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been identified as a central ingredient of ocean-atmosphere fluctuations responsible for year-to-year variability of climate over the world as a whole.

The low-level atmospheric winds in the Equatorial Pacific are the link between the Southern Oscillation pressure seesaw and changes in the ocean related to El Niño warmings Under normal conditions, the tradewinds over the northeast and southeast Pacific converge just north of the equator, along a line called the Intertropical Convergence Zone (ITCZ) From here, the air moves westward near the equator into a semi-permanent low-pressure region in the vicinity of Indonesia. When the Southern Oscillation Index (Tahiti-minus-Darwin pressure difference) is high, the east-west pressure gradient along the equator increases, and the westward flow of air intensifies. This persistent westward flow of air literally drags the surface

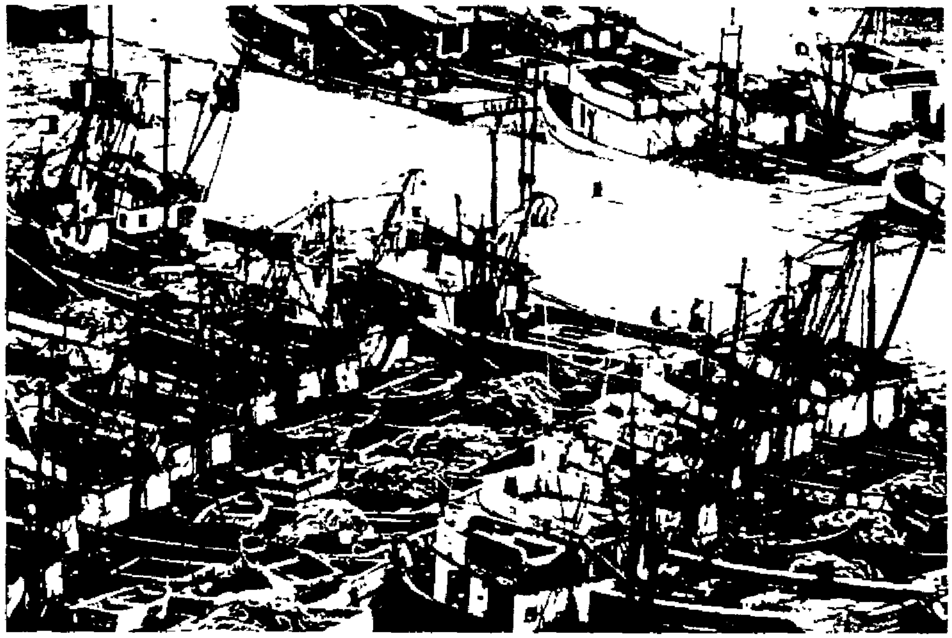


Figure 1. The warm Pacific waters have caused fish to seek new feeding areas, idling the anchovy fleets of Peru and Ecuador. (NOAA Photo)

El Niño: The Global Weather Connection

El Niño is the name given to a general warming of the surface waters of the tropical eastern Pacific Ocean that happens at irregular intervals of years (see the accompanying article by Eugene Rasmusson and Michael Hall). Its cause is not known. But El Niño events are intimately connected with the "flop" side of a flip-flop of atmospheric circulation of the tropical Pacific known as the Southern Oscillation. Probably El Niño and the Southern Oscillation are two different manifestations of a joint large-scale ocean-atmosphere interaction that takes several years to run its course Presumably it is the ocean part of the interaction that causes it to cycle so slowly. We know that the ocean moves much more ponderously than the atmosphere and takes many months, or years, to reverse its circulation once established in a given direction. This helps explain the survival of the excess warmth in the tropical eastern Pacific surface water for as long as a year after an El Niño event first develops

During the time the elevated ocean temperatures of an El Niño persist, enormous amounts of additional heat and moisture are added to the atmosphere by evaporation to the overlying air. This is tantamount to shoveling extra coal into the firebox of the global atmospheric heat engine, speeding up the tropical jetstream winds and providing the raw material for additional storminess and rainfall, mainly over the Western Hemisphere but perhaps stretching eastward across the Atlantic as well. By this reasoning the rather miserably wet weather that beset the sunbelt of the United States this past winter and spring along with a host of other weather anomalies, among them the huge mountain snowpack that has recently brought the Colorado River to flood stage, can be traced back to the strong El Niño event of recent months.

In fact, many meteorologists who are in the business of trying to puzzle out—and to predict—long-range weather tendencies around the world have fingered El Niño as the cause of such recent happenings

The chart on page 169 gives one indication of the extraordinary geographical reach of the effects of unusual weather conditions in the tropical Pacific Ocean associated with the Southern Oscillation and El Niño. This chart shows the statistical correlation of atmospheric pressure variations over the world with a measure of the variations of the Southern Oscillation Index explained by Rasmusson and Hall. It indicates that there is virtually no place on Earth where the weather is indifferent to air and ocean conditions in the tropical Pacific: the Southern Oscillation and El Niño events associated with it are now understood to have a significant influence on the state of weather and climate almost everywhere. This fact is already being used as a valuable tool in the hands of long-range weather forecasters in many nations of the world. Should it turn out that El Niño events and the flip-flops of the Southern Oscillation can be predicted a year or more ahead, as many meteorologists believe eventually they can, better long-range forecasts of weather and climate throughout the world would follow.

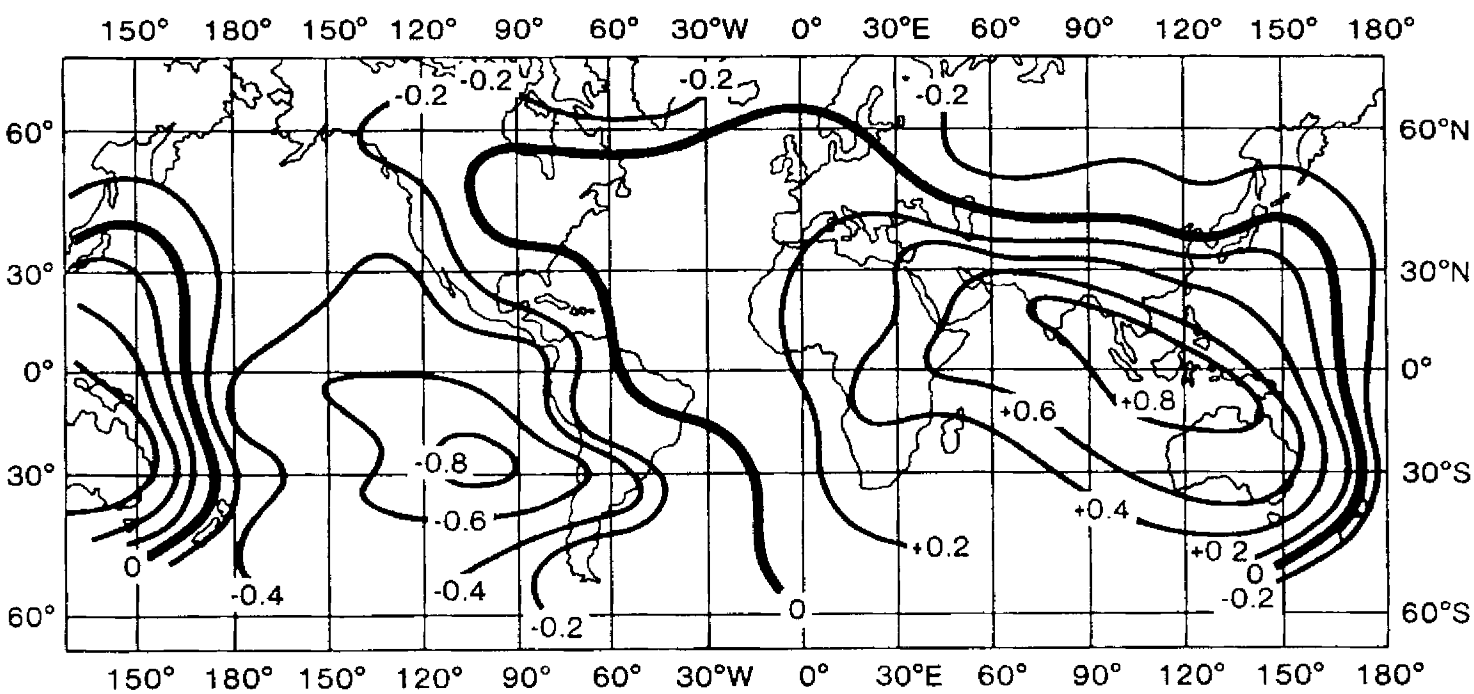
—J. M. M

water to the west. The result is a rise of sea level in the western Pacific and a lowering of sea level in the eastern Pacific The oceanic "thermocline," which separates the warm, mixed layer of the upper ocean from the colder water below, slopes in the opposite direction, giving rise to a thick layer of warm surface water in the west, and a shallow layer of warm water in the east. The shallowness of the warm surface layer in the east allows the upwelling of deep water, rich in nutrients, that normally supports a major fishery industry off the Ecuador-Peru coast.

Reversing Winds

With a falling Southern Oscillation Index, pressure rises over the Indonesian region. The pressure gradient along the equator decreases, and, in the case of unusually strong events such as of the past several months, actually reverses The equatorial easterly winds in the western Pacific diminish, then change direction so that they become westerly winds. The resulting reversal in the direction of the wind drag on the ocean surface, which normally persists for a period of several months, sets in motion a complex dynamical response in the ocean, resulting in major changes in the equatorial current system and a return to a more horizontal east-west slope in sea level. The oceanic readjustment involves both rapid (weeks-long) and slower (months or seasons-long) components. Oceanographers believe that an internal oceanic perturbation called a Kelvin wave plays a role in the adjustment process and in the initiation of an El Niño event. Such an underwater wave when initiated in the western or central Pacific by a change in the winds there, will travel eastward along the equator at a speed of a few meters per second, reaching the South American coast several weeks later. According to some oceanographers, the arrival at the South American Coast of one (or more) of these slowly moving sub-surface waves results in a thickening of warm surface water layer there, which helps to choke off the upwelling of deeper, colder water and to bring about El Niño conditions

Figure 4 shows the history of the Southern Oscillation Index since 1968. The minima in 1969, 1972, and 1976–77 reflect three previous El Niño episodes By early 1982, the index started to fall, showing a precipitous drop between May and June and then a further drop to record low values later in the year. The wind field changes in the western equatorial Pacific were equally remarkable, as shown in Figure 5 The easterly winds in that area collapsed between May and June of 1982, and by July the average flow over the area had changed to westerly and was to remain



The global pattern of the coefficient of correlation between variations of barometric pressure at Jakarta, Indonesia, and those at other locations throughout the world. Jakarta pressure is a faithful indicator of the Southern Oscillation. The pattern shown here is based on data in the form of annual averages of sea-level pressure in each of a large number of years. Patterns based on data for different seasons of the year or on data for different periods of years are rather similar to this one. The map is derived from a 1967 publication by H. P. Berlage of The Netherlands.

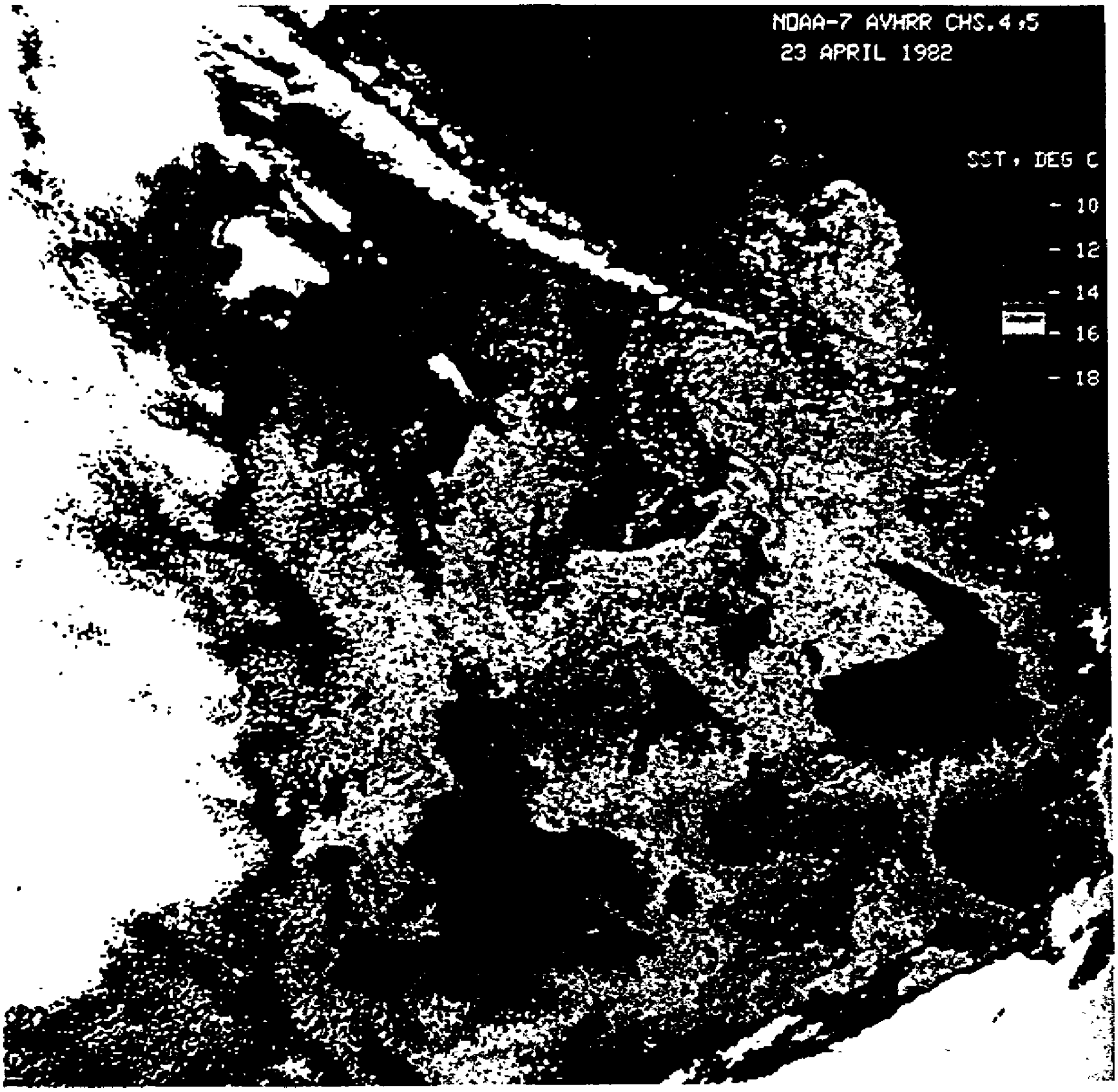


Figure 2. Sea surface temperatures in false-color images from the NOAA-7 satellite on April 23, 1982. The black area to the upper right of the figure is the southern coast of California. The dark blues and purples are in the range of 10°C, the reds around 18°C. The white portions of the picture are cloud cover.

from that direction until December. The strength of the westerly winds in 1982, which far exceeded that recorded at any earlier time during the previous decade, was associated with a dramatic shift in the large-scale precipitation regime of the tropical Pacific. Normally, precipitation is concentrated in the South Pacific Convergence Zone (SPCZ) which extends from around New Guinea southeastward across the dateline. As a typical warm El Niño episode develops, the ITCZ usually shifts slightly southward and the SPCZ shifts eastward. Normally dry areas in the central and eastern equatorial Pacific receive copious amounts of rainfall while, in the west, much of Indonesia and eastern Australia suffer drought. Conditions during 1982 and early 1983 reflected this pattern but to an unusually extreme degree. Southeastern Australia and Indonesia experienced severe, in places record, drought. In Kiribati (The Gilbert Islands) and the Line Islands further east, the reverse was the case with day after day of heavy rainfall disrupting the economy and the ecology of these equatorial islands. Nearly the entire marine bird population of Kiritimati (Christmas) Island, about 17 million birds in all, disappeared from the island, suffering an unknown fate.

The 1982–83 Episode

Widespread warming first appeared in the equatorial Pacific in May, 1982. By June, ocean surface temperatures reached 1 to 2°C above normal from the South American coast to 170°E. By August, the warm ocean anomaly had disappeared west of the dateline, but increased slightly east of 140°W. In September, two to three months after the collapse of the equatorial easterlies, there followed a rapid development of warmer water in the eastern equatorial Pacific.

The readjustment of sea level after the collapse of the easterlies is reflected in tide gage measurements. A rise in sea level, which began at Nauru (1°S, 167°E) in June of 1982, progressed eastward, reaching the Galapagos Islands (1°S, 90°W) in August. In the western Pacific, sea level decreased after the beginning of May 1982 in the Solomon Islands and from July onward in the Caroline Islands.

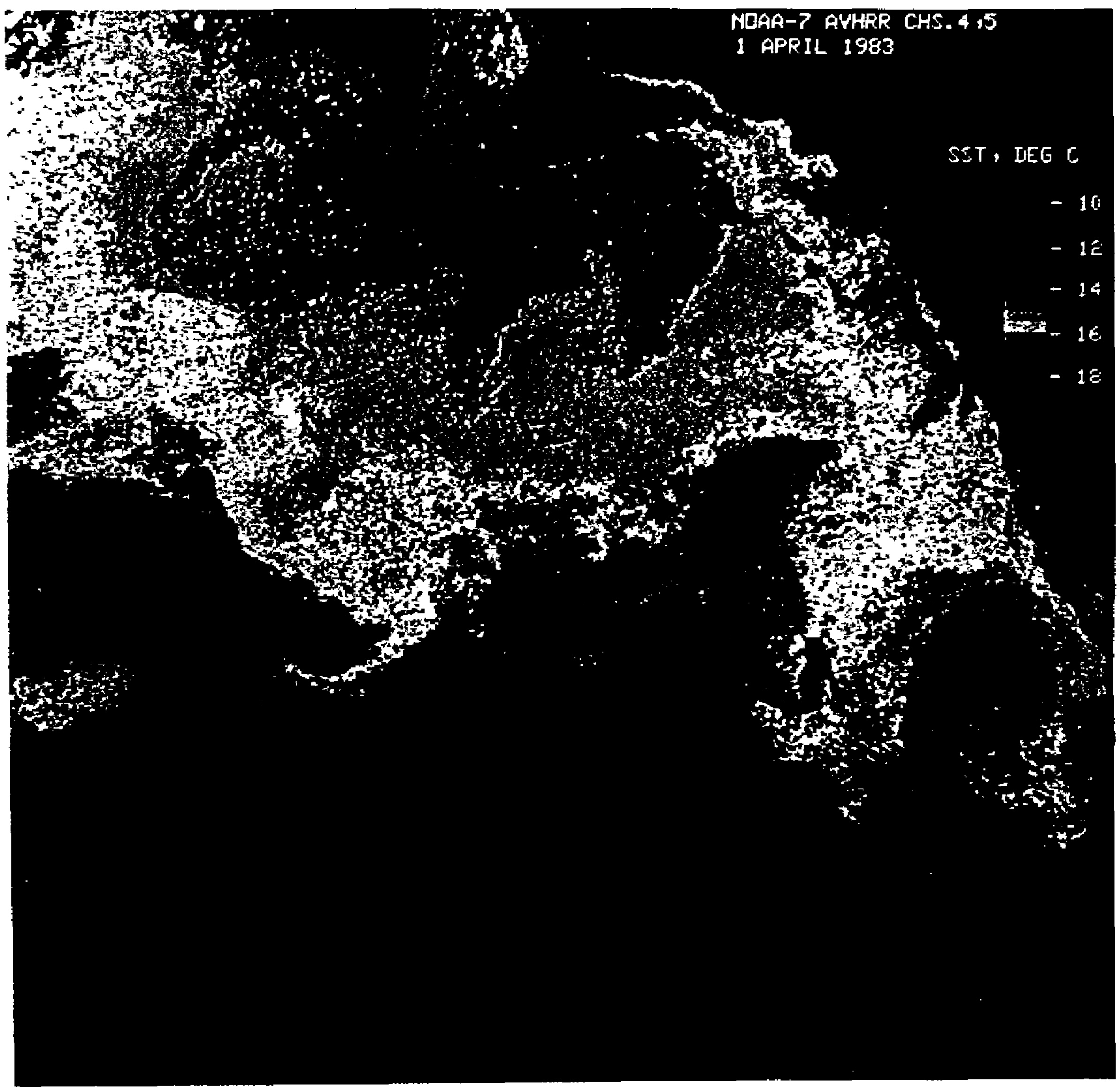
These developments led to the onset of strong El Niño conditions along the South American coast in October. The ITCZ shifted southward, bringing an early rainy season to Ecuador. The record rains and flooding during the next nine months over Ecuador and the northern provinces of Peru were part of the most catastrophic and prolonged El Niño visitation ever recorded.

By last December, the warm water anomaly exceeded 4°C over large areas of the eastern equatorial Pacific, and reached as much as 6°C in places. The large area of unusually strong westerly winds which first appeared over the western Pacific in June had by then migrated eastward, reaching a position well east of the dateline. West of the dateline, easterly winds had replaced these westerlies. In the past, the renewal of strong easterlies in the western equatorial Pacific has normally signaled the mature phase of the El Niño episode and the imminent decrease of the warm water anomalies in the central and eastern equatorial Pacific. Figure 6 illustrates the month to month evolution of warm water anomalies for several equatorial Pacific index areas. West of 90°W, the warm anomalies showed a steady decrease from their December 1982 peak through April of this year, then rose slightly in May. East of 90°W, the anomalies briefly decreased during January and February, then increased again, with April-May values exceeding the previous December peaks.

Although the atmospheric anomalies in the eastern equatorial Pacific continued to diminish during June, extremely high sea surface temperatures persisted in the extreme eastern equatorial Pacific and unseasonably heavy rainfall continued along the Ecuadorian coast. By mid-June, drifting buoys located near the equator indicated that the surface current had changed direction and was again flowing westward. However, indicators in early July clearly showed a sharp falling trend in sea surface temperatures between the Galapagos Islands and the South American coast, indicating that El Niño may finally be entering its decay phase.

The central equatorial and southeast tropical areas of the Pacific were also plagued by excessive rainfall. The unusually large eastward shift of the South Pacific Convergence Zone was

Figure 3. A satellite picture of the same area as shown in Figure 2 taken one year later in April 1983 shows the dramatic increase in sea surface temperatures over the Pacific off the southern California coast. The reddish purple area reflects water that is nearly 20°C. (NOAA Photos)



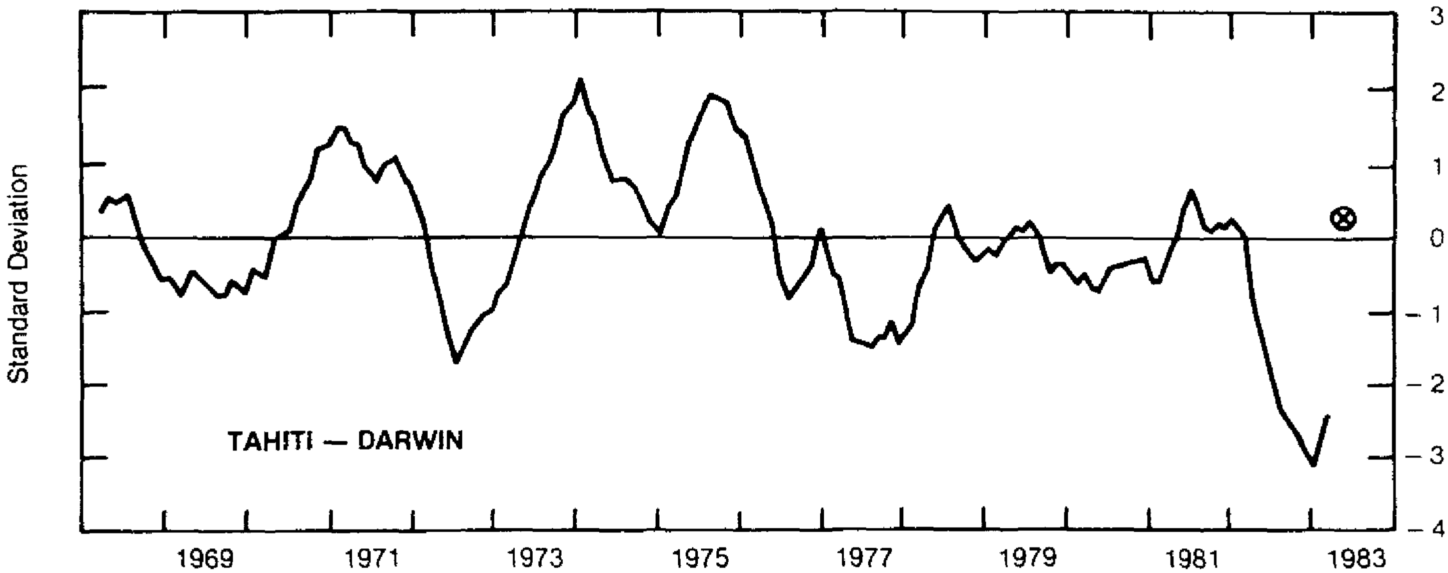


Figure 4. Time history of the Tahiti minus Darwin atmospheric pressure anomaly at sea level, which is used as a Southern Oscillation Index (SOI). The curve represents five month averages of normalized values, i.e., the anomaly difference divided by the standard deviation for the appropriate month. $\bar{X}$ indicates the individual monthly value for May 1983.

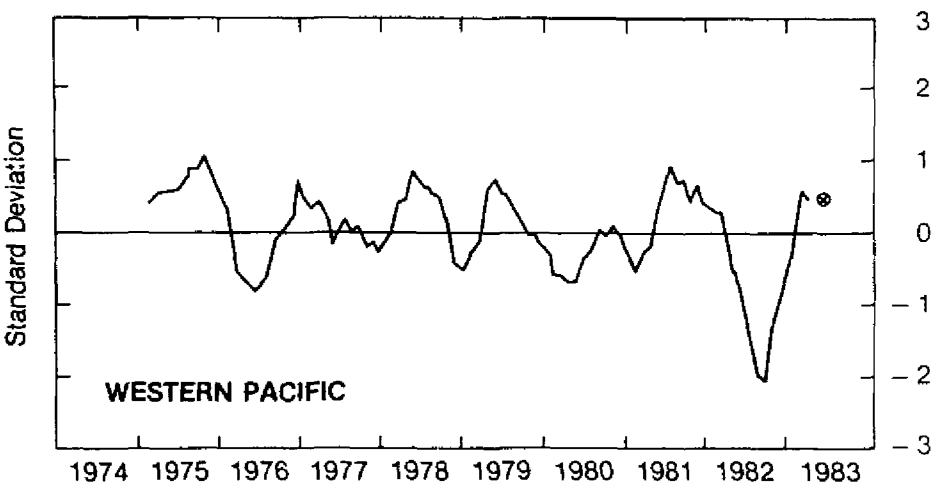


Figure 5. Time history of the average easterly wind speed anomaly over the western equatorial Pacific in the area between 135°E and 170°W, from 5°S to 5°N. The curve represents five month averages of normalized values (See Fig. 4). Negative values indicate westerly anomalies. $\bar{X}$ indicates the individual monthly value for May 1983.

associated with a similar eastward shift of the region of the Pacific where tropical storms are formed. As a result, French Polynesia was devastated by a series of 6 major tropical cyclones between December and April, one of which (Veena) was described as the most severe hurricane to strike Tahiti in modern times The unusual location and behavior of the northward moving hurricane (Iwa) which struck the Hawaiian Islands last November may also have been related to the El Niño pattern.

Regional droughts typical of a warm El Niño episode were strongly in evidence during this event. Particularly hard hit were the areas of Australia, Indonesia, and southern Africa. The nearly year-long drought in Australia is reported to have cut the 1982 production of wheat, oats, and barley to roughly half that of the previous year. More than one million people were said to be facing possible famine in East Indonesia due to drought-related crop losses. Southern Africa suffered under one of its worst droughts of this century, leading to severe water shortages, major crop losses, and widespread human suffering

Near the end of 1982, the same winter pattern of weather and circulation anomalies that typically develop in connection with El Niño appeared over the North Pacific and parts of North America. Drought conditions developed from the Philippines eastward through the Hawaiian Islands The tropical jetstream over the Pacific, which had been observed to intensify during the mature phase of earlier El Niño episodes, did so again, this time reaching record strength. The eastward extension of this jetstream across the Gulf of Mexico was associated with wet spells and storminess all across the "sunbelt," from California to Florida and Cuba, that persisted through much of the spring season.

Record Low Pressures

The intensification of the Pacific jetstream related to El Niño is usually connected with very low barometric pressure in the North Pacific. This intensification reached record proportions during the winter of 1982-83. The mean monthly sea-level pressure in the Gulf of Alaska was lower in February 1983, than in any previous month of this century. The tracks of storms entering North America from the Pacific were at times displaced hundreds of miles south-

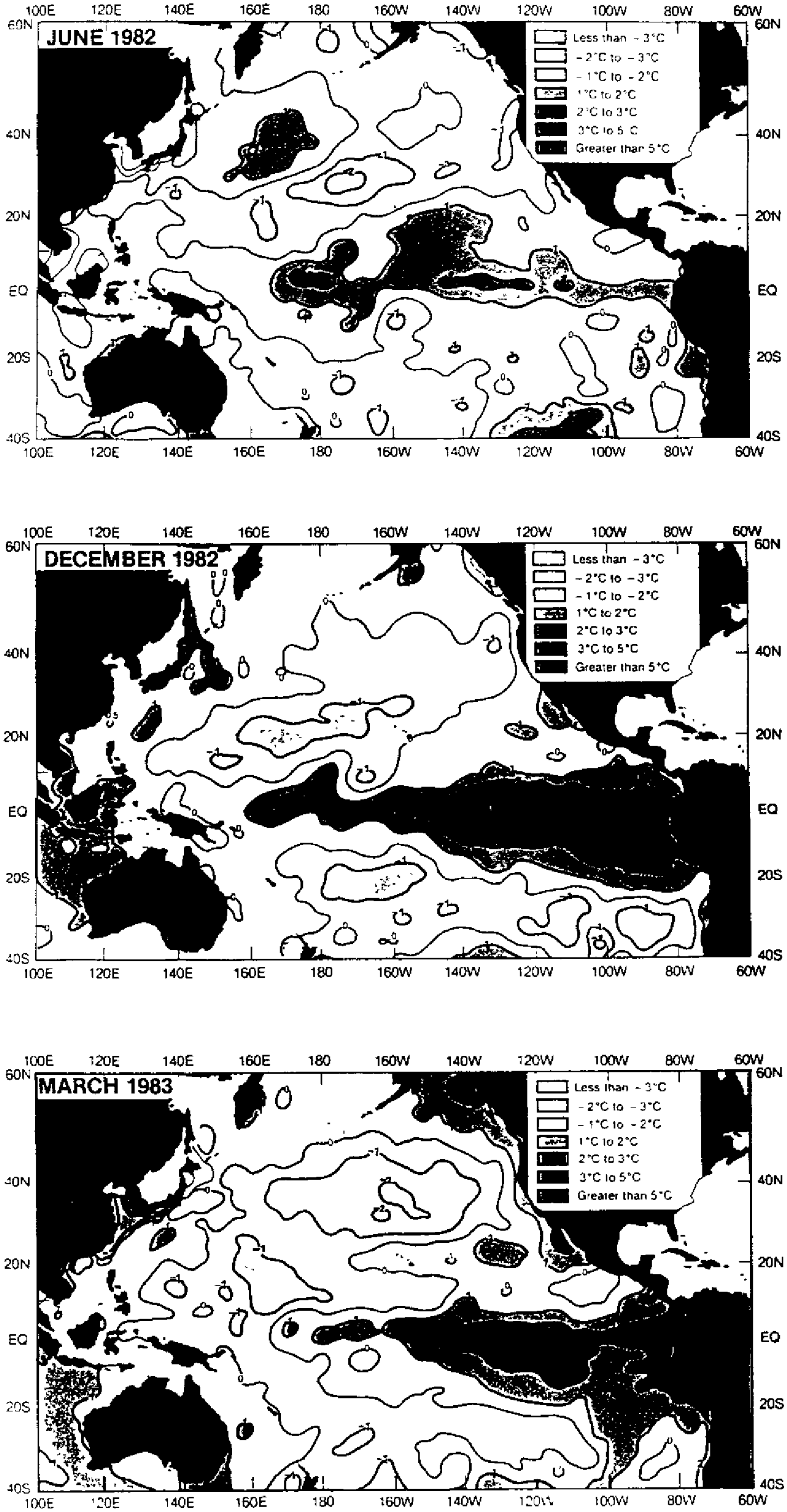


Figure 6. Pacific Ocean SST anomalies for June and December, 1982, and March 1983, computed from ship and buoy surface observations by the National Atmospheric and Oceanic Administration, NMC, Climate Analysis Center.

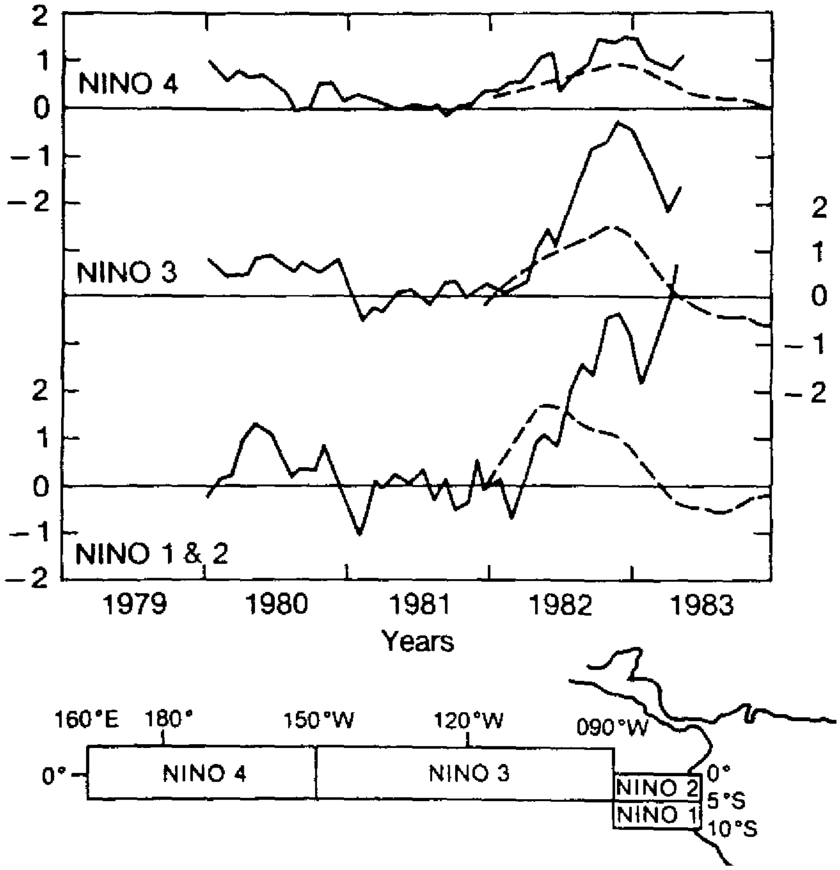


Figure 7. Sea surface temperature indices. Monthly average SST anomalies (°C) (solid lines) for January 1980–May 1983. Averages are for areas shown at bottom of figure. The dashed curve is the composite anomaly for six warm episodes (1951, 53, 57, 65, 67, 72).

eastward, bringing destructive winds and tides to the California coast

The 1982–83 El Niño event, like earlier such events, has caused severe dislocations of the marine ecosystem along the west coast of the Americas. Reports from Ecuador and Peru indicate that the warming of their coastal waters, and its associated decrease in the distribution and abundance of plankton, the basic food supply, resulted in a drastic decrease in the populations of fish eggs and larvae and in sharp drops in the catches of commercial fish. Peruvian officials have estimated that the 1982–83 El Niño will result in a 50 percent decline in the 1983 total commercial catch compared with that of 1982. As the warm water has spread poleward along the west coast of the Americas significant changes have taken place in the distribution and abundance of many species of fish along the Chilean coast to the south, and along the west coast of the United States to the north.

This Pacific warm water episode will go into the record books as one of the strongest and in some respects one of the most unusual El Niño events of the past century. From a human and economic standpoint, it may also have been one of the most costly. A full accounting of the many socio-economic problems associated with it, in all parts of the world, will

Figure 8. Commercial fishermen off the California coast have shifted their ranges northward to follow tuna and other fish seeking cooler, nutrient-laden waters. (NOAA Photo)

not be possible for some time to come after conditions return to normal.

The El Niño event of 1982-83 is noteworthy also for the high degree of international cooperation it has brought about in efforts to monitor it and assess its impacts. It has resulted in the most rapid exchange among countries, institutions and individuals of meteorological, oceanographic, and fishing information that has ever transpired in response to a weather disturbance in the Western Hemisphere. In the past, it has often taken months, even years, to assemble data that during the 1982-83 El Niño event have been made available within a matter of days or weeks.

Although limited and incomplete in many respects, these data are far superior to any collected in previous El Niño events. They should significantly advance our understanding of this disruptive yet fascinating and extremely important aspect of global-scale climate behavior. Plans are being formulated for a major decade-long international research program to study the phenomenon of El Niño. What is ultimately learned could well lead to a variety of new skills including improved long-range weather and climate forecasts, better projections of agricultural and fishery yields, and wiser management of our marine living resources. **WW**

Economic and Human Costs

The cost of the El Niño event in economic and human terms is beyond exact accounting but scientists feel that many of the extraordinary weather conditions experienced over the globe can be attributed to the effects of El Niño. Among the most extraordinary weather events in this extraordinary year have been:

Pacific Coast Storms—High winds and excess rains caused hundreds of millions of dollars damage in California, Oregon, and Washington during 1982-83. In California, property damage for February alone was estimated at more than $200 million.

Flooding in Louisana, Florida and Cuba—Excess rain hit the Gulf Coast between December and April, leading to heavy flooding and erosion. More than 50,000 residents were forced to evacuate their homes in April.

Hawaii—A prolonged dry spell affected the islands December through March. In November, a rare hurricane caused $200 million in damage to the western parts of the Hawaiian Islands.

Mexican Drought—Summer drought affected large areas of Mexico reducing water supplies, harming grazing land, and cutting farm production.

Flooding in Ecuador, Peru, and Bolivia—Between mid-November 1982 and late January 1983, several weeks of torrential rainfall triggered Ecuador's worst flooding disaster of the century. At least 23 people were killed and thousands were left homeless. Temperatures near the coast of Ecuador and Peru were also abnormally high resulting in many deaths. The fishing industry off the coast of the South America was badly damaged by the warmer ocean currents which decimated the population of anchovies and drove larger fish from their normal feeding grounds.

Widespread Drought in Southern Africa, Sri Lanka and Southern India, the Philippines, Indonesia, and Australia—Extreme droughts affected many parts of the world causing hundreds of deaths and ruining crops for the year to come. Australia was especially hard hit losing more than $2 billion in crops. An outbreak of bush fires killed 71 people and caused over $400 million in damage.

French Polynesia—Five extremely rare hurricanes from December through April including the worst hurricane in modern times struck Tahiti on April 12, killing one person and leaving 25,000 homeless. Damage may reach $50 million.

Figure 9. Scientists are probing the disappearance of over 17 million seabirds, virtually the entire adult bird population of the mid-Pacific atoll of Christmas Island. Researchers feel that the changes in wind patterns, salinity, ocean currents, and sea levels that have resulted from the El Niño event may be the underlying cause for the disappearance of the birds.