EL NIÑO AND THE SOUTHERN OSCILLATION

Contents

Observation

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Introduction

During 1877 and 1878 much of China was struck by famine, due to a severe drought. More than nine million people perished. In India, at the same time, more than eight million deaths were attributed to famine also caused by a drought. In many districts, a quarter of the population died. Drought in the same period also caused crop failures, scarcity of food or even famine, in north-eastern Brazil, Egypt, Indonesia, Fiji, Australia, and southern Africa. In other parts of the world, including Ceylon, the Pacific coast of South America, and Tahiti, many lives were lost from unusual storms or extended periods of heavy rain and flood. The El Niño Southern Oscillation, a major pattern of climate variation, links these climatic extremes in different parts of the world; the first major El Niño event for which good records exist was the 1877 event. Subsequent El Niño events have often reproduced the pattern of climate extremes and societal impacts observed in the 1877 event. We now use the phenomenon to make predictions of seasonal climate variations in many parts of the world.

How Was the El Niño Southern Oscillation Discovered?

The famine in India in 1877 led to the first scientific attempts to understand and predict monsoon failures and drought, and eventually to the mapping of the El Niño Southern Oscillation. Henry Blanford, then the head of the India Meteorological Department, noticed that atmospheric pressures were higher than usual over India during the drought. He advised meteorologists in other parts of the British Empire of this and asked them about atmospheric pressures in their colonies.

Blanford's message reached the South Australian Government Astronomer and Meteorologist, Charles Todd, who noticed that Australian atmospheric pressures were also high, and that the country had been experiencing a drought at the same time as India. When another drought struck Australia in 1888, Todd realised that India and Australia often experienced drought at the same time. This synchronism of drought in the two countries is part of the suite of long-range connections (teleconnections) between climate fluctuations in different parts of the world that we now call the Southern Oscillation. For the next few decades, several meteorologists around the world were occupied in mapping these teleconnections into a coherent pattern. Sir Gilbert Walker was the most prominent among these mappers, and it was he who named the teleconnection patterns the Southern Oscillation. Walker used these teleconnections to develop statistical systems for forecasting climate anomalies in many parts of the world.

In the middle of the twentieth century, interest in the Southern Oscillation declined. This was partly because the focus of atmospheric scientists shifted to shorter time scales, as computer models exhibited their ability to forecast weather. A second reason for the decline in interest was the absence of any theory explaining the teleconnections or the long time scale of the phenomenon. In the early 1960s, Hendrik Berlage and Jacob Bjerknes separately demonstrated that the El Niño and the Southern Oscillation were related. The term El Niño originally (at the end of the nineteenth century) referred to the annual weak warm current that runs southward along the coast of Peru and Ecuador at the end of the year. Subsequently, scientists applied the term to denote the occasional large warmings that occur every few years and result in major disruptions to the region. Bjerknes developed a theory for how this essentially tropical phenomenon could affect climate at higher latitudes. This step, along with the severe ecological and human consequences of the major El Niño episodes of 1972 and 1982, revived scientific interest in the study of interannual climate variations and their prediction. The phenomena are now jointly referred to as the El Niño Southern Oscillation, reflecting their close relationship.

What Causes the El Niño Southern Oscillation?

The joint name El Niño Southern Oscillation, is appropriate because ocean–atmosphere interaction is the cause of the phenomenon. Easterly winds over the eastern and central equatorial Pacific cause oceanic 'upwelling' (cooler subsurface waters being lifted to the surface) along the Equator. Southerly winds in the eastern Pacific also cause upwelling along the South American coast. As a result, the Pacific Ocean is usually cooler in the east than in the west by several degrees.

At tropical latitudes, heavy rains accompany warm oceans, so the warm west Pacific (including Indonesia and New Guinea) is a heavy rainfall region, while the cooler east Pacific receives little rainfall. **Figure 1** shows the mean sea surface temperatures for December. The relative coolness of the east Pacific, compared to the west equatorial Pacific is evident.

This is the 'average' situation, but during an El Niño the ocean temperature gradient from one side of the Pacific to the other weakens, and the easterly winds weaken. Droughts occur in the west (around the Indian Ocean and the west Pacific) associated with cooler than normal ocean temperatures, while the unusually warm waters in the east bring heavy rains and floods to the normally arid Pacific coast of South America. **Figures 2** and **3** show the strong warming of the east equatorial Pacific that took place during the 1997/98 El Niño. **Figure 2** shows the sea surface temperatures during December 1997, at the peak of the El Niño. Warming in the east Pacific at that time had almost completely removed the east–west temperature gradient. The east equatorial Pacific warming of about 5°C is shown in **Figure 3**, which exhibits the anomalies (deviations from climatology).

How does an El Niño start? A small change in the usual sea surface temperature pattern can produce a change in the winds along the Equator. In turn, these wind changes affect the currents that change the pattern of sea surface temperatures even more. This process continues, with ocean temperatures affecting winds that affect currents that, in turn, affect ocean temperatures. One important change is related to bursts of westerly winds in the western Pacific. These can trigger eastward-moving ocean disturbances that cause the thermocline (the transition layer between warm surface water and cooler, lower waters) to deepen in the east Pacific. This means that it is harder for the upwelling to cool the surface (because the upwelled water is now coming from the upper, warmer layer), so the east Pacific warms. Eventually, in the biggest El Niño events, the difference in temperature

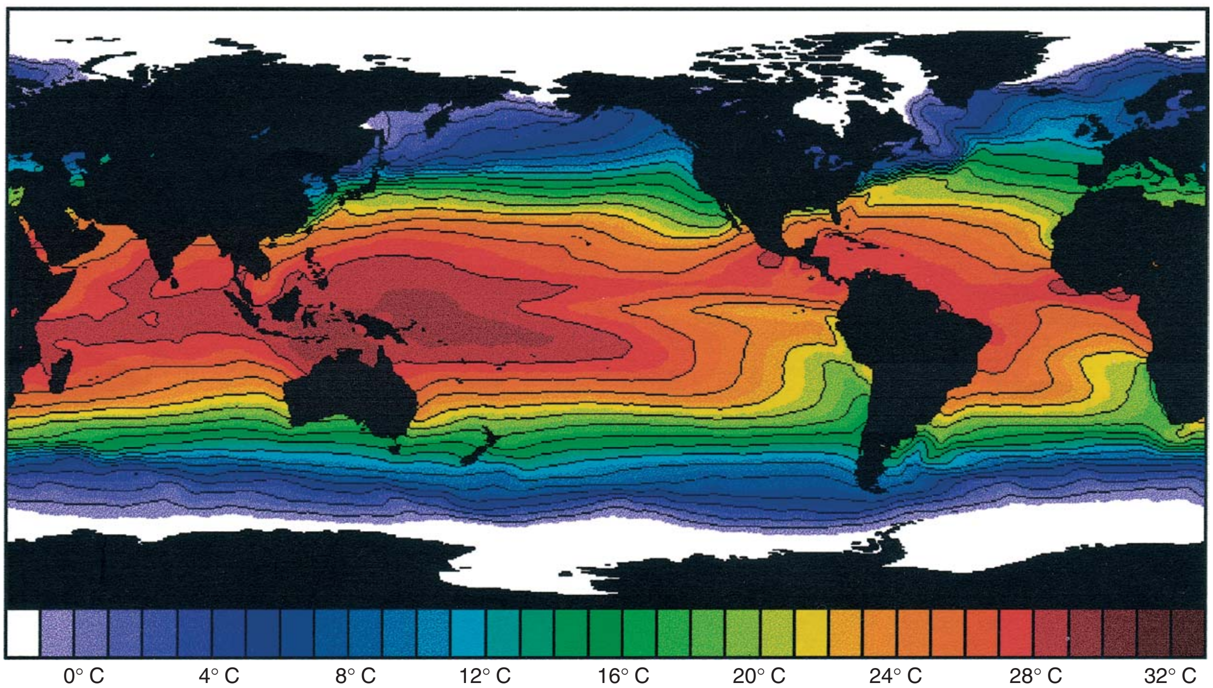

Figure 1 Climatological sea surface temperature for December. (Analysis from Bureau of Meteorology, Australia.)

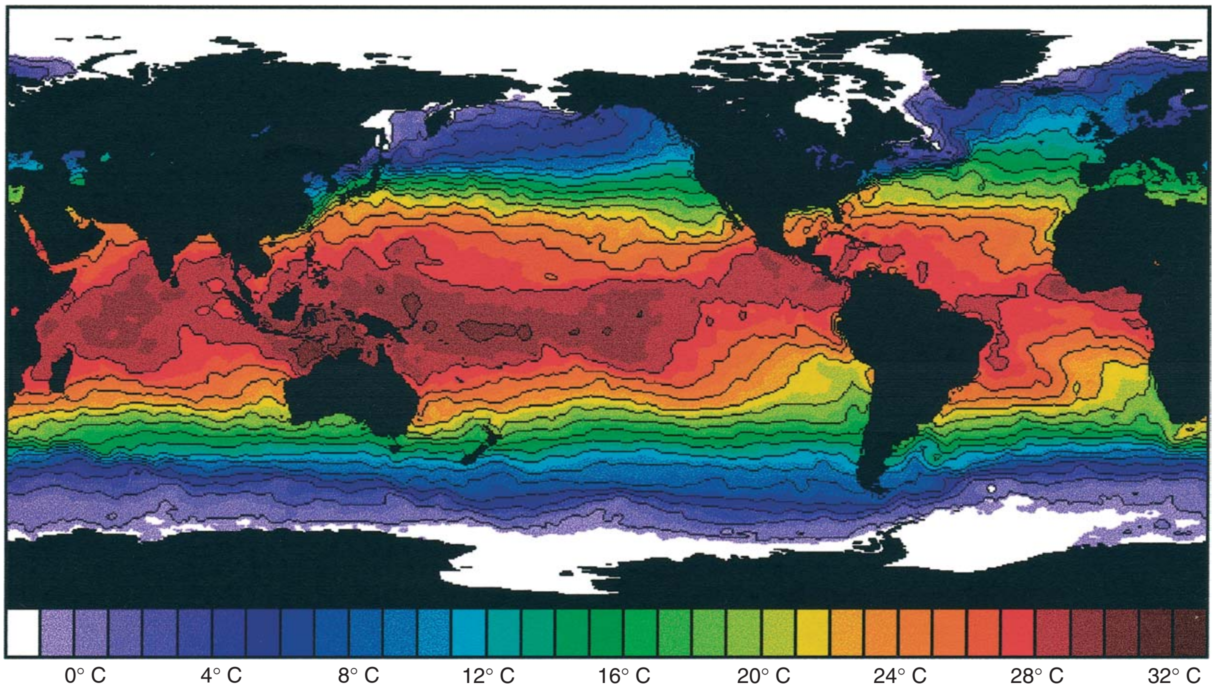

Figure 2 Sea surface temperature for 15–21 December 1997. (Analysis from Bureau of Meteorology, Australia.)

between the west and east equatorial Pacific Ocean can disappear altogether. As a result of these major changes in sea surface temperature and the surface winds, the whole pattern of climate and atmospheric circulation across the Pacific and Indian Oceans, and the surrounding continents, is disrupted, with droughts in normally wet areas and heavy rains over normally arid regions.

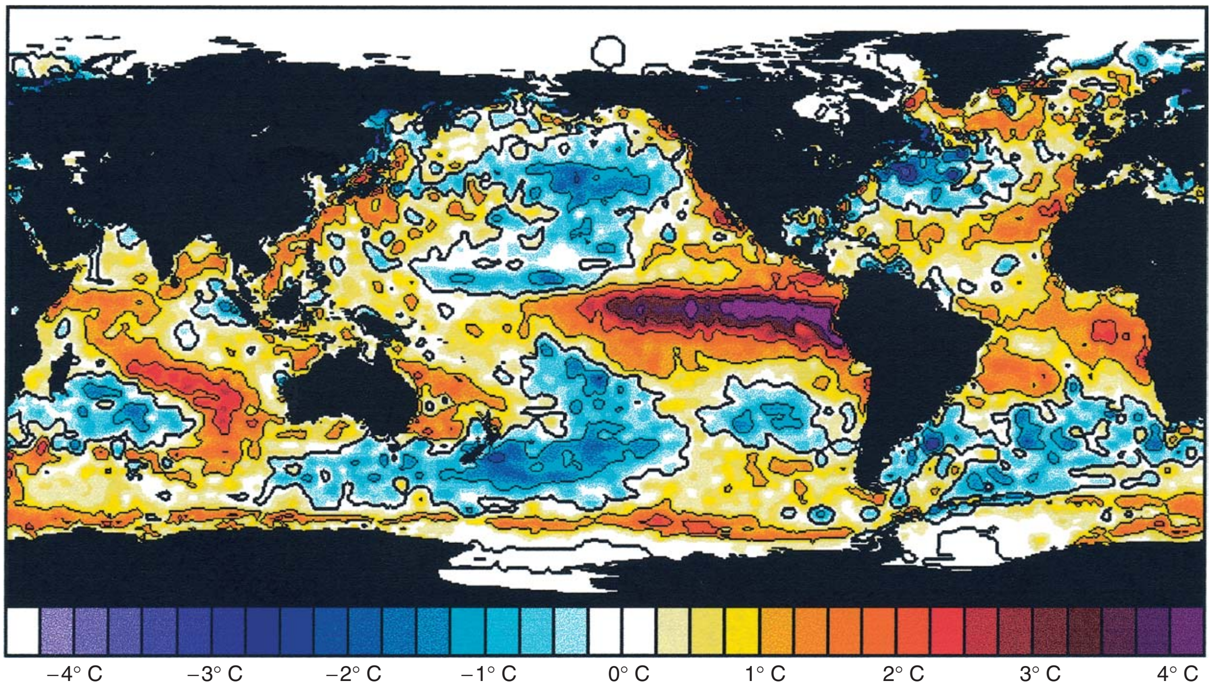

Figure 3 Sea surface temperature anomalies (deviations from climatology) for 15–21 December 1997. (Analysis from Bureau of Meteorology, Australia.)

The changes associated with the El Niño often persist for about a year and then usually collapse quite quickly. Sometimes a mirror-image pattern of climate disturbances, with flooding in Australia, India, Indonesia, northeast Brazil, and dry conditions on the Pacific coast of South America, follows. This set of conditions is called La Niña. La Niña episodes also usually last about a year or so.

As alluded to earlier, the atmospheric variations associated with El Niño and La Niña events are called the Southern Oscillation. This name derives from the observation (dating back to the time of Blanford and Todd) that, during an El Niño, atmospheric pressures are usually higher than normal over Australian and the Indian Ocean and lower than normal in the southeast Pacific. During the opposite phase, the La Niña, the pressure anomalies are reversed. So, in a sense, the atmosphere acts like a seesaw, with high or low pressures on either side of the Pacific.

We can monitor this seesaw in atmospheric pressure with the Southern Oscillation Index or SOI. This is the standardized difference in pressure between Tahiti and Darwin. When the SOI is negative, pressures are high over the Australian region and relatively low in the southeast Pacific. This is an indication that the Trade Winds are weak across the Pacific, and these weaker winds result in warm east equatorial Pacific sea surface temperatures – an El Niño. **Figure 4** shows time-series of the Darwin mean sea level pressure and sea surface temperatures in the 'cold tongue' of the east equatorial Pacific (180°–90° W, 6° N–6° S). The close relationship between the atmospheric pressure on one side of the Pacific and sea surface temperatures on the other side is clear, as is the tendency for El Niño and La Niña events to last about 12 months.

This tendency to last about 12 months means that the climate effects related to the El Niño Southern Oscillation are strongly persistent and thus predictable. This persistence is greater during the second half of the calendar year, because El Niño episodes tend to start around March–May and finish around the same time a year later. Thus, if an event is under way by midyear it is likely to persist through the second half of the year. This means that climate anomalies usually associated with the presence of an El Niño at this time can often be predicted well in advance. The tendency for El Niño events to start around March–May is illustrated in **Figure 5**, which shows east equatorial Pacific sea surface temperature anomalies during the major events of the second half of the twentieth century. In each of the five events, sea surface temperature anomalies in the east equatorial Pacific were relatively low at the start of the year, and then increased rapidly from about March, reaching a peak near the end of the calendar year. The temperature anomalies subsequently weakened over the next few months.

What Areas Does the El Niño Southern Oscillation Affect?

The pattern of climate anomalies seen in the 1877 El Niño tends to be repeated each time an El Niño occurs. The typical pattern of rainfall anomalies associated with an El Niño is shown in **Figure 6**. The figure indicates, for each area consistently affected by the El Niño, the months in which the anomalies are most consistent. The pattern of precipitation anomalies associated with the other extreme of the El Niño Southern Oscillation, the La Niña, is essentially the opposite of that depicted in **Figure 6** (i.e., where drier than normal conditions are usually experienced during an El Niño, then wetter than normal conditions can be anticipated during a La Niña episode).

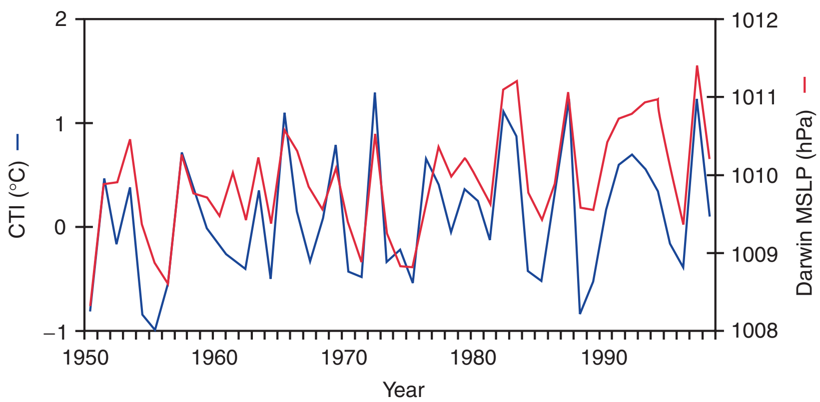

Figure 4 Time series of annual mean Darwin mean sea level pressure (MSLP) and sea surface temperature in the area 180°–90° W, 6° N–6° S ('Cold Tongue Index', CTI). (Darwin data from Bureau of Meteorology, Australia. CTI data from Todd Mitchell, JISAO, University of Washington.)

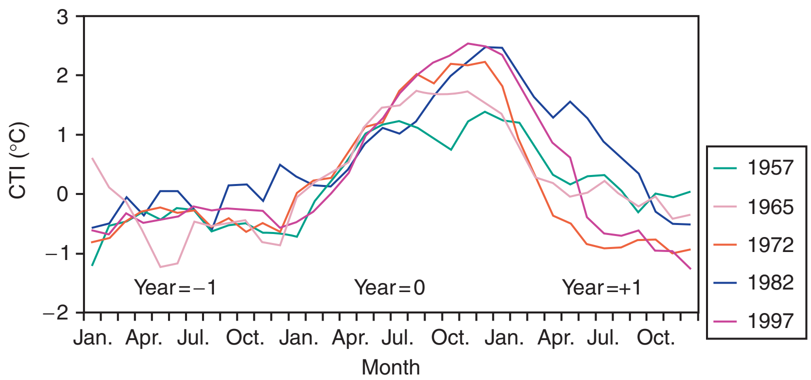

Figure 5 Time-series of monthly CTI during the major El Niño events of the second half of the twentieth century (1957, 1965, 1972, 1982, 1997). (CTI data from Todd Mitchell, JISAO, University of Washington.)

The El Niño Southern Oscillation also affects temperatures in some parts of the world. Thus in December–February at the peak of an El Niño, temperatures are usually above average throughout central and southern Africa, southern Asia, and the western Pacific, Canada, and the Pacific coasts of North and South America. The south-east of the United States tends to be cooler than average. Severe frosts can occur in places where drought accompanies an El Niño episode, such as the highlands of Papua New Guinea and inland eastern Australia.

The El Niño Southern Oscillation also affects tropical cyclones and some other weather and climate extremes. **Figure 7** is a time-series of the SOI and of the number of tropical cyclones around Australia. When an El Niño is under way (i.e., when the SOI is strongly negative), fewer than normal tropical cyclones are observed around Australia. Similarly, Atlantic hurricane activity is reduced during El Niño episodes. On the other hand, tropical cyclones are more frequent than usual in the east Pacific during these episodes.

Prehistoric Behavior of the El Niño Southern Oscillation

Instrumental records relevant to the study of the El Niño Southern Oscillation are available back into the late nineteenth century. The study of El Niño episodes prior to this depends on documentary records, and paleoclimatic (proxy) records. Documentary evidence of heavy rains and floods on the Pacific coast of South America (always associated with El Niño episodes during the instrumental era) are available from the sixteenth century. Comparisons of the dates of heavy rains and floods in South America with dates of droughts in other parts of the world have confirmed that the El Niño Southern Oscillation has been

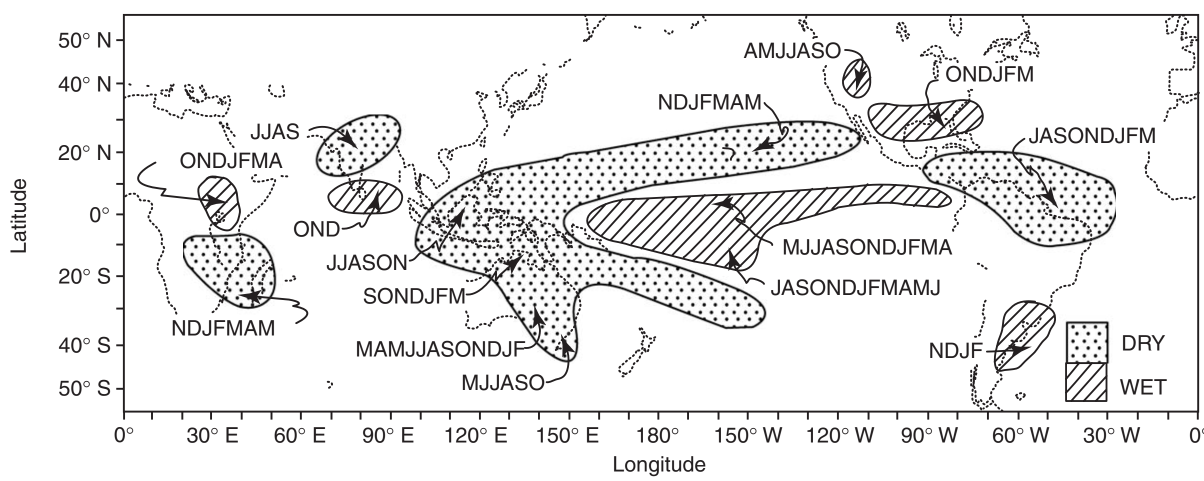

Figure 6 Schematic of areas with a consistent precipitation signal associated with El Niño events. For each region the months are shown during which it is consistently wetter or drier than normal. In each region the list of months begins in the initial year of the El Niño (year = 0). (Reprinted with permission from Cambridge University Press of Trenberth KE (1991), in Glantz *et al.* (1991).)

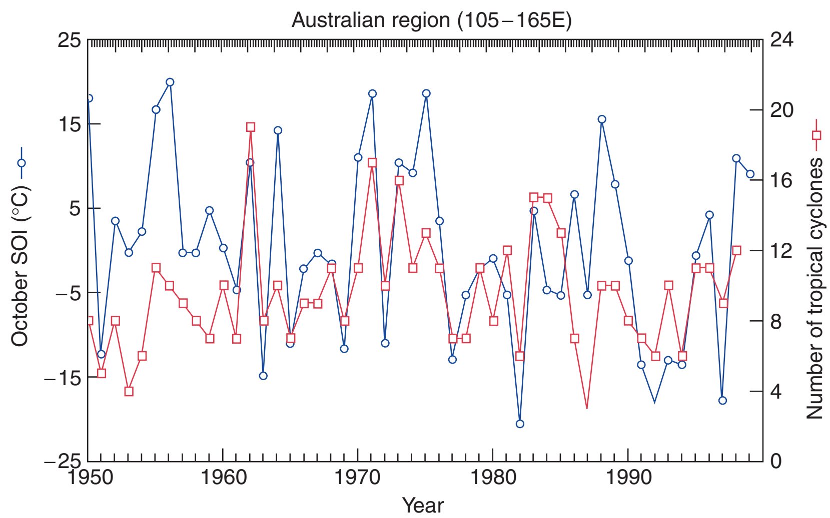

Figure 7 Time-series of the Southern Oscillation Index (SOI) (○) and the number of tropical cyclones in the Australian region (0°–15° S, 105°–165° E) (□). (Data from the Bureau of Meteorology, Melbourne, Australia.)

operating for at least hundreds of years. The teleconnections between droughts and floods in these various parts of the world have been similar throughout these five centuries, reflecting the effects of the El Niño Southern Oscillation throughout this period.

Paleoclimatic data, from corals, ice cores in glaciers, tree rings, and marine and lacustrine sediments also provide information regarding the occurrence of El Niño episodes prior to the instrumental period. This evidence, although not conclusive, suggests that El Niño episodes have been occurring for at least several thousand years.

The El Niño Southern Oscillation in the Recent Past

The prominence of the El Niño Southern Oscillation has varied through the instrumental period. Very strong El Niño episodes occurred in the first quarter of the twentieth century, with only relatively infrequent, and weak, events in the period 1925–1950. After 1950, more intense El Niño and La Niña events were observed. Since the mid-1970s, there appears to have been a shift toward more frequent, or stronger, El Niño episodes, with La Niña episodes becoming relatively infrequent. Some analyses suggest that this behavior is very unusual, given the (admittedly short) historical record.

Future Observations of the El Niño Southern Oscillation

For most of the period during which the El Niño Southern Oscillation has been monitored and studied, observations originally intended for other purposes have been the main source of information. Atmospheric pressure, rainfall, and temperature observations originally taken for the purposes of weather recording and forecasting, or to determine the 'average' climate, have been used in studies of how the phenomenon affects climate variations around the globe. Sea surface temperatures recorded by merchant and other ships have been the main source of information about the ocean variations associated with the El Niño. In recent decades, however, new and improved observations, specifically designed for climate studies, have been initiated. These include satellite observations of rainfall and sea surface temperature and sea-level, moored buoys monitoring the ocean and atmosphere in critical parts of the ocean, and subsurface analyses of the ocean thermal structure. The analysis of these new data is in its infancy, but the data have already enhanced our ability to monitor, understand, and predict the El Niño Southern Oscillation.

See also

El Niño and the Southern Oscillation: Theory. **Monsoon:** ENSO–Monsoon Interactions. **Walker Circulation**.

Further Reading

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Theory

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Introduction

The El Niño Southern Oscillation is a spectacular, planetary-scale climate phenomenon that is inherently caused by interactions between the atmosphere and the ocean. Historically, El Niño refers to unusually warm ocean temperatures that occur every 2–7 years around Christmas time along Peruvian coast, extending into equatorial eastern and central Pacific Ocean. The Southern Oscillation, named by its discoverer – Sir Gilbert Walker – on the other hand, refers to a 'seesaw' of the atmospheric pressure between the Pacific and Indian Oceans. It was not until the seminal work of Jacob Bjerknes in the late 1960s that scientists realized that these two phenomena are intimately linked. The acronym ENSO (El Niño Southern Oscillation) has now been widely used to describe this fascinating interannual climate fluctuation, emphasizing the inherent ocean–atmosphere coupling.

Although the origins of ENSO lie in the tropical Pacific, the impact of ENSO is global, owing to planetary waves of the atmosphere that redistribute vorticity from tropics to extratropics. The 'teleconnection' of ENSO can disrupt weather patterns around the globe. For this reason, ENSO has been recognized as the most important climate phenomenon at interannual time scales.

Theoretical understanding of the development and evolution of ENSO, and of underlying dynamical mechanisms for its irregular oscillation at interannual time scales, goes beyond the boundary of traditional dynamical meteorology and oceanography, because it requires knowledge about how the tropical atmosphere responds to sea surface temperature changes, how the equatorial ocean adjusts to changes in winds, and how various feedback loops between the atmosphere and ocean operate and interplay. This understanding provides the theoretical basis for the development of ENSO prediction systems, which are critical for operational seasonal-to-interannual climate forecasting.

The Southern Oscillation and Walker Circulation

From an atmospheric perspective, the Southern Oscillation can be viewed as a perturbation about a thermally driven east-to-west circulation of the tropical atmosphere across the Pacific Ocean. This circulation, known as the Walker circulation, is caused by the sharp contrast in sea surface temperature across the tropical Pacific Ocean. The western tropical Pacific contains the warmest regions of the world's ocean, known as the Western Pacific Warm Pool, where the sea surface temperature is above 28°C. In contrast, the eastern equatorial Pacific features relatively cold ocean surface waters, extending from South America coasts westward along the Equator. This is known as the Eastern Equatorial Pacific Cold Tongue, where the sea surface temperature is 5–10°C colder than the surface water of the warm pool. The warm water in the western Pacific creates low surface pressure, which causes moisture-laden air to converge into the region. The air rises and the moisture condenses in strong convective events, resulting in widespread cloudiness and heavy precipitation. The rising air descends from the upper troposphere to the surface in the Eastern Equatorial Pacific Cold Tongue as dry air. Cool temperatures result in relatively high surface pressure, divergent flow, and little rainfall. These motions – rising in the west, sinking in the east – are connected through easterly trade winds near the surface and a westerly wind aloft, forming the Walker Circulation.

Fluctuations in the position and intensity of the Walker Circulation cause the Southern Oscillation. When sea surface temperature in the eastern Pacific is warmer than normal, such as during El Niño