El Niño Southern Oscillation (ENSO)☆

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Introduction

A major El Niño began in April of 1997 and continued until May 1998. It was labeled by some as the 'El Niño of the century' as it was certainly the biggest on record by several measures. It brought with it many weather extremes and unusual weather patterns around the world. Moreover, the event was predicted by climate scientists and received unprecedented news coverage, so that the term 'El Niño' became part of the popular vernacular. Many things were blamed on El Niño, and some of them indeed were influenced by El Niño, although in some instances, the connection was, at best, tenuous. Although El Niño was relatively new to the public, it had been known to scientists, at least in some respects, for decades and even centuries.

El Niño refers to the exceptionally warm sea temperatures in the tropical Pacific, but it is linked to major changes in the atmosphere through the phenomenon known as the Southern Oscillation (SO), in particular, so that the whole phenomenon is called El Niño–Southern Oscillation (ENSO) by scientists. This article outlines the current understanding of ENSO and the physical connections between the tropical Pacific and the rest of the world.

ENSO Events

El Niños are not uncommon. Every three to seven years or so, a pronounced warming occurs of the surface waters of the tropical Pacific Ocean. The warmings take place from the International Dateline to the west coast of South America and result in changes in the local and regional ecology, and are clearly linked with anomalous global climate patterns. In 1997, the warming can be seen by comparing the sea surface temperatures (SSTs) in December 1997 at the peak of the 1997/98 event with those a year earlier (Figure 1). As well as the total SST fields, this figure also displays the departures from average.

The warmings have come to be known as 'El Niño events.' Historically 'El Niño' referred to the appearance of unusually warm water off the coast of Peru, where it was readily observed as an enhancement of the normal warming about Christmas (hence Niño, Spanish for 'the boy Christ child') and only more recently has the term come to be regarded as synonymous with the basin-wide phenomenon. The oceanic and atmospheric conditions in the tropical Pacific are seldom close to average, but instead fluctuate somewhat irregularly between the warm El Niño phase of ENSO, and the cold phase of ENSO consisting of basin-wide cooling of the tropical Pacific, dubbed 'La Niña events' ('La Niña' is 'the girl' in Spanish). The most intense phase of each event typically lasts about a year.

The SO is principally a global-scale seesaw in atmospheric sea level pressure involving exchanges of air between eastern and western hemispheres (Figure 2(a)) centered in tropical and subtropical latitudes with centers of action located over Indonesia and the tropical South Pacific Ocean (near Tahiti). Thus the nature of the SO can be seen from the inverse variations in pressure anomalies (departures from average) at Darwin (12.4°S 130.9°E) in northern Australia and Tahiti (17.5°S 149.6°W) in the South Pacific Ocean (Figure 3) whose annual mean pressures are strongly and significantly oppositely correlated. Consequently, the difference in pressure anomalies, Tahiti–Darwin, is often used as a Southern Oscillation Index (SOI). The sequences of swings in the SOI shown in Figure 3 are discussed below in conjunction with those of SST. Figure 2 also presents the surface temperature and rainfall fields associated with the sea level pressure pattern identified with ENSO.

Higher than normal pressures are characteristic of more settled and fine weather, with less rainfall, whereas lower than normal pressures are identified with 'bad' weather, more storminess and rainfall. So it is with the SO. Thus for El Niño conditions, higher than normal pressures over Australia, Indonesia, southeast Asia, and the Philippines signal drier conditions or even droughts. Dry

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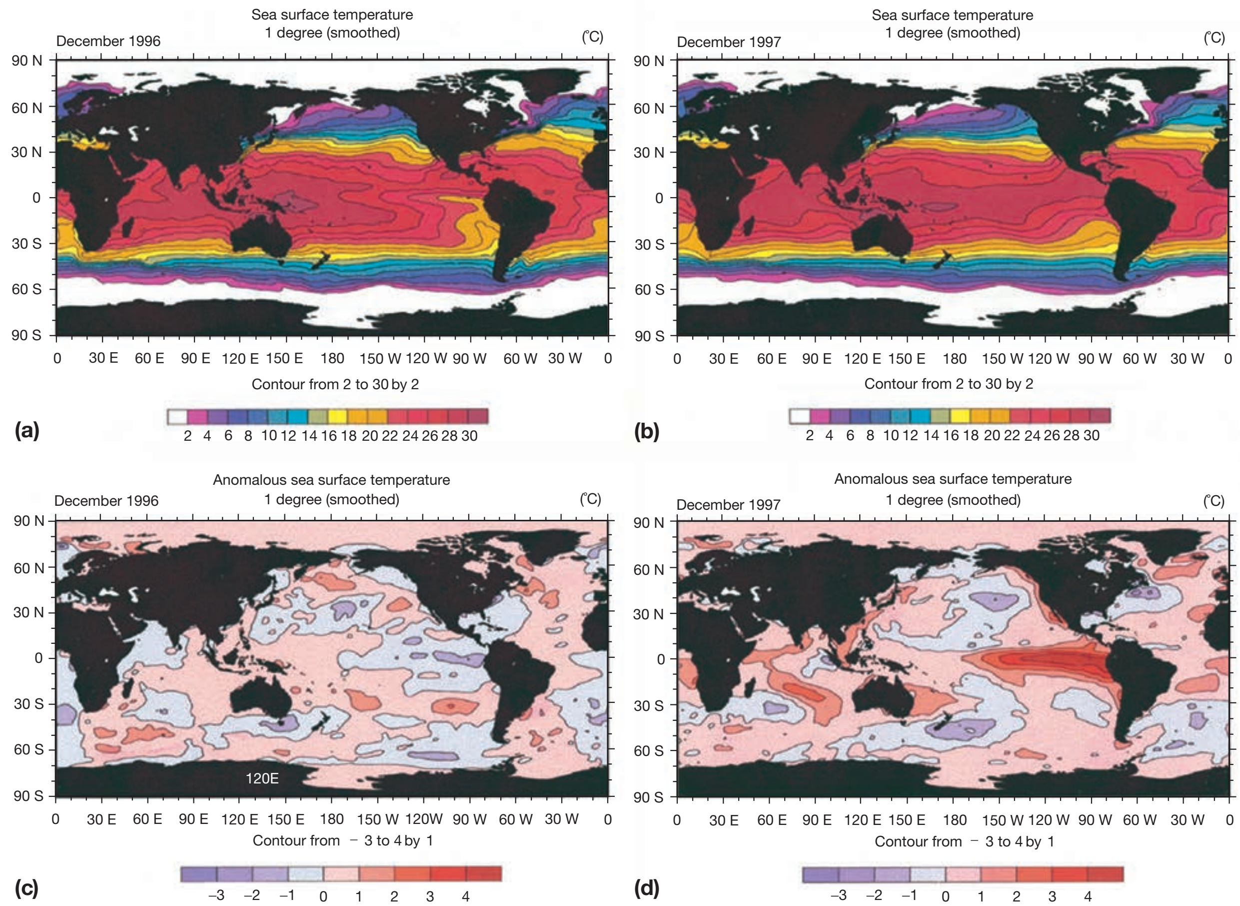

Figure 1 Monthly mean sea surface temperatures in °C for December 1996 (A, C) and 1997 (B, D), before and during the peak of the 1997–98 El Niño event. (A) and (B) show the actual SSTs and (C) and (D) show the anomaly, defined as the departure from the mean for 1950–79 with contour interval 2 °C (top) and 1 °C (bottom). Based on data from US National Oceanic and Atmospheric Administration.

conditions also prevail at Hawaii, parts of Africa, and extend to the northeast part of Brazil and Colombia. On the other end of the seesaw, excessive rains prevail over the central and eastern Pacific, along the west coast of South America, parts of South America near Uruguay, and southern parts of the United States in winter (cf. Figure 2) often leading to flooding. When the pressure pattern in Figure 2 reverses in sign, as for La Niña, the regions favored for drought in El Niño tend to become excessively wet, and vice versa.

The Tropical Pacific Ocean – Atmosphere System

The distinctive pattern of average sea surface temperatures in the Pacific Ocean sets the stage for ENSO events. The pattern in December 1996 (Figure 1) is sufficiently close to average to illustrate the main points. One key feature is the 'warm pool' in the tropical western Pacific, where the warmest ocean waters in the world reside and extend to depths of over 150 m with values at the surface >28 °C. Other key features include warm waters north of the equator from about 5 to 15°N, much colder waters in the eastern Pacific, and a cold tongue along the equator that is most pronounced about October and weakest in March. The warm pool migrates with the sun back and forth across the equator but the distinctive patterns of SST are brought about mainly by the winds (Figure 4).

The existence of the ENSO phenomenon is dependent on the east–west variations in SSTs (Figure 1) in the tropical Pacific, and the close links with sea-level pressures (Figure 2(a)) and thus surface winds in the tropics (Figure 4), which in turn determine the major areas of rainfall (Figure 2(c)). The temperature of the surface waters is readily conveyed to the overlying atmosphere and because warm air is less dense it tends to rise whereas cooler air sinks. As air rises into regions where the air is thinner, the air expands, causing cooling and therefore condensing moisture in the air, which produces rain. Low sea-level pressures are set up over the warmer waters while higher pressures occur over the cooler regions in the tropics and subtropics, and the moisture-laden winds tend to blow toward low pressure so that the air converges, resulting in organized patterns of heavy rainfall. The rain comes from convective cloud systems, often as thunderstorms, and perhaps as tropical storms or even hurricanes, which preferentially occur in

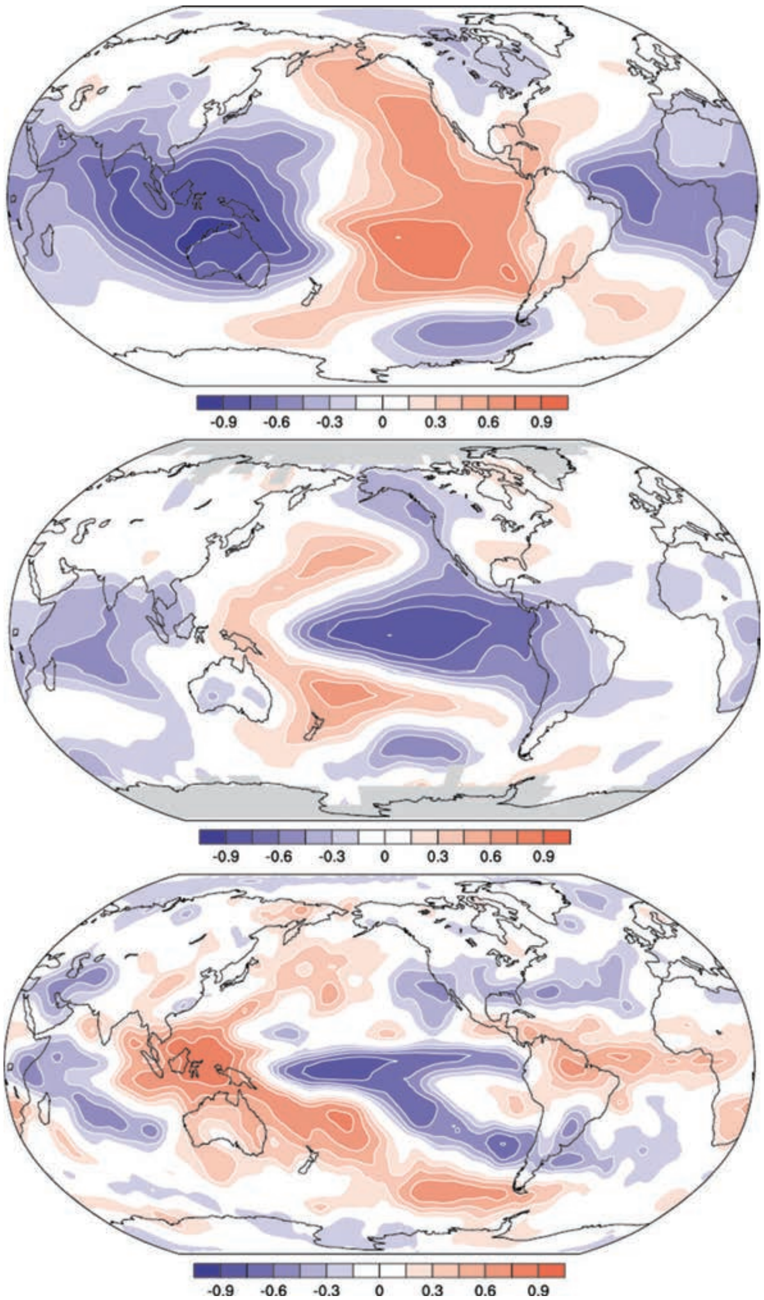

Figure 2 Correlations with the SO index (SOI), based on normalized Tahiti minus Darwin sea level pressures, for annual (May to April) means for sea level pressure (top) and surface temperature (center) for 1958–2004, and GPCP precipitation for 1979–2003 (bottom) updated from Trenberth and Caron (2000). (Reproduced from Trenberth, K.E.,Jones, P.D., Ambenje, P., Bojariu, R., Easterling, D., Klein Tank, A., Parker, D., Rahimzadeh, F., Renwick, J.A., Rusticucci, M., Soden, B. and Zhai, P. (2007) "Observations: Surface and atmospheric climate change". In Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. Climate change 2007: The physical science basis. *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press. pp. 235–336).

the 'convergence zones.' Because the wind is often light or calm right in these zones, they have previously been referred to as the 'doldrums.' Of particular note are the Intertropical Convergence Zone (ITCZ) and the South Pacific Convergence Zone (SPCZ) (Figure 5) which are separated by the equatorial dry zone. These atmospheric climatological features play a key role in ENSO as they change in character and move when SSTs change.

The rainfall patterns in the tropics can be illustrated by quantities sensed from satellite (Figure 5). There is a strong coincidence between the patterns of SSTs and tropical convection throughout the year, although there is interference from effects of nearby land

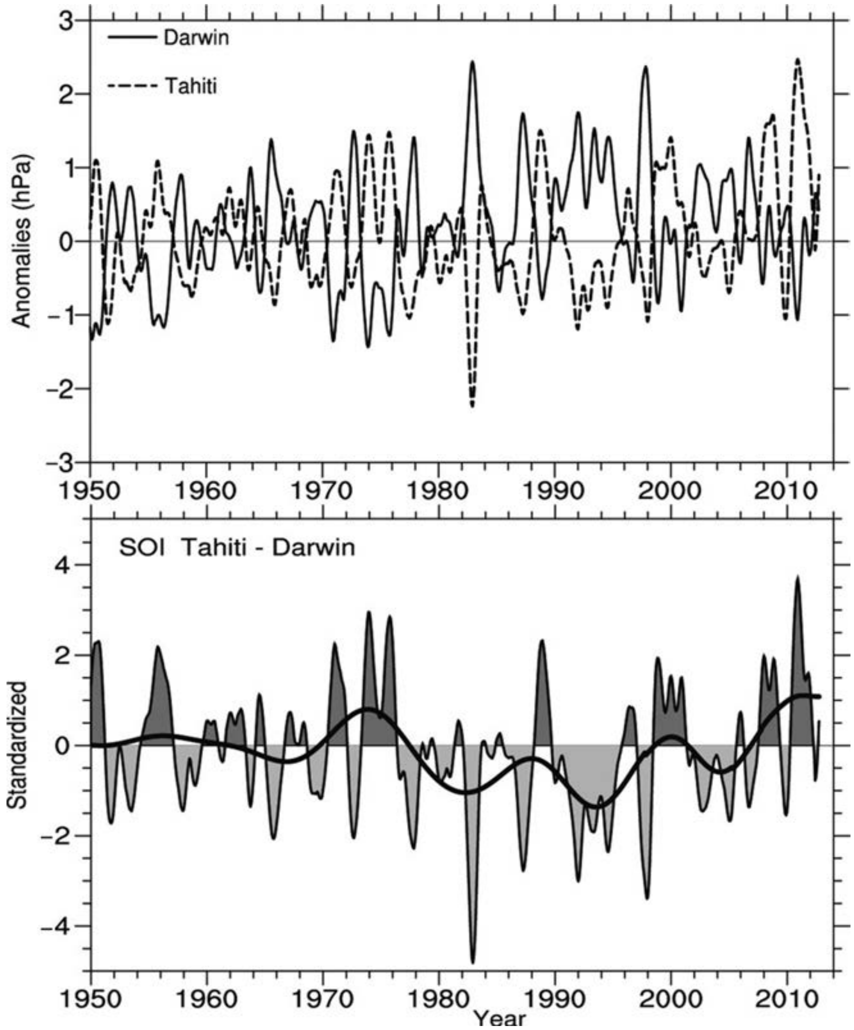

Figure 3 (A) Time series of anomalies in sea level pressures at Darwin (solid line) and Tahiti (dashed line) from 1950 to 2012 smoothed to remove fluctuations of period less than about a year. (B) Corresponding time series of the Southern Oscillation Index, normalized Tahiti minus Darwin pressures, in standardized units, along with a decadal smoothed curve.

and monsoonal circulations. The strongest seasonal migration of rainfall occurs over the tropical continents, Africa, South America and the Australian–Southeast Asian–Indonesian maritime region. Over most of the Pacific and Atlantic the ITCZ remains in the Northern Hemisphere year round, with convergence of the tradewinds favored by the presence of warmer water. In the subtropical Pacific, the SPCZ also lies over waters warmer than about 27 °C. The ITCZ is weakest in January in the Northern Hemisphere when the SPCZ is strongest in the Southern Hemisphere.

The surface winds (Figure 4) drive surface ocean currents which determine where the surface waters flow and diverge, and thus where cooler nutrient-rich waters upwell from below. Because of the Earth's rotation, easterly winds along the equator deflect currents to the right in the Northern Hemisphere and to the left in the Southern Hemisphere and thus away from the equator, creating upwelling along the equator. Thus the winds largely determine the SST distribution, the differential sea levels and the heat content of the upper ocean. The presence of nutrients and sunlight in the cool surface waters along the equator and western coasts of the Americas favors development of tiny plant species (phytoplankton), which in turn are grazed on by microscopic sea animals (zooplankton) which provide food for fish.

Temperatures in the upper ocean are measured by about 70 instrumented buoys moored to the bottom of the ocean throughout the tropical Pacific (Figure 6). Thus for December 1996 and 1997 the temperature structure throughout the equatorial region could be mapped (Figure 7). The heat content of the upper ocean depends on the configuration of the thermocline (the region of sharp temperature gradient within the ocean separating the well-mixed surface layers from the cooler abyssal ocean waters). Normally the thermocline is deep in the western tropical Pacific (150 m) and sea level is high as waters driven by the easterly tradewinds pile up. In the eastern Pacific on the equator, the thermocline is very shallow (50 m) and sea level is relatively low. The Pacific sea surface

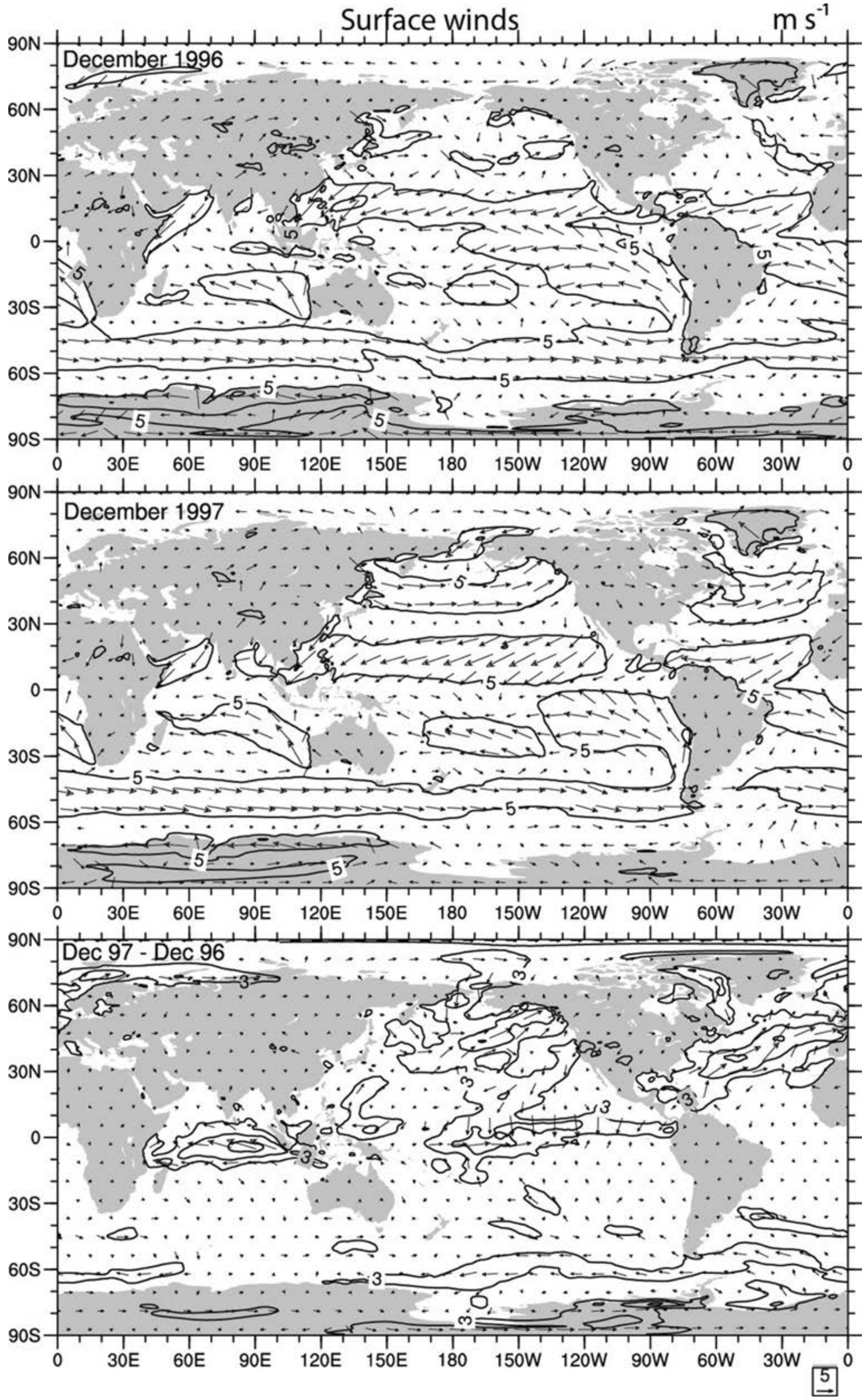

Figure 4 Mean surface winds for December 1996 (A) and 1997 (B) from global analyses by the European Centre for Medium Range Forecasts, and their difference (C). Contours are 5 m s^{-1} for (A) and (B) and 3 m s^{-1} for (C). The reference vector is plotted at bottom.

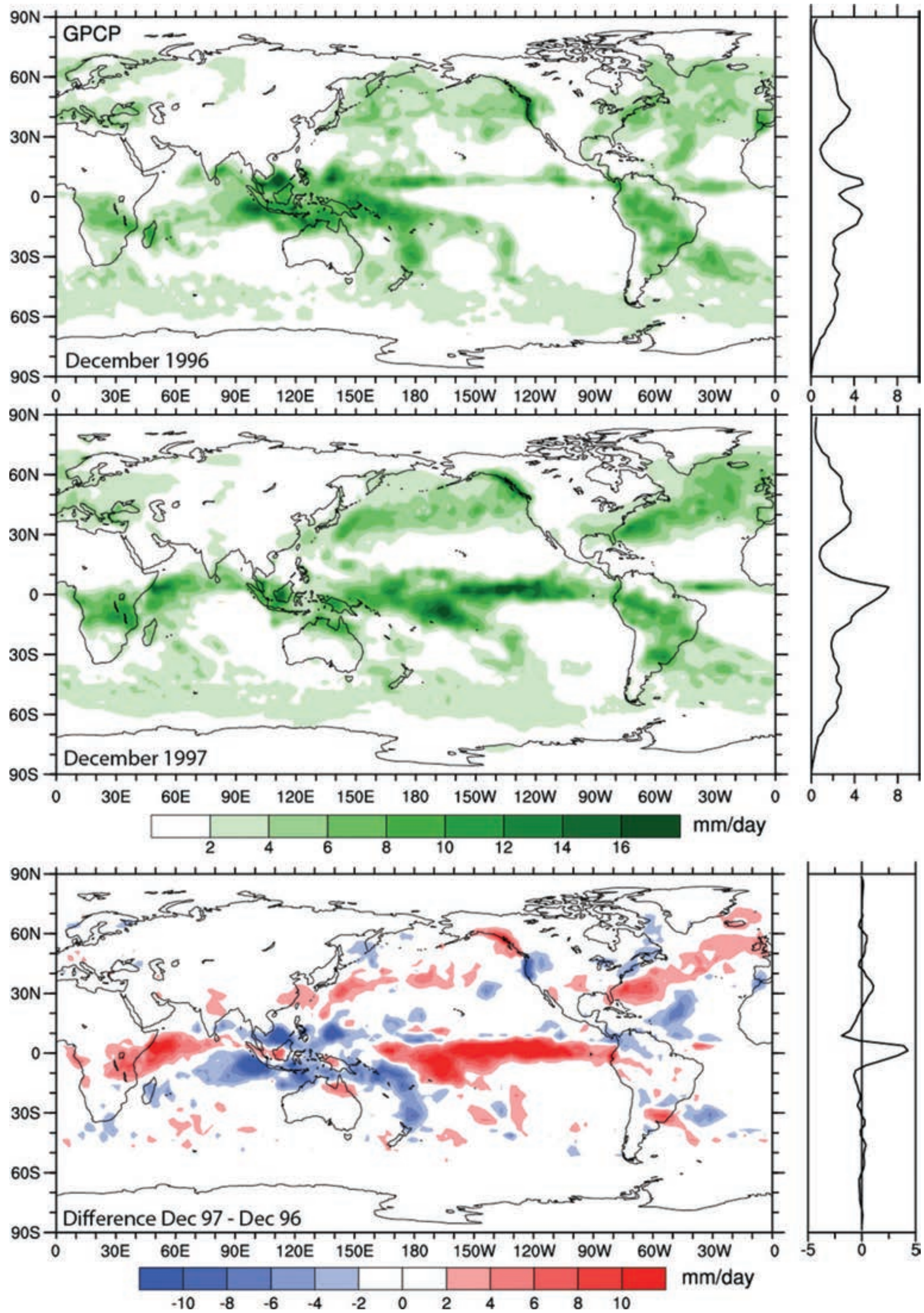

Figure 5 Mean precipitation rate (mm d^{-1}) for December 1996 (A) and 1997 (B), and the difference (C), as constructed from gauge measurements and various estimates from satellite. The zonal mean values are given at right. From Global Precipitation Climatology Project dataset.

slopes up by about 60 cm from east to west along the equator. The temperatures in December 1996 depict conditions somewhat similar to average, but with signs of the incipient El Niño developing in the western tropical Pacific at 100–150 m depth as a warm anomaly (Figure 7) but no such signs at the surface (Figure 1).

The tropical Pacific, therefore, is a region where the atmospheric winds are largely responsible for the tropical SST distribution which, in turn, is very much involved in determining the precipitation distribution and the tropical atmospheric circulation. This sets the stage for ENSO to occur.

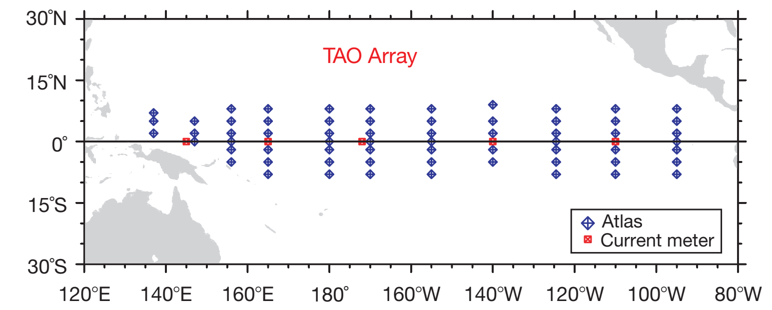

Figure 6 A center piece of the Pacific El Niño observing system is an array of buoys in the tropical Pacific moored to the ocean bottom known as the TAO/Triton (Tropical Atmosphere–Ocean) array. The latter is maintained by a multinational group spearheaded in the United States by National Oceanic and Atmospheric Administration. Each buoy has a series of temperature measurements on a sensor cable on the upper 500 m of the mooring, and on the buoy itself are sensors for surface wind, sea surface temperature, surface air temperature, humidity, and a transmitter to satellite. Observations are continually made, averaged into hourly values, and transmitted via satellite to centers around the world for prompt processing. Right, an ATLAS (Autonomous Temperature Line Acquisition System) buoy. Courtesy Pacific Marine Environmental Laboratory (NOAA).

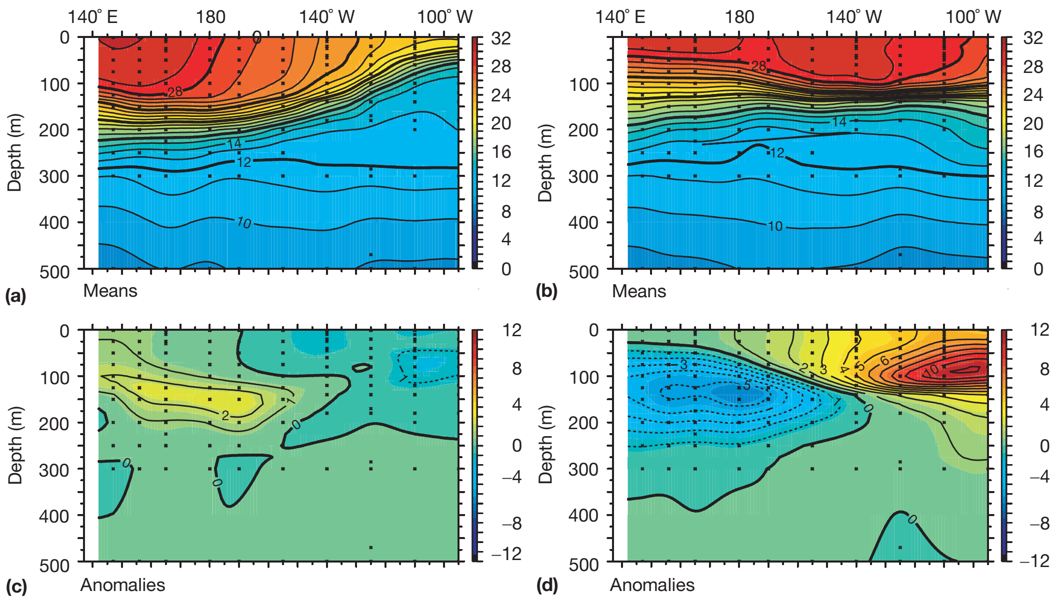

Figure 7 Zonal cross sections along the equator across the Pacific Ocean (2°N to 2°S) from the TAO array temperatures for December 1996 (A, C) and 1997 (B, D). (A, B) total field; (C, D) anomalies. Contours every 1 °C.

Mechanisms of ENSO

Most of the interannual variability in the atmosphere in the tropics and a substantial part of the variability over the extratropics is related and tied together through ENSO. ENSO is a natural phenomenon arising from coupled interactions between the atmosphere and the ocean in the tropical Pacific Ocean, and there is good evidence from cores of coral and glacial ice in the Andes that it has been going on for millennia.

During El Niño, the tradewinds weaken (Figure 4) which causes the thermocline to become shallower in the west and deeper in the eastern tropical Pacific (Figure 7), while sea level falls in the west and rises in the east by as much as 25 cm as warm waters surge eastward along the equator. Equatorial upwelling decreases or ceases and so the cold tongue weakens or disappears (e.g., as in December 1997, Figure 1) and the nutrients for the food chain are substantially reduced. The resulting increase in sea temperatures (e.g., Figure 1) warms and moistens the overlying air so that convection breaks out, and the convergence zones and associated rainfall move to a new location with a resulting change in the atmospheric circulation (Figure 5). A further weakening of the surface trade winds completes the positive feedback cycle leading to an El Niño event. The shifts in the location of the organized rainfall in the tropics and the latent heat released alters the heating patterns of the atmosphere. Somewhat like a rock in a stream of water, the anomalous heating sets up waves in the atmosphere that extend into midlatitudes altering the winds and changing the jet stream and storm tracks (e.g., Figure 8). Note especially the strong westerly jets in the Pacific of both hemispheres, and in the Northern (winter) Hemisphere the jet stream in December 1997 extends into California and across the southern United States, carrying with it disturbances that result in extensive rains. Weaker westerlies exist farther north and so the overall storm track shifts towards the equator in the Pacific.

Although the El Niños and La Niñas are often referred to as 'events' which last a year or so, ENSO is oscillatory in nature. The ocean is a source of moisture and its enormous heat capacity acts as the flywheel that drives the system through its memory of the past, resulting in an essentially self-sustained sequence in which the ocean is never in equilibrium with the atmosphere. The amount of warm water in the tropics builds up prior to and is then depleted during El Niño. During the cold phase with relatively clear skies, solar radiation heats up the tropical Pacific Ocean, the heat is redistributed by currents, with most of it being stored in the deep warm pool in the west or off the equator such as at about 10 or 20°N. During El Niño, heat is transported out of the tropics within the ocean toward higher latitudes in response to the changing currents, and increased heat is released into the atmosphere mainly in the form of increased evaporation, thereby cooling the ocean. Added rainfall contributes to a general warming of the global atmosphere that peaks a few months after a strong El Niño event. It has therefore been suggested that the time scale of ENSO is determined by the time required for an accumulation of warm water in the tropics to essentially recharge the system, plus the time for the El Niño itself to evolve. Thus a major part of the onset and evolution of the events is determined by the history of what has occurred one to two years previously. This also means that the future evolution is predictable for several seasons in advance.

Interannual Variations in Climate

The subsurface temperature anomalies which eventually developed into the 1997–98 El Niño were traceable at least from about September 1996 on the equator in the far western Pacific. However, positive subsurface temperature anomalies in the upper 100–200 m in the far western Pacific exceeded 1 °C for all the months of 1996, and so this was not a sufficient predictor. By December 1996 (Figure 7) subsurface temperature anomalies in the vicinity of the equator had grown to exceed 2.5 °C at 150 m depth and the warm anomaly extended from at least 140°E (the westernmost buoy) to 140°W. However, conditions were still below normal in the eastern Pacific. By December 1997, the subsurface warm anomaly had progressed eastward and amplified to produce positive anomalies exceeding 11 °C (Figure 7) at about 100 m depth, accompanying the surface SST anomalies exceeding 5 °C (Figure 1). Also note, however, in December 1997 the subsequent cold anomaly of over 5 °C in the western equatorial Pacific near 150 m depth, as the warm pool was displaced into the central Pacific. The warm pool in the east continued to diminish with time as the cold anomaly intensified and subsequently spread all the way across the Pacific as part of the signature of the La Niña that began about June 1998, although it did not develop to a fully fledged event until later in the year. A key aspect of these changes was the obvious loss of heat content throughout the equatorial Pacific beginning late 1997 and continuing through 1998.

The evolution of SST in several recent ENSO events after 1950 is shown in Figure 9 for two regions. The region of the Pacific Ocean which is most involved in ENSO is the central equatorial Pacific, especially the area 5°N to 5°S, 170°E to 120°W, whereas the traditional El Niño region is along the coast of South America. The latter is less important for the global changes in weather patterns but is certainly important locally. Variations in both regions are closely related but differ in detail from event to event in relative amplitudes and sequencing. For SSTs, the departure from average required for an El Niño is 0.5 °C over the central Pacific region, which is large enough to cause perceptible effects in Pacific rim countries. Larger El Niño events have traceable influences over more extensive regions and even globally.

The ENSO events clearly identifiable in Figure 9 since 1950 occurred in 1951, 1953, 1957–58, 1963, 1965, 1969, 1972–73, 1976–77, 1982–83, 1986–87, 1990–95, 1997–98, 2002–03, 2004–05, 2006–07 and 2009–10. The 1990–95 event might also be considered three modest events where the conditions in between failed to return to below normal so that they merged together. Worldwide climate anomalies lasting several seasons have been identified with all of these events. The 1997–98 event has the biggest SST departures on record, but for the SOI, the El Niño event of 1982–83 still holds the record (Figure 3).

Each El Niño event has its own character. In the El Niño winters of 1992–93, 1994–95, and 1997–98, southern California was battered by storms and experienced flooding and coastal erosion (in part aided by the high sea levels). However, in more modest El Niños (e.g., 1986–87 and 1987–88 winters) California was more at risk from droughts. Because of the enhanced activity in the Pacific and the changes in atmospheric circulation throughout the tropics, there is a decrease in the number of tropical storms and hurricanes in the tropical Atlantic during El Niño. A good example is 1997, one of the quietest Atlantic hurricane seasons on record, whereas the 1990–95 and 1997–98 El Niños terminated before the 1995 and 1998 hurricane seasons which unleashed the Atlantic storms and placed those seasons among the most active on record.

The SO has global impacts, however; the connections to higher latitudes (known as teleconnections) tend to be strongest in the winter of each hemisphere and feature alternating sequences of high and low pressures accompanied by distinctive wave patterns in the jet stream (Figure 8) and storm tracks in mid-latitudes. Although warming is generally associated with El Niño events in the Pacific and extends, for instance, into western Canada and Alaska, cool conditions typically prevail over the North and South Pacific Oceans. To a first approximation, reverse anomaly patterns occur during the La Niña phase of the phenomenon.

The prominence of the SO has varied throughout the last century (Figure 10). Very slow long-term (decadal) variations are present; for instance SOI values are mostly below the long-term mean from 1976 to 1998. This accompanies the generally above

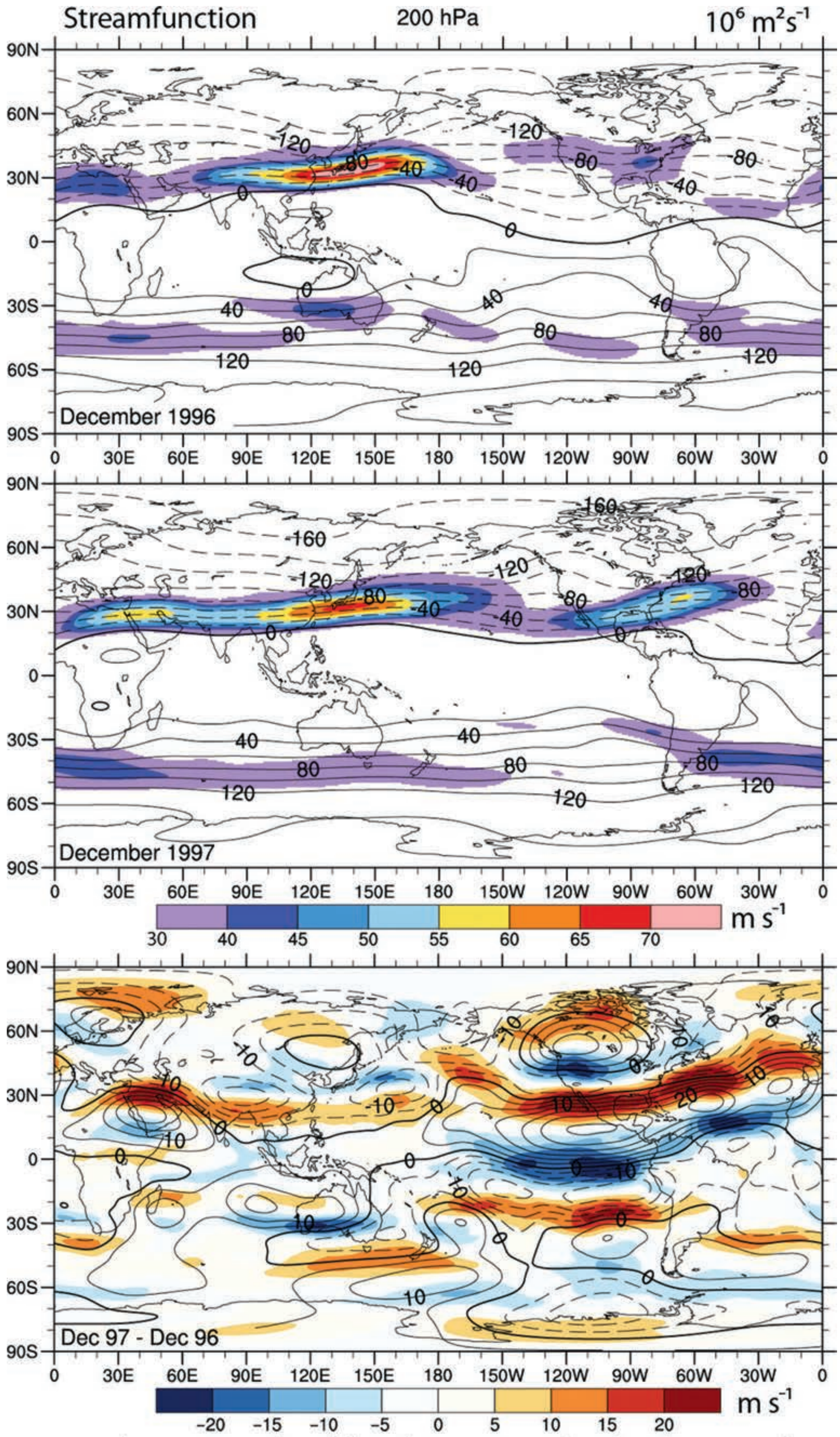

Figure 8 Flow patterns (winds) at the jet stream level, 10 km or so above the surface of the Earth, for December 1996 (A) and 1997 (B), and their differences (C) based on global analyses by the European Centre for Medium Range Prediction. The contours are stream-lines at the 200 hPa level and the region where winds exceed 30 m s^{-1} (5 m s^{-1} for (C)) are colored to indicate the jet streams. El Niño conditions favor a more vigorous jet stream and storm track from the Pacific to the Gulf of Mexico, bringing heavy rains to the southern United States. Note similar effects in the South Pacific from South America to New Zealand.

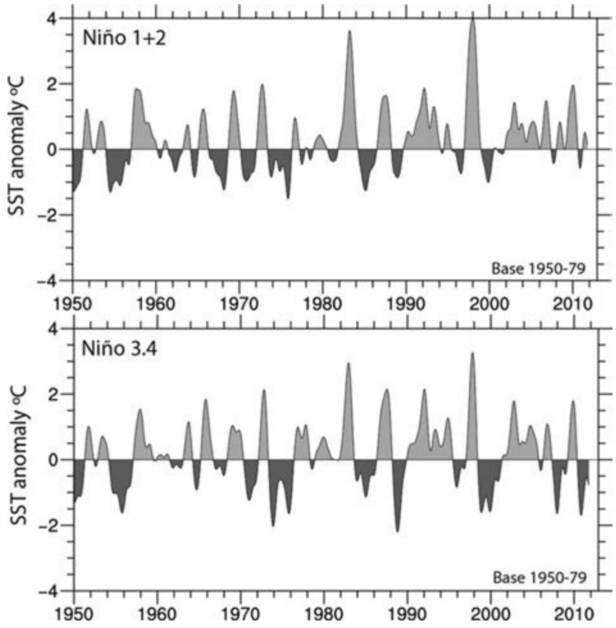

Figure 9 Time series of sea surface temperature (SST) anomalies from 1950 through 1912 relative to the means of 1950–79 for (A) the traditional El Niño area: 0°–10°S 90°W–80°W, and (B) the region most involved in ENSO 5°N–5°S, 170°E–120°W.

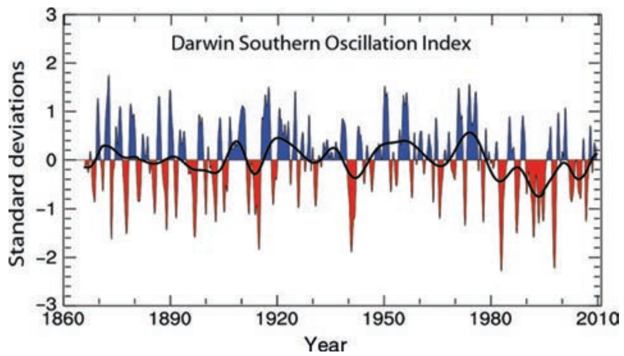

Figure 10 Time series of the Southern Oscillation Index (SOI) based solely on observations at Darwin from 1866 to 2009. Red values indicate positive sea level pressure anomalies at Darwin and thus El Niño conditions. Also shown in a curve designed to show the multidecadal fluctuations. The zero corresponds to the mean for the first 100 years 1866 to 1965, highlighting the trend for more El Niños from 1976 to 1998. (Reproduced from Trenberth, K.E.,Jones, P.D., Ambenje, P., Bojariu, R., Easterling, D., Klein Tank, A., Parker, D., Rahimzadeh, F., Renwick, J.A., Rusticucci, M., Soden, B. and Zhai, P. (2007) "Observations: Surface and atmospheric climate change". In Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. Climate change 2007: The physical science basis. *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press. pp. 235–336).

normal SSTs in the western Pacific along the equator (Figure 9). The decadal atmospheric and oceanic variations are even more pronounced in the North Pacific and across North America than in the tropics and are also clearly present in the South Pacific, with evidence suggesting that they are at least in part forced from the tropics. Although not yet clear in detail, it is likely that climate change associated with increased greenhouse gases in the atmosphere, which contribute to global warming, are changing ENSO, perhaps by expanding the west Pacific warm pool.

The character of recent ENSO events seems to be different than before 1976, and several have had a lot more activity in the central Pacific, in which the traditional coastal temperature anomaly is not affected, but an anomaly arises in the central Pacific (Nino 3.4), called El Niño Modoki. Modoki is Japanese for "similar, but different." However, this pattern is part of the evolution of ENSO, and it is unclear whether this is simply part of the continual variety: the different flavors of El Niño, or whether it might be part of a climate change signal.

Impacts

Changes associated with ENSO produce large variations in weather and climate around the world from year to year and often these have a profound impact on humanity because of droughts, floods, heat waves and other changes which can severely disrupt agriculture, fisheries, the environment, health, energy demand, and air quality, and also change the risks of fire. The normal upwelling of cold nutrient-rich and CO_2-rich waters in the tropical Pacific is suppressed during El Niño. The presence of nutrients and sunlight fosters development of phytoplankton and zooplankton to the benefit of many fish species. Therefore El Niño-induced changes in oceanic conditions can have disastrous consequences for fish and seabirds and thus for the fishing and guano industries, for example, along the South American coast. Other marine creatures may benefit so that unexpected harvests of shrimp or scallops occur in some places. Rainfall over Peru and Ecuador can transform barren desert into lush growth and benefit some crops, but can also be accompanied by swarms of grasshoppers, and increases in the populations of toads and insects. Human health is affected by mosquito-borne diseases such as malaria, dengue, and viral encephalitis, and by water-borne diseases such as cholera. In Africa, Rift Valley fever outbreaks may occur.

Economic impacts can be large, with losses typically overshadowing gains. One assessment placed losses during the 1997–98 El Niño event at over US$34 billion, although it did not account for the widespread human suffering and loss of life. An estimate of the economic loss of production in Queensland, Australia due to drought in the prolonged warm ENSO phase from 1990 to 1995 was $1 billion (Australian) per year. The La Niña in 1988 was linked to the extensive, severe, and persistent 1988 North American spring–summer drought, which brought losses of over US$40 billion, as well as major climate anomalies elsewhere over the globe. (The $40 billion is in 1988, which would be $78 billion in 2013).

ENSO also plays a prominent role in modulating carbon dioxide exchanges with the atmosphere. The decrease in outgassing of CO_2 during El Niño is enough to reduce the buildup of CO_2 in the atmosphere by 50%. El Niño also influences the incidence of fires, which result in more CO_2 emissions, while changing rainfall and temperatures over land through the teleconnections, such that CO_2 uptake by the terrestrial biosphere is enhanced.

In 1997, the strongest drought set in over Indonesia and led to many fires, set as part of activities of farmers and corporations clearing land for agriculture, raging out of control. With the fires came respiratory problems in adjacent areas 1000 km distant and even a commercial plane crash in the area has been linked to the visibility problems. Subsequently in 1998, El Niño-related drought and fires evolved in Brazil, Mexico and Florida. Flooding took place in Peru and Ecuador, as usual with El Niño, and also in Chile, and coastal fisheries were disrupted. The strong winter 1997–98 Northern Hemisphere jet stream created wet conditions from California to Florida. Normally these storms veer to the north toward the Gulf of Alaska or enter North America near British Columbia and Washington, where they could subsequently link up with the cold Arctic and Canadian air masses and bring them down into the United States. Instead, the pattern was persistently favorable for relatively mild conditions over the northern states such that temperatures averaged over 10 °C (18 °F) above normal in February in the Great Lakes area. Similar changes occurred in the Southern Hemisphere and spread downstream to South America. Globally, it seems that the land temperature for February 1998 was relatively higher than average than for any other month on record. The calendar year 1998 was the warmest year on record – going back 1000 years – beating 1997, in no small part because of the El Niño influences in both those years. Only recently, in 2005 and 2010, has this value been exceeded.

ENSO and Seasonal Predictions

The main features of ENSO have been captured in models, in particular in simplified models which predict the anomalies in SSTs. Lead times for predictions in the tropics of at least six months have been shown to be practicable. For instance, an El Niño was predicted for 1997 in late 1996 and it began in April 1997. However, its full extent was not predicted accurately until about mid-1997, about 6 months in advance. Further improvements in the climate observing system and more realistic and comprehensive models provide prospects for further advances.

It is already apparent that reliable prediction of tropical Pacific SST anomalies can lead to useful skill in forecasting rainfall anomalies in parts of the tropics. Although there are certain common aspects to ENSO events in the tropics, the effects at higher latitudes are more variable. One difficulty is the vigor of weather systems in the extratropics which can override relatively modest ENSO influences from the tropics. Nevertheless, systematic changes in the jet stream and storm tracks do tend to occur on average, thereby allowing useful predictions to be made in some regions, although with some inherent uncertainty, so that the predictions are couched in terms of probabilities.

Skillful seasonal predictions of temperatures and rainfalls have the potential for huge benefits for society, although because the predictability is somewhat limited, a major challenge is to utilize the uncertain forecast information in the best way possible throughout different sectors of society (e.g., crop production, forestry resources, fisheries, ecosystems, water resources, transportation, energy use). The utility of a forecast may vary considerably according to whether the user is an individual versus a group or country. An individual may find great benefits if the rest of the community ignores the information, but if the whole community adjusts (e.g., by growing a different crop), then supply and market prices will change, and the strategy for the best crop yield may differ substantially from the strategy for the best monetary return. On the other hand, the individual may be more prone to small-scale vagaries in weather that are not predictable. Vulnerability of individuals will also vary according to the diversity of the operation: whether there is irrigation available, whether the farmer has insurance, and whether he or she can work off the farm to help out in times of adversity.

Further Reading

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