

So I think you can see that computer models of the climate system can start with some fairly simple ideas but quickly become extremely complicated in practice. The computer power necessary to work through these equations is as large as that in any field of study. As we get more observations, we learn more about the system, and modelers are constantly struggling to represent these processes more accurately. One of the main difficulties is that while we know pretty well how the system will change over a short time (like a day or so), once we ask for longer predictions we come up against the problem that we don't know the initial state perfectly. Therefore there will be some error in the forecast since it won't be starting from exactly where the real system starts. For a one day forecast, the error probably won't be too great, perhaps resulting in nothing more than some clouds in the wrong place. If we run the model further into the future, however, those wrong clouds will soon produce erroneous water temperatures, which will produce an even worse cloud pattern, and pretty soon the whole solution is garbage. What this implies is that there is an inherent limit to the predictability of a system as complicated as the ocean-atmosphere system.

How accurate weather and climate models are depends on how far in advance you want a prediction, and how much detail you want. If I want to know the weather in Seattle for a specific day, then I can get it no more than 3-4 days out. If I only want a general forecast for a season, averaged over a large region, then sometimes our models have useful skill for as much as a few months in advance, particularly if a major influence such as El Niño that has reasonably-well understood effects is present. At other times, when a more complicated mix of weaker processes is present, there may be little predictive long-range skill at all.

In general, I don't take seriously forecasts for more than a few months in advance. For example, in February 1998 most models suggested that El Niño would wind down by early summer 1998 and that a strong La Niña (the opposite phase, in which it is abnormally cold in the tropical Pacific and many, but not all, of the far-field effects of El Niño are reversed) would arise the following winter. Frankly, I didn’t have much confidence in a forecast that far ahead. I agreed that El Niño was winding down (the signs were obvious in the observations), but I didn’t think anyone could predict what would happen the following winter. However, the scientists who made these forecasts did it publically as a means of "ante-ing up" the forecast competition. And believe me this is a real competition. Everyone wants to be the first to develop a successful El Niño model, and if you don't publish a forecast in advance, you can't claim later that you had it right. So you see a lot of long-range forecasts, but that doesn't mean that anyone, including the winter 1998 forecast authors, necessarily have much confidence in them. Unfortunately, with the media frenzy about El Niño in 1997, many of these experimental forecasts were trumpeted around the newspapers and TV shows as if they were truth. [editor note: They were not. The El Niño that began abruptly in 1997 ended unexpected as quickly in May 1998. It was followed by a longer-than-expected La Niña episode.]

As it turned out, a moderate La Niña did arise in the winter of 1998-99, justifying the forecast; however, the accuracy of the forecast was more to do with coincidence than with a breakthrough in predictive power. In other words, and the authors of the forecast would likely agree, which is not to downplay their contribution, the cold event could have just as easily not have happened, which is the point of this response.

5. **What have been the major new developments for *in situ* monitoring of SSTs?**

There have been two major developments: First is the much better satellite coverage. Second is the development of a simple, inexpensive design for buoys that can be deployed in mid-ocean and that remain active for a year or more. Previously, most buoys were placed only in shallow coastal waters or for only short times in deep water. Only in the early 1980s was the technology developed to place and maintain a large network of buoys in mid-ocean for a full year or more in what is known as the TAO (Tropical Atmosphere Ocean) buoy array, which across the equatorial Pacific monitors not only SSTs but also surface winds, air temperature and humidity, and subsurface temperature (sometimes currents, too) in the upper 500m.

These buoys transmit data daily (in some cases hourly) to the weather forecast network and for research and prediction. The big advantage of moored buoys is their high temporal resolution. Also, knowledge of subsurface processes is necessary to understand and predict how the SST is likely to change over a few weeks and even months. Finally, there is the need for ground-truthing AVHRR (satellite SST) values. SST products are usually a blending of satellite AVHRR ground-truthed by means of buoy and other data. This is the case because AVHRR by itself can be biased because of unknown amounts of water vapor in the atmospheric column that affects the radar returns. (The AVHRR must be corrected based on an estimate of the atmospheric water, which affects the SST measurement, and many AVHRR satellites have instruments to make these estimates). But where there are buoys, as in the equatorial Pacific, the AVHRR estimate can be fixed by the buoy SST, providing a better check than a satellite estimate of water vapor.

6. **What technology is used to detect, monitor and predict El Niño and La Niña events?**

Recent technological advances have made it possible to monitor, diagnose and predict El Niño and La Niña events in near-real time. Some of the major technologies used are:

- Satellites, which provide data on tropical rainfall, wind and ocean temperature patterns, as well as changes in conditions for hurricane formation;
- Ocean buoys, which help monitor sea-surface and upper ocean temperatures;

- Radiosondes, which help to monitor global weather and climate patterns, and to survey and predict El Niño and La Niña influences on U.S. weather. High-density surface data network helps to monitor and predict El Niño and La Niña influences on U.S. weather;
- Super computers, which are used to gather all of the weather data around the world and put it into useful formats used by scientists. They also run sophisticated computer models to help scientists better understand and predict El Niño and La Niña; and
- An entire suite of diagnostic and prediction tools run on high-speed computers, which enable El Niño and La Niña to be monitored in near-real time.

7. How are El Niños Predicted?

Scientists are now taking our understanding of El Niños a step further by incorporating the descriptions of these events into numerical prediction models (computer programs designed to represent, in terms of equations, processes that occur in nature). Such models are fed information, mostly in the form of sets of numbers, describing the present state of the atmosphere-ocean system (e.g. observations of wind speeds, ocean currents, sea levels and the depth of the thermocline along the equator). Updated sets of numbers, which the models produce, indicate how the atmosphere-ocean system might evolve over the next few seasons or years.

Such models enable scientists to test their understanding of how complex systems operate. One such test is to see whether the models are able to replicate past El Niños. If the models are realistic enough, researchers can even use them to make predictions of what will happen in the future.

Similar numerical models based on the laws of physics have been used since the 1960s to forecast weather. In the early years, these forecasts were no better than those made by skilled meteorologists relying on their own experience in watching weather systems evolve. But thanks to advances in our understanding of weather systems and in the numerical models that are used to represent them, today's weather prediction models consistently outperform even the most seasoned forecasters.

Numerical models of El Niño are not as reliable as those used in weather forecasting, but they have advanced to the point where they can reproduce the characteristics of a typical event. In recent years, several research groups have pioneered the use of models to predict the comings and goings of individual El Niño events and their effects on weather patterns throughout the world before these events actually occurred. The results thus far, though by no means perfect, give a better indication of the climatic conditions that will prevail during the next one or two seasons than simply assuming that rainfall and temperature will be "normal."

How Predictions are Used: An Example

Peru provides a prime example of how even short term El Niño forecasts can be valuable. There, as in most developing countries in the tropics, the economy (and food production in particular) is highly sensitive to climate fluctuations..

Year-to-year swings between above- and below-normal sea-surface temperatures along the Peruvian coast produce a wide range of local impacts. Warm (El Niño) years tend to be unfavorable for fishing and some of them have been marked by damaging floods along the coastal plain and in the western Andean foothills in the northern part of the country. Cold years are welcomed by fishermen but not by farmers because these years have frequently been marked by drought and crop failures. Such cold years often come on the heels of strong El Niño years. Hence, Peruvians have reason to be concerned, not only about El Niño events, but about both extremes of the El Niño cycle.

Before the flood waters from the record breaking 1982-83 El Niño event had fully receded, farmers in Peru were already beginning to worry that sea-surface temperatures might drop below normal the following year, bringing drought and crop failures. It was at this time that the Peruvian government decided to develop a program to forecast future climate swings.

The first task was to make a forecast for the next rainy season, which was expected to occur in early 1984. Information available in early November of 1983 indicated that the climatic conditions in the equatorial Pacific were near normal and were likely to remain so through the rainy season, producing favorable conditions for agriculture. This information was conveyed to numerous organizations and to the Minister of Agriculture, who incorporated it into the planning for the 1983-84 growing season. The forecast proved to be correct, and the harvest was an abundant one. Since that time, forecasts of the upcoming rainy season have been issued each November based on observations of winds and water temperatures in the tropical Pacific region and the output of numerical prediction models. The forecasts are presented in terms of four possibilities: (1) near normal conditions, (2) a weak El Niño with a slightly wetter than normal growing season, (3) a full blown El Niño with flooding, and (4) cooler than normal waters offshore, with higher than normal chance of drought.

Once the forecast is issued, farmers representatives and government officials meet to 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 highly sensitive to the quantities and timing of rainfall. Rice thrives on wet conditions during the growing season followed by drier conditions during the ripening phase. Cotton, with its deeper root system, can tolerate drier weather. Hence, a forecast of El Niño weather might induce farmers to sow more rice and less cotton than in a year without El Niño.

Looking Ahead

Peru is one of several countries that are already successfully using predictions of El Niño in connection with agricultural planning. Other countries that have taken similar initiatives include Australia, Brazil, Ethiopia and India. It is not a coincidence that all these countries lie at least partially within the tropics. Tropical countries have the most to gain from successful prediction of El Niño because they experience a disproportionate share of the impacts and, coincidentally, occupy the part of the world in which the accuracy of climate prediction models is greatest. But for many countries outside the tropics, such as Japan and the United States, more accurate prediction of El Niño will also benefit strategic planning in areas such as agriculture and the management of water resources and reserves of grain and fuel oil.

Encouraged by the progress of the past decade, scientists and governments in many countries are working together to design and build a global system for (1) observing the tropical oceans, (2) predicting El Niño and other irregular climate rhythms, and (3) making routine climate predictions readily available to those who have need of them for planning purposes, much as weather forecasts are made available to the public today. The ability to anticipate how climate will change from one year to the next will lead to better management of agriculture, water supplies, fisheries and other resources. By incorporating climate predictions into management decisions, humankind is becoming better adapted to the irregular rhythms of climate.

8. Why do diagrams of El Niño show a pointy wedge of warm water pointed west from South America?

You see the westward-pointing wedge in plots of anomalies, not in plots of the actual temperatures. Anomalies mean the normal temperatures in each location have been subtracted from the observed values at the time of the plot. An anomaly plot therefore shows whether the water is warmer or cooler than its normal state, and the normal state is different in different places. For example, if on some (very unusual!) day the temperature was 20°C (68°F) everywhere in the ocean, that would be normal along the coast of Baja California, but anomalously warm in Seattle, and anomalously cold in the Philippines. An anomaly map for this hypothetical flat 20°C day would show positive values in mid-latitudes and negative values in the tropics.

In the tropical Pacific, normal sea surface temperatures (SSTs) are much colder in the east than in the central/western Pacific (say 23°C (73.4°F) in the east vs. 29°C (84.2°F) in the west). Further, the cold water in the east is concentrated in a band along the equator. That may sound strange, since we usually think of the equator as warm, but upwelling of deeper (hence colder) water occurs on the equator in the east, resulting in the cool water there.

During El Niño, water of about 28°C is found across a huge region from the central Pacific along the equator to South America. In terms of anomalies, this is near-normal in the central Pacific, but gets progressively more anomalous along the equator to the east. That's why there appears to be a wedge.

D. SEA SURFACE TEMPERATURE MONITORING

1. **What is the forecast for sea surface temperatures for the remainder of 1998 and into winter 1999 and how strong will the event be?**

   The latest National Oceanic and Atmospheric Administration (NOAA) coupled-model forecast (an ocean-atmosphere model) (July 1998) indicate strengthening cold episode conditions in the tropical Pacific during the remainder of 1998.

   Other statistical and coupled-model forecasts indicate a similar evolution. The consistency among the available predictions together with the evolution of oceanic and atmospheric conditions since early May indicate that a cold episode is developing and will likely continue through the northern 1998-99 winter.

   The current forecasts indicate that the 1998/99 La Niña will be a moderate to strong episode.

2. **How are sea surface temperatures monitored?**

   Sea surface temperatures in the tropical Pacific Ocean are monitored with oceanic buoys, ships and satellites. NOAA operates a network of 70 moored buoys in the equatorial Pacific that provide important data about upper-ocean and sea surface conditions. This array of moored buoys is called the TOGA/ TAO Array. These data are used to calibrate sea surface temperature analyses derived from the NOAA series of polar orbiting satellites.

3. **How are the data buoys used to monitor ocean temperatures?**

   Observations of conditions in the tropical Pacific are essential for the prediction of short-term (a few months to one year) climate variations. To provide necessary data, NOAA operates a network of buoys that measure temperature, currents and winds in the equatorial band. These buoys transmit data that are available to researchers and forecasters around the world in real time.

4. **How come the sea surface temperature of Savannah, GA and San Diego are different . . . since they lie at the same latitude?**

   In general, the east coast of continents have much warmer SST (sea surface temperature) than the west coasts. The ocean temperatures are controlled by the great "western boundary currents" (WBCs) that carry warm water poleward against the east coasts of all the continents. In the North Atlantic there is the Gulf Stream and the North Pacific has the Kuroshio. The South Atlantic has the Brazil Current, and the South Pacific the East Australian Current. The Indian Ocean WBC is the Agulhas Current. All these currents carry the return flow from the subtropical gyres, which are the basin-scale circulations that rotate clockwise in the northern hemisphere and counterclockwise in the southern. The eastern sides of all oceans have (weaker) currents that carry cool water towards the equator. This east-west difference in the current structure ("western intensification") was explained by the preeminent oceanographer Henry Stommel in 1948. The Coriolis effect, due to the rotation of the earth, means that a given pressure difference produces a larger current closer to the equator, so the westward flow on the equatorial side of all the gyres is larger than the eastward flow on the poleward side. As a result, the gyres are compressed to the west and the WBCs are stronger than the corresponding eastern boundary flows. The locally-warm water due to the western boundary currents can be a significant moderating influence on land temperatures within a few kilometers of the coasts in winter.

   There is, however, an opposite effect for areas further inland. In mid-latitudes, westerly ("from the west") winds (the "jet streams") blow persistently in the latitude band from about 30° to 60°. As they traverse the wide oceans, they acquire the temperature of the water, which in winter is warmer than the land, then carry this heat hundreds of km eastward over the land on the east sides of oceans and moderating winter air temperatures. Similarly, when the westerlies blow over winter continents, they become cold and carry that temperature to the east coasts. Thus air temperatures over Japan in winter are colder than those of California, at the same latitude, even though the nearby ocean temperatures are warmer off Japan. It is estimated that the westerly wind effect is more important than the ocean current effect in giving Europe mild winters.

XVIII. SOLUTIONS

A. Has there been any research to cause a small manmade El Niño or the replication of some of its effects to control weather systems? If it were possible to change the temperature of the water, would it reverse an El Niño?

To answer this question we need to consider how much heat change is involved in climate oscillations such as El Niño.

The increase in SST during January through July 1997, averaged over the equatorial Pacific (10S-10N, 150E-75W) was about 1.62°C.

But the quantity we need is heat content, which is proportional to the mass of water times its temperature. This can be estimated from the TAO buoy array, by multiplying the density of water (1030 kg/m3) times the heat capacity of seawater (4000 J/kg/K) times the area of the TAO array times the vertical integral of buoy temperature with depth. (See note on units below) (The area was estimated by dividing the array into regions each assumed to be represented by one buoy. Each day, the above calculation was made summing over the area of only those buoys with data for that day). Performing this calculation with TAO temperatures, the time series of heat content in the upper 500m shows that this quantity increased by about 3.5e22 J ("3.5 times ten to the twenty-second Joules") during July 1996 through March 1997, then decreased slightly.

Now we can compare that heating to human engineering power. One of the most powerful devices humans have created is the H-bomb. The heating during El Niño can be related to the power of the H-bomb as follows. One kiloton of TNT is about 4.18e12 J. Therefore. 3.5e22 J is about equivalent to 8e9 kilotons, or about 400,000 20-Mt bombs. That assumes the power of those bombs could be directed entirely to heating (i.e. not to moving) the water.

Another way to look at this is to estimate the heating that would be done by a bomb if all the energy went into heating. Consider a 1-Mt H-bomb, releasing 4.18e15 J of energy. That energy would heat a volume of about 1 cubic kilometer of seawater 1°C. That certainly seems like a lot of energy, but the volume of just the upper water of the equatorial Pacific (10°S-10°N, upper 200m) is about *6 million* cubic kilometers. Compared to H-bombs, climate changes are a different order of beast entirely.

Another way to look at it is in terms of power plants. Increasing the heat content by 3.5e22 J over the period July 1996 to March 1997 is a heating rate of about 1.5e15 W (1.5 PW). A large power plant can generate about 1000 MW, so the El Niño-related heating is equivalent to the total output of roughly 1,500,000 power plants working continuously for 8 months.

Of course, this argument is misleading in that El Niño probably does not actually heat that much water. What it does is redistribute the heat already in the ocean, first moving it in to the TAO array region, then out. However, it probably is the case that the work required to move that much water is similar in magnitude to the work required to do the heating as above. This calculation is harder to do because we can't measure the currents nearly as well as the temperatures.

Other ideas to avert El Niño might be conceived. In principle, one could imagine some mechanism that would lower the temperature of the surface water by mixing with deeper water. Obviously, any kind of stirring would take work, a lot of it. What about dissolving a huge amount of salt in the surface water, increasing its density without changing the temperature, and thereby causing it to sink, and cooler water to rise? A rough calculation shows that raising the salinity by about 2 parts per thousand would make water at 28°C denser than water at 23°C, and thus cause it to sink significantly (and consequently cooler water would rise). To do this to a 50 meter high column of water 1 meter square (50 tons) would take about 100 kg of salt. For a smallish area of the equatorial Pacific (say 1000 km square) it would take about 10 to the 11th tons of salt. Let's say a pile 1 km square and 100 km high. I guess not!

Even if we could make the kind of deliberate changes of ocean temperature suggested above, it is not at all clear that this would be desirable. It is useful to remember that El Niño is a normal part of the climate system of the Pacific, as much as, say, winter is a feature of continents. While it might seem convenient to make winter go away, in practice much vegetation and animal life has evolved to require either the rain or cold of winter and would be severely disrupted if these changed. (Not to mention the difficulty of keeping children in school through endless summer!). Similarly, El Niño serves the function of draining excess warm water from the equatorial Pacific, and preventing this function would reverberate through the rest of the system in unpredictable ways. Some of those we might not like, and we are not in a position to predict what those would be. The ecology of the Pacific has adapted to El Niño fluctuations, so even though there can be devastating effects in certain areas, in the long run El Niño is part of the ecosystem—not to be messed with lightly.

One example of this is that it is hypothesized that the unusual eastward winds and currents associated with El Niño have enabled some species of plants, fish and birds to colonize the islands of the central Pacific, whereas if there were only the westward trades winds this could not have happened. I have even read that it may have been only because of these anomalous El Niño winds that the Polynesians were able to reach as far east as the islands around Tahiti. During the normal trade wind regime, the westward winds would have made such voyages much more difficult. Also, in El Niño conditions Polynesians could undertake exploratory voyages to the east with the knowledge that the winds would change in a few months, guaranteeing them a ride home.

In any case, even if we had a way to channel these effects into direct heating of ocean water, it is clear from the magnitudes involved that people are nowhere near the ability to modify the climate on this scale.

There is one exception. By burning fossil fuels at the rate we do, we increase the CO2 concentration in the atmosphere in a way that could well cause climate changes (global warming), as most scientists think is now happening. The difference is that this change represents the "efforts" of all the industrial world acting over a century to just get the change under way.

A note on units used here:
kg = kilogram.
m = meter.
K = degrees Kelvin (same units as °C, but starting from absolute zero or -273.15°C)
J = Joule. This is a unit to measure work or energy.
W = Watt. 1 W = 1 J/second. This is the power (rate of doing work).
Abbreviations for large numbers: M = meta (10e6 or 1 million). P = peta (10e15 or 1 million billion).

B. Would you be able to give me some feed back on how we as global citizens can do something about el Niño and its effects?

El Niño happens when tropical Pacific Ocean trade winds die out and ocean temperatures become unusually warm. There is a flip side to El Niño called La Niña, which occurs when the trade winds blow unusually hard and the sea temperature become colder than normal. El Niño and La Niña are the warm and cold phases of an oscillation we refer to as El Niño/Southern Oscillation, or ENSO, which has a period of roughly 3-7 years. Although ENSO originates in the tropical Pacific ocean-atmosphere system, it has effects on patterns of weather variability all over the world. It also affects Pacific marine ecosystems and commercially valuable fisheries such as tuna, sardines, salmon, and Peruvian anchoveta.

Information contained in the chemical composition of ancient tropical Pacific coral skeletons tells us that ENSO has been happening for at least 125 thousand years. This span of time covers the last ice age cycle when the earth's climate was cooler and very different from today's climate. In addition, we can reasonably assume that the ENSO cycle has been operating ever since geologic processes closed the Isthmus of Panama about 5 million years ago, an event that formed the modern boundaries of the Pacific basin.

There is nothing we can do to stop El Niño and La Niña events from occurring. The year-to-year oscillations between normal, warm and cold conditions in the tropical Pacific associated with the ENSO cycle involve massive redistributions of upper ocean heat. For instance, the accumulation of excess heat in the eastern Pacific during a strong El Niño like that which occurred in 1997-98 is approximately equivalent to the output of one million medium-sized 1000 megawatt power plants operating continuously for a year. The magnitude of these natural variations clearly indicates that society cannot hope to consciously control or modify the ENSO cycle. Rather, we must learn to better predict it and adapt to its consequences.

The challenge for physical scientists therefore is to improve ENSO forecast models, to improve our understanding of underlying physical processes at work in the climate system and to improve the observational data base needed to support these goals. Capitalizing on advances in the physical sciences for practical purposes is a challenge for social scientists, economists, politicians, business leaders and the citizenry of those countries affected by ENSO variations. The promise of the future is that continued research on ENSO and related problems will be rewarded with new scientific breakthroughs that translate into a broad range of applications for the benefit of society.

C. If El Niño is such a big problem, why aren't people doing anything to solve it? Why aren't they trying to find a way to prevent El Niño?

First, El Niño isn't all bad news. For example, El Niño usually brings a warm winter to the northern USA from the Pacific Northwest across to the Midwest and sometimes the Northeast. I'm sure that no one in the Dakotas who saved a lot of money on fuel during the mild winter of 1997-98 thinks of El Niño as bad, especially when they look back on the bitter winter of 1996-97, which was not only cold but also left huge amounts of snow on the ground that caused major floods when it melted in the spring.

Also, El Niño tends to reduce the numbers of hurricanes that form over the Atlantic Ocean, especially strong hurricanes. I don't think you'll hear complaints about El Niño from the people on Caribbean Islands or the U.S. East and Gulf coasts who weren't hit by a hurricane in 1997.

Second, and probably even more important, no one really knows what the consequences would be if somehow people could stop El Niño. You can think of El Niño as kind of like a safety valve that helps release heat that builds up in the western Pacific during ordinary years. If an El Niño didn't come along every few years to spread out the hot water that's built up in the western Pacific, nature would find another way to ease the heat. No one knows what this way would be, but one good bet would be more and stronger tropical cyclones in the western Pacific. This could happen because all kinds of storms, including tropical cyclones, along with ocean currents helps the earth keep its heat budget in balance.
Even if we wanted to, changing El Niño would be extremely difficult. As William S. Kessler, an oceanographer at the National Oceanic and Atmospheric Administration's Pacific Marine Environmental Laboratory in Seattle, puts it: "It is important to remember that El Niño is not the only climate fluctuation that is occurring. El Niños occur on a changing background state, which is probably the reason that the various El Niños are somewhat different. So it would not be simple to figure out how to modify the ocean temperatures to get the changes we wanted, even if we had the technological means to do that."

But, we don't have the technological means to change an El Niño because the amounts of heat involved make any possible human efforts - including hydrogen bombs - look pretty small.

Instead of trying to defeat El Niño, scientists are working to learn more about it in order to predict it and its effects better. Such predictions would make it easier for people in parts of the world where El Niño has harmful effects to plan for events and cope with them.

D. Is it feasible to haul icebergs from Antarctica to the tropical Pacific to cool down El Niño?

The answer is "NO".

The simple reason is that to cool the tropical Pacific down to its normal state once an El Niño is underway would take an amount of ice 10 m thick covering an area equal in size to the continental US. That's a lot of ice, and there's no way to extract and transport that amount of ice with existing technology. Even if it were technically feasible, it would in all likelihood cost an astronomical amount of money, many times over the combined global losses due to El Niño.

Furthermore, it would take a long time to transport. The inevitable delays that attend any grand project would probably mean you'd get all the ice to the tropical

Pacific just as the El Niño was ending. It would be too late to do any good. But worse, since El Niño is often followed by La Niña (which has its own set of adverse consequences on weather), you could end up exacerbating the effects of natural climate variability on society.

Finally, the extraction of that much ice would seriously damage the environment of Antarctica. It could also have potentially serious consequences on global climate if it lead to changes in surface reflection of sunlight, or had other effects on land surface processes. So economically and environmentally, investing in research on how to better predict and adapt to El Niño is a much better strategy.

XIX. TIDBITS

A. Any ideas for a science fair project?

Here's an idea. This experiment is similar to what actual scientists are doing right now.

The project is to construct some forecast models of El Niño's development over the next few months. We don't know what it will do. Will it get more intense?, weaken?, remain strong?, and if so for how long? These questions are the subject of much debate in the scientific community right now, and many efforts are under way to predict and understand it.

The models would be forecasts made using several assumptions, and the main result would be graphs showing how the forecasts compared with actual evolving conditions.

One model would be called "persistence". That is, whatever conditions are occurring now, they will continue. Surprisingly, persistence is often a hard-to-beat forecast, and weather forecasters score themselves on how much better than persistence they can do. A second model is continuation of the trend. That is, if the sea surface temperature (SST) is warming up it will continue to warm at the same rate. Obviously that can't go on forever but in many ways a trend is a good indicator of future trends. A third model is random changes. Get a random number generator (or pick numbers out of a hat). Each day or week, use the random numbers to predict what the change of SST will be (scale the numbers to keep it reasonable). Those are three simple models that can be used to project forward from current conditions. Essentially that's what weather forecast models do, just more sophisticatedly. Maybe you can think of some other ways to make forecasts.

Choose a few buoys from our network in different regions of the tropical Pacific (for example, on the equator, off the equator, in the east and in the west). Get the data from our web page. Make and graph predictions for each buoy chosen for a month or two ahead, then collect observations as they come in (the data files are updated daily). Graph the observations against the three predictions. My guess is that each model would be successful in some regions for some periods of time. Other extensions would be to compare forecasts beginning at different times. Perhaps a forecast begun with September conditions is good for 3 months, but one begun in December is only good for one month. Etc.

Another simple project is to determine how significant an effect El Niño has on your local region. Do this by gathering an assortment of local weather time series from your region (monthly rainfall, temperature, etc) (available at the web pages of the National Weather service). Then get an index of El Niño like the Southern Oscillation Index, and download the values at NOAA's Climate Prediction Center. The specific data links are: values for 1951-today and 1882-1950. Note that the SOI monthly values are very jumpy and must be smoothed by a 5-month running mean). Compare the turns of the El Niño/La Niña cycle with changes in your local weather; this could either be through a listing of El Niño/La Niña years and good/bad local weather, or by correlation of the two time series. You will probably find out that some aspects of your local weather are related to the El Niño/La Niña cycle and some are not. Also that some strong El Niño or La Niña years make a difference but some do not. This reflects the fact that, far from the center of action in the tropical Pacific, El Niño is only one of many influences on weather.

B. Why is the ocean salty?

The ocean is salty because of the weathering of rocks in the early stages of the formation of the oceans and continents. The ocean probably is continuing to become saltier very slowly (on geologic timescales) as rivers bring dissolved material to the sea. Even though the concentrations of dissolved salts in "fresh" river water is tiny, evaporation from the ocean surface (which is how water gets back to the rivers) removes only pure water so whatever salt enters from rivers remains in the sea and slowly builds up.

Seawater is about 3.5% salt by weight, which means the total quantity of dissolved salt, if dried, would form a layer 45m thick over the entire earth, or 153m thick over the present land area.

The salt in seawater is composed of a variety of components, primarily sodium chloride (table salt), magnesium chloride, magnesium sulfate and calcium carbonate, along with many trace elements. One of the remarkable aspects of ocean salinity is how constant the relative ratios of these constituents are in seawater, no matter where in the oceans one looks. This suggests that the oceans are "well-mixed" on the timescale of salt input. Total salinity, however, varies from about 3.3% to 3.8% in open-ocean surface waters, depending on the rainfall/evaporation/river runoff in different regions. Salinity in bays or near the mouths of rivers is less; for example, the salinity of Puget Sound near Seattle is about 2.9-3.2%. Deep-ocean salinity is much less variable.

It should also be noted that a fascinating controversy is now unfolding regarding the hypothesis that about 10 million small water-rich comet-like objects, each about the size of a small house and weighing about 20-40 tons, bombard the earth annually, depositing water vapor into the upper atmosphere. The protagonists of this theory suggest that this process may have introduced sufficient water into the earth system to fill the oceans over geological time. The evidence was first presented by Frank and Sigwarth of the Univ. of Iowa from images taken by NASA's Polar spacecraft. It is a highly controversial idea about which I can offer no guidance. But if the hypothesis proves viable, it will fundamentally change the ways we view planetary accretion, the origin and evolution of the ocean, and the interplay between the solid earth and the oceans.

C. Where can I find other information sources on El Niño and La Niña?

The Internet is the greatest source of information on El Niño, La Niña and weather and climate data. NOAA has created one primary web site that allows you to link to many other resources: http://www.elnino.noaa.gov/

Specific information on La Niña predictions and other background is available from NOAA's Climate Prediction Center at: http://www.cpc.ncep.noaa.gov

Information on NOAA's latest research initiatives is available at from the Climate Diagnostic Center at: http://www.cdc.noaa.gov/ENSO/

NOAA's Pacific Marine Environmental Laboratory also has lots of valuable data including current observations from the network of data buoys in the tropical Pacific Ocean: http://www.pmel.noaa.gov/toga-tao/el-Niño/