Progress in understanding El Niño

David B. Enfield

Prior to the work of Jacob Bjerknes the El Niño phenomenon was regarded as an aperiodic climatic event confined to the Pacific coast of South America. Spurred by a growing consciousness of the oceans' role in global climate, there has been an explosion of El Niño research in the last two decades. El Niño is now recognized to be an integral part of a Pacific-wide ocean relaxation, with global climatic impacts and economically important ecological consequences. However, we are still groping for the final prize: the ultimate cause of this climate anomaly and the ability to reliably predict its onset and intensity.

In the latter half of this century scientists have gained much greater insight into the true nature of El Niño. It is a regional but important manifestation of a very large-scale interactive process involving the tropical ocean and global atmosphere. With our increased knowledge we have come to realize that El Niño is not merely a curious but isolated phenomenon, but rather an important link in the physical processes that affect our global climate from one year to another. By understanding the role of El Niño in these processes we can hopefully gain the ability to forecast short-term climatic changes, in particular, and appreciate the role of ocean-atmosphere interaction in climate changes on all time scales, in general.

The Southern Oscillation

Research during the first half of this century focused mainly on the meteorological aspects of the ocean-atmosphere system, embodied in the global-scale atmospheric pressure fluctuation identified by Sir Gilbert Walker as the Southern Oscillation (SO) [1]. The SO was recognized as a coherent variation of barometric pressures at interannual intervals that is related to weather anomalies in many different regions, particularly in the tropics and subtropics. The early research [2] has shown that the surface atmospheric pressure in regions dominated by tropical convection (ascending air) and rainfall, such as Indonesia, is inversely correlated with the pressure in regions typified by subsidence (descending air) and dry conditions, such as the eastern South Pacific (figure 1). Air is continually transferred at low levels – through the zonal trade wind circulations – from the subsidence regions to the convective regions. The air returns at upper tropospheric levels, completing a series of zonal cells around the globe that compromise the Walker Circulation (figure 2). The SO has been defined as a fluctuation of the mass exchange in the dominant Indo-Pacific Walker cell; that is, between the eastern (Indonesian and Indian subcontinent) and western (southeast Pacific) hemispheres.

The state of the SO pressure see-saw is characterized by the Southern Oscillation Index, or SOI (figure 3). The SO reaches its maximum development (high index) when the Pacific cell of the Walker Circulation (including the trade winds) is strong. At these times the pressures in the Indonesian region are lowest and the convection and rainfall there reach maximum intensity; then also, the South Pacific subtropical high pressure region is most intense and a dry zone extending along the equator from South America toward the dateline is best developed. The SO enters a low index phase when the Walker Circulation weakens; at such times the barometric pressures rise in the Indonesian region and fall in the southeast Pacific. There are periods when low pressure regions (such as Indonesia and northeast Brazil) undergo drought conditions. At the same time, the equatorial dry zone in the Pacific contracts eastward and the Amazon convective regime appears to shift toward the desert region in the northwestern portion of the South American continent. The El Niño (east Pacific warming) typically occurs following a prolonged period of high index, just as the SO is entering a low index phase.

El Niño

Apart from a few scientific analyses based on oceanographic expeditions or

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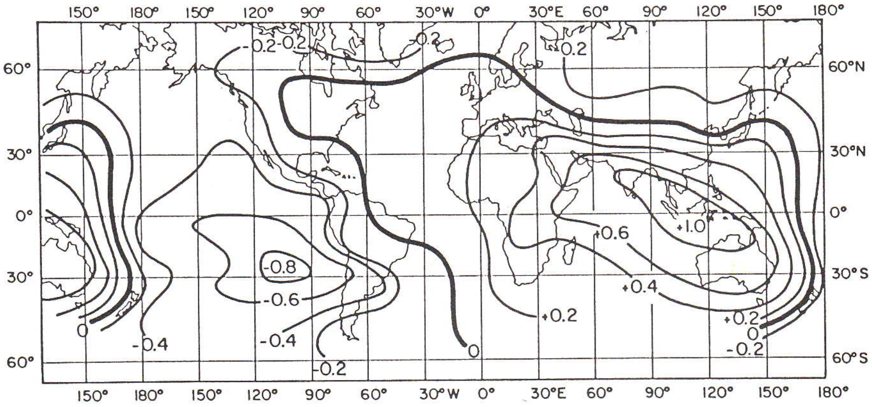

Figure 1 The global distribution of the correlation coefficient between the barometric pressure variations at Djakarta, Indonesia, and those elsewhere. The negative correlation between the eastern and western hemispheres, with centres over Indonesia and the southeast subtropical Pacific, characterizes the pressure see-saw associated with the SO, an interannual fluctuation in the strength of the Walker Circulation. (After H. P. Berlage [2])

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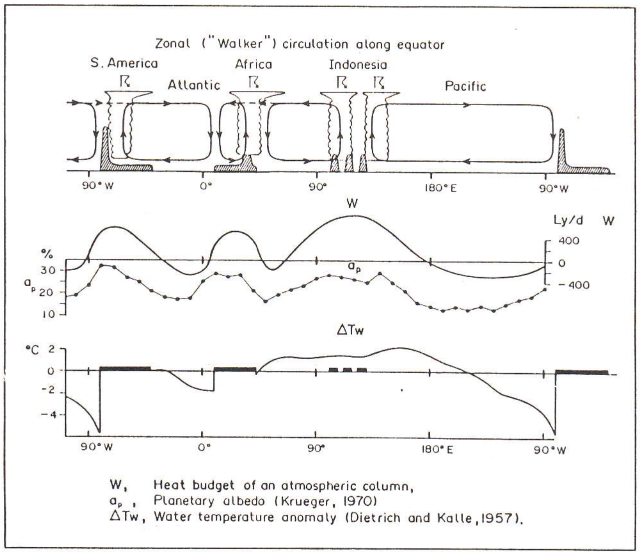

Figure 2 Transverse view (looking north across the equator), of the Walker Circulation that girdles the globe in the tropics. Individual Walker cells occur between regions of uplift and tropical convection, on the western sides of oceans where water temperatures are high, and regions of subsidence over the colder eastern oceans. The convection regions show a net heat gain from latent heat release and have high albedo due to the reflective cloud cover; the same properties have opposite tendencies over the cool regions. (After H. Flohn, *Atmosphere*, **13**, 96, 1975)

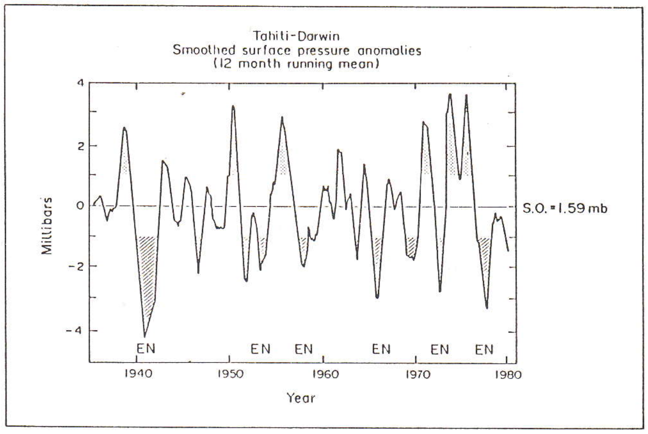

Figure 3 A 45-year time series of anomalies of the SOI derived from differences between the barometric pressures at Tahiti (eastern South Pacific subsidence region) and Darwin, Australia (Indonesian convective region). Positive (negative) swings of the SOI, shaded when large, coincide with cool (warm) oceanic conditions in the eastern Tropical Pacific. Occurrences of El Niño are designated as 'EN'.

regional data from South America [3, 4] knowledge of El Niño prior to the early 20th century consisted largely of information from military campaigns, missionaries, privateers (ship logs), explorers, historical compilations, and geographic reports, as well as from the economically oriented activities of construction engineers, hydrologists, farmers, guano administration officials, and so on. The limited climatic information obtained from these sources, dating back nearly five centuries, has been extensively researched and summarized by W. H. Quinn [5]. The El Niño, which we recognize today as an anomalous east Pacific warming episode, originally received its name in reference to the Christ child, because of the annual appearance of warm water near the Ecuador-Peru border at about Christmas-time. The accompanying changes in coastal marine fauna and seasonal onset of light rains over this normally dry desert region have always oriented the fishing and agricultural activities of the local inhabitants, who take maximum advantages of them. However, most of these same activities are adversely affected when the occasional atypical El Niño occurs every few years, greatly enhancing the normal annual changes. The more spectacular cases have prompted often colourful accounts of desert floods, infestations of insects, disease outbreaks, exuberant blooms of desert plants (figure 4) and southward invasions of unusual tropical marine fauna. Nowadays, people associate the term 'El Niño' with the extraordinary but less frequent occurrence rather than the annual event.

The early atmospheric workers recognized El Niño as one of the important climatic aberrations that occur during the low-index phase of the SO. They did not, however, understand the cause-effect relationships between the SO and El Niño; that is, that El Niño is the regional manifestation of a large-scale oceanic counterpart to the SO, and that the two are intimately related through large-scale ocean-atmosphere interactions.

The Bjerknes revolution

The first major advance in our understanding of El Niño and its relationship

Figure 4 During the 1982–83 El Niño, record rains fell over coastal Ecuador and the northernmost desert region of Peru. This scene depicts a portion of the Sechura desert in November 1983, about five months after the rains subsided and a shallow lake had dried up, parching the soil. Many vestiges remain of the copious vegetation that spontaneously emerged from the deluge. (*Photo by H. Solidi.*)

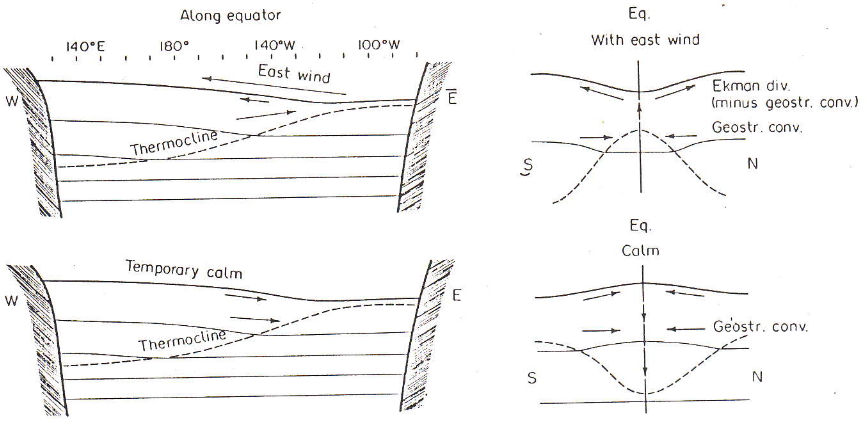

Figure 5 Left, looking north across the equator in the Pacific: Schematic representation of the equatorial flow patterns under conditions of normal (positive SOI) and abnormal (negative SOI) trade winds. Right, looking westward along the equator: Schematic view of the normal and abnormal transverse circulation patterns near the equator. At top, westward wind stress forces a surface 'Ekman' transport poleward into either hemisphere; sea level and temperatures are low at the equator due to upwelling and a convergence at depth compensates for the Ekman divergence at the surface. At bottom, Ekman divergence and upwelling cease as the winds relax, the convergence continues throughout the upper ocean, however, raising sea level and depressing the thermocline. (From J. Bjerknes [6], *reprinted courtesy of the Inter-American Tropical Tuna Commission.*)

to the Southern Oscillation came with the work of Jacob Bjerknes (1897–1975) in the 1960s. The earlier SO research had been phenomenological, seeking compound periodicities that coincided with those of external agents such as sunspot cycles. Bjerknes, on the other hand, sought to explain the SO through the internal dynamical mechanisms of the atmosphere and ocean, and he accepted the importance of their mutual interactions.

Initially, Bjerknes tried to explain El Niño as an occasional exaggeration of the El Niño-like state that occurs during every southern hemisphere summer, centered about March. As had others before him, he argued that El Niño is caused by local trade wind weakening and north-south ocean density gradients within the El Niño region itself. As the normal equatorward coastal winds decrease, cease, or reverse, the ubiquitous upwelling of cold, nutrient-rich waters along the Peru coast would be interrupted; the water would warm from the lack of a cool source and also because warm, low-salinity water of low density north of the equator would flow southward in the absence of opposing winds. Both mechanisms would explain the collapse of the coastal ecosystem due to deficits in the nutrient supply.

He quickly realized, however, that the regional El Niño is closely related to a Pacific-wide relaxation of the equatorial ocean in response to weakened trade winds on a much larger scale [6]. This was a major, new contribution that has been confirmed by subsequent research. His arguments, though based on the assumption of steady conditions, have essentially captured the character of the transient ocean response we have observed extensively since his time (figure 5): a deceleration of the normally westward equatorial surface currents accompanied by cessation of equatorial upwelling; accumulation of warm upper layer water in the equatorial zone; and consequent large-scale warming.

There are two principal shortcomings in Bjerknes' contributions. As already noted, his analysis assumes a steady ocean and contrasts two quite different but essentially equilibrium states: El Niño and non-El Niño. This approach precludes recognition of the wave-like nature of the transient El Niño response that we are now familiar with. The oversight was probably due in large part to the second difficulty that he faced: a lack of data. Because he had few observations of Pacific-wide wind distributions, he assumed that the trade winds weaken everywhere and that the El Niño condition can be understood everywhere, including the region off South America, as an adjustment to locally reduced winds. This assumption led Bjerknes and other investigators at the time [7] to erroneously conclude that the Peruvian El Niño is a locally produced warming due to the cessation of coastal upwelling under reduced (or reversed) alongshore winds, simultaneous with the physically similar response occurring much farther west, along the equator. As we shall see, the Bjerknes scenario would need modification to adequately explain what happens off South America during El Niño.

Evolution of modern concepts

In the mid-1970s, as more data became available and was analyzed, it became obvious that the coastal winds along most of the Peru coast do not decrease during El Niño episodes (figure 6), although the large-scale trades farther offshore do indeed weaken [8]. At some coastal locations the upwelling-favourable winds actually intensify. Clearly, the physical process of upwelling is not diminished and cannot explain the well documented warming and decreased productivity that occur in the Peru coastal waters during El Niño. Could it be that the larger scale anomalies in the equatorial Pacific, described and explained by Bjerknes, were in some way transmitted to the coastal region?

Beginning in 1975, a flurry of observational and theoretical studies provided compelling evidence that El Niño is, indeed, remotely forced in the equatorial Pacific [8, 9, 10]. Prior to El Niño the SO is in its high-index phase, with a well developed southeast Pacific high pressure system and strong southeast trade winds. Many oceanographers believe this is an important precondition to El Niño, because the strong trade circulation amasses a large pool of warm, upper layer ocean water in the western tropical Pacific. Then, as the SO enters its low-index phase, the normally westward blowing winds in the western and west-central equatorial Pacific weaken or reverse, allowing the accumulated warm water to move eastward. However, because of the impulsive nature of the wind collapse, the ocean response is wave-like, although physically very similar to the mechanism proposed by Bjerknes.

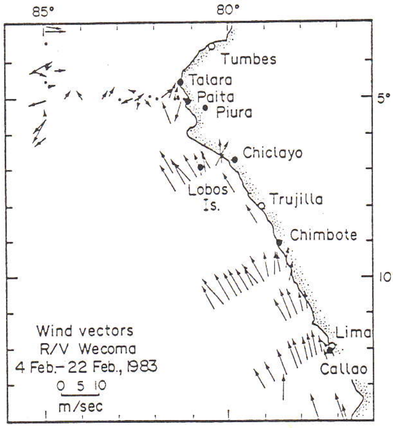

Figure 6 Distribution of winds within several hundred kilometres of the Peru coast observed during the February 1983 cruise of the *R/V Wecoma*. The coastal winds remain normal and upwelling favourable south of 6°S, in spite of severe El Niño conditions prevalent at the time. North of there winds are weak and variable and coincide with convective activity and rainfall over the adjacent Sechura Desert.

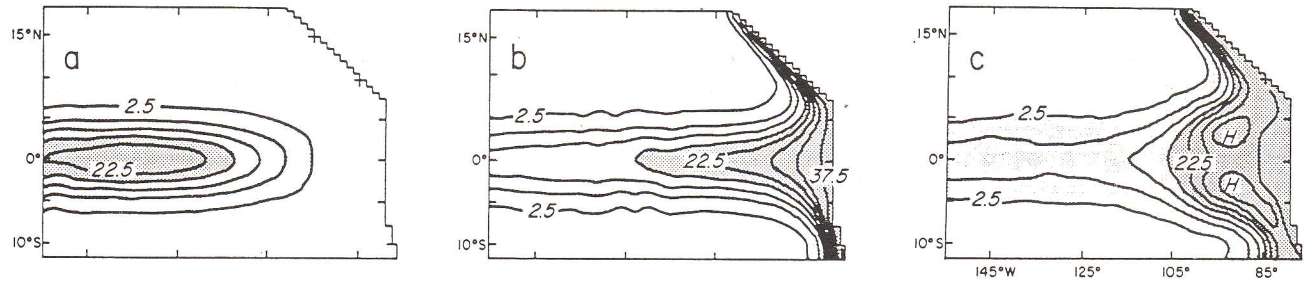

Figure 7 Looking down on the equator from above, a numerical simulation of an equatorially trapped internal Kelvin wave that impinges on the South American coast. Contours approximately represent the anomalous rise in sea level (centimetres) and depression of the thermocline (metres). The three panels depict conditions at successive monthly intervals. (From D. B. Enfield [11] after O'Brien *et al.*)

Because the wave response involves an eastward perturbation of existing currents, the earth rotation deflects the flow just off the equator – in either hemisphere – towards the equator. The unleashed wave, or series of waves, is thus trapped on the equator and advances eastward much like an elongated bubble of liberated upper layer water (figure 7). Called Kelvin waves (after Lord Kelvin, who first described such waves mathematically), these pulses propagate across the Pacific to the South American coast in about two or three months. They are internal waves, supported by the density contrast at the equatorial thermocline, a zone found 50–150 metres below the sea surface where the temperature decreases downward most rapidly. The behaviour of these waves is not altogether unlike the sloshing of an oil layer overlying vinegar. As they pass (say, for example, an island tide gauge or an array of submerged instrumentation), the sea level at the equator typically rises by 10–30 centimetres, the thermocline is depressed downward by a comparable number of metres, and the normally westward flowing equatorial currents are reversed.

As Kelvin waves reach the South American coast, several things happen. Consistent with their behaviour along the equator, sea level rises and the thermal structure along the coast is depressed, but due to the confining effect of the continental boundary, the amplitude of these disturbances is increased considerably (figure 7, third panel). Immediately, part of the energy begins to reflect westward as pairs of slowly propagating, counter-rotating eddies, called planetary or Rossby waves. More importantly for the coastal ecosystem, much of the energy continues poleward into both hemispheres, as the Kelvin waves split into diverging coastal waves (also with Kelvin-like characteristics).

The impact of the wave arrivals on the ocean thermal structure is well illustrated by a two-year series of temperature sections off Ecuador, spanning the strong 1972–73 El Niño (figure 8) [11]. In November-December 1971 conditions

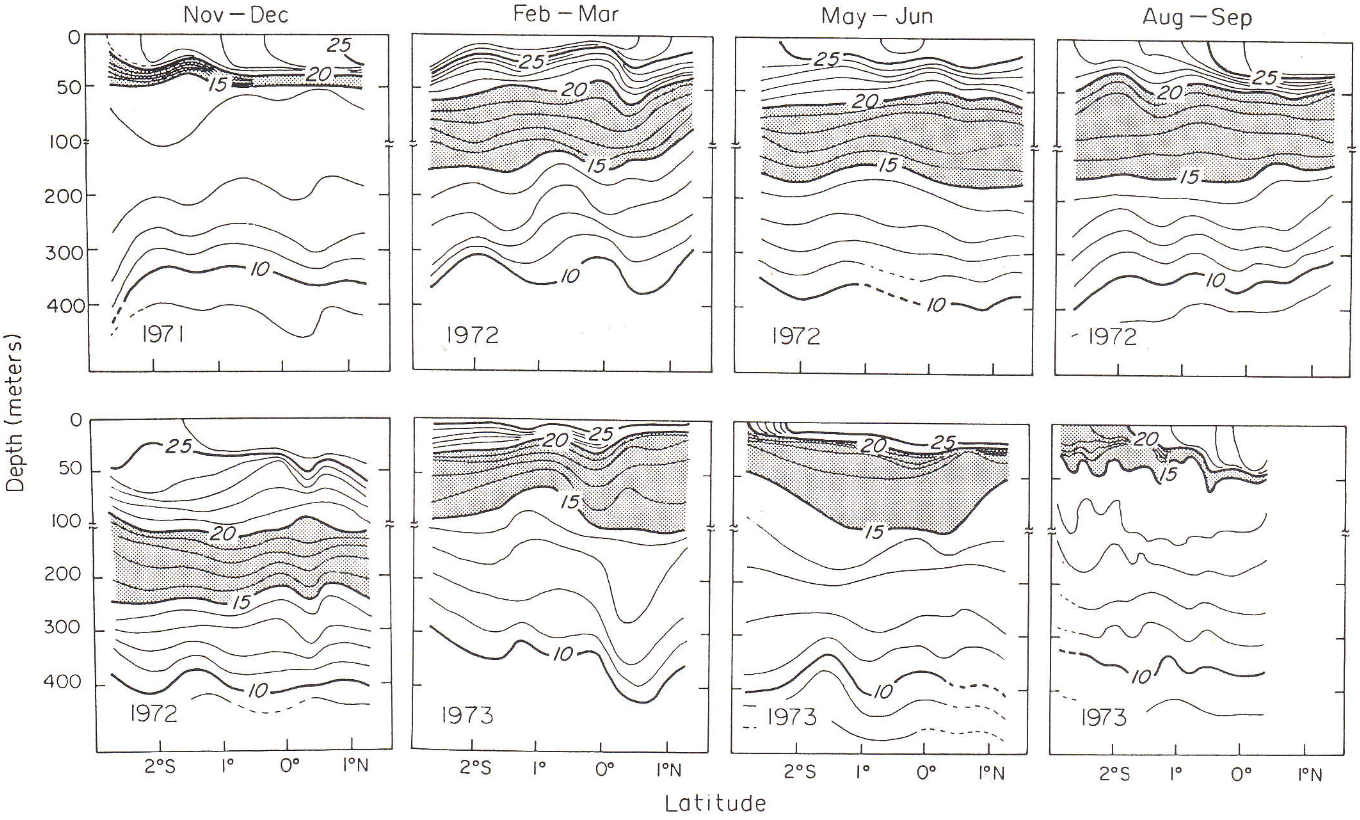

Figure 8 Eight successive ocean temperature (°C) sections across the equator off Ecuador at three-month intervals before, during, and after the 1972–73 El Niño. The first (top) and second (bottom) years of the sequence begin in November-December (left) and end in August-September (right). (From D. B. Enfield [11])

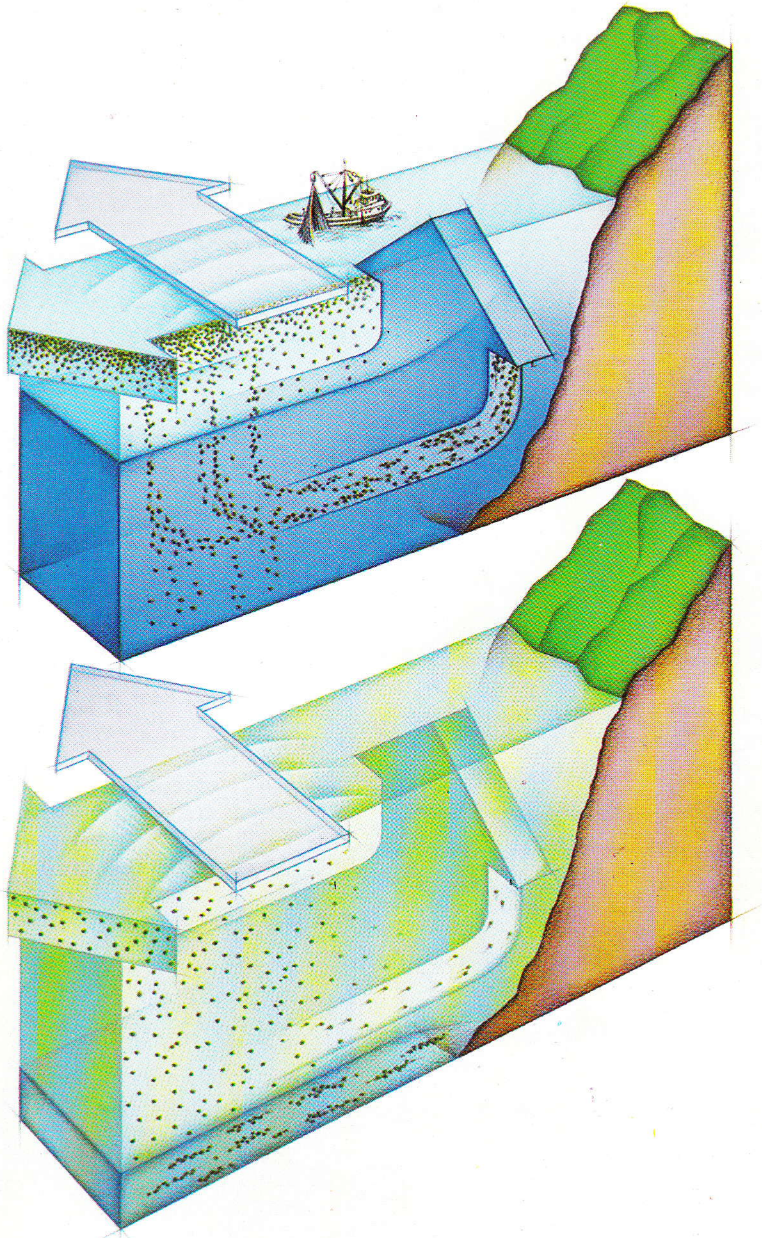

Figure 9 Schematic illustration of upwelling characteristics along the coast of Peru during normal (top) and El Niño (bottom) conditions. A thermocline and nutricline separate the warm, nutrient-deficient upper layer (light colour) from the cool, enriched lower layer below (dark colour). (*Artwork by Allen Carroll based on original drawing by R. R. Barber © National Geographic Society* [21]

were normal with a shallow tropical thermocline at 30–50 metres and relatively isothermal water below. The thermocline depression due to the first Kelvin wave arrival was detected in February-March 1972. Taking the pre-El Niño condition of November-December 1971 as a benchmark for the 'normal' temperature distribution, the maximum depression occurred one year later when a second rise in coastal sea level signalled the probable arrival of another series of Kelvin pulses. At that time, most of the isotherms at depths less than 400 metres were 50–150 metres deeper than normal, and maximum temperature increases of about 9–10°C were found 50 metres below the surface. By March 1973 the system was returning to normal, and by the end of that year appeared to have completely recovered.

As the southern hemisphere portion of the El Niño disturbance propagates southward, it quickly spreads the deepened thermocline and sea level rise along the Peru coast. In a matter of weeks the entire coast may be affected, much sooner than could occur under the action of currents alone. Although the coastal flow is accelerated southward, water that starts at the equator can travel only a short distance in the time it takes the waves to propagate southward. However, since the coastal upwelling of subsurface water from depths of 50–100 metres continues unabated, and because the water at those depths is much warmer than normal, the surface temperatures of the upwelled water become unusually high. Coastal surface temperature anomalies of 3–4°C above normal are common for moderate El Niños and they reached as much as 8–10°C during the very intense 1982–83 episode. More significantly for the coastal ecosystem, the upwelled water is also poor in nutrients and subsequently leads to a collapse of the primary productivity and of the heavily exploited commercial fish stocks that it normally sustains (figure 9) [12].

Such is the conceptual model of El Niño that has evolved since the work of Bjerknes, a paradigm widely accepted by oceanographers as a framework for modern research. The rapid developments in El Niño research over the last decade probably would not have occurred, however, if the effects of this phenomenon were geographically confined to the equatorial Pacific. Instead, we owe much of our progress to the realization by scientists, news media, and legislators that El Niño has far-reaching climatic and economic repercussions around the globe.

Teleconnections

It was Bjerknes who, using data from the unusual 1957–58 event, advanced a major hypothesis to explain the geographic extensions of El Niño [13]. He argued that the equatorial warming feeds back on the lower atmosphere (troposphere) through evaporative heat transport from the warmed ocean surface. Thunderstorm activity then becomes frequent and unusual amounts of rainfall assault the normally dry equatorial zone. As the atmospheric moisture condenses, unusual amounts of latent heat are released, propelling additional heat and momentum north or south toward higher latitudes at the upper levels of the troposphere. The jet streams intensify, altering significantly the extratropical atmospheric circulation and weather patterns, especially in the winter hemisphere. Bjerknes adapted the term 'teleconnections' to characterize the linkages between the equatorial source region and these remote, but related weather phenomena.

Ironically, the first strong evidence for teleconnections came from the ocean and not the atmosphere. During El Niños, unusual increases in mean sea level occur simultaneously, not only off

South America but also along most of the Pacific coast of Central and North America as far north as Canada and Alaska (figure 10) [14]. The data are consistent with the continued poleward propagation of the El Niño wave along the coast. As sea level rises off California, the normal southward drift of the California Current is decreased or reversed within about 500 km of the coast and marine organisms tend to be found north of their usual habitats [15, 16].

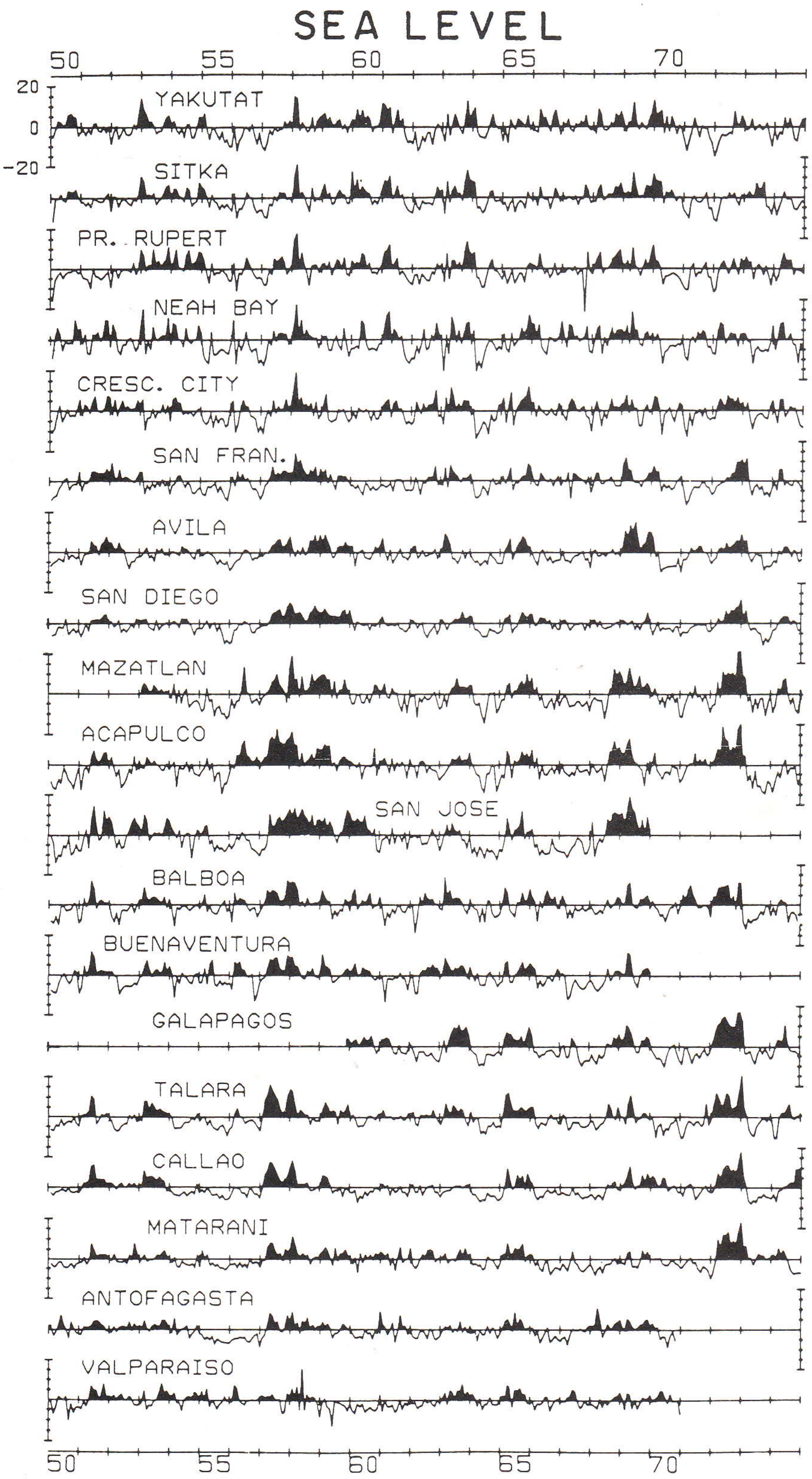

Figure 10 Time series of sea-level anomalies for a 25-year period at 19 tide gauge stations from Valparaiso, Chile to Anchorage, Alaska. Periods of persistent positive anomalies at Galapagos, Talara, and Callao (black shading) correspond to El Niño episodes, and are coherent with similar fluctuations at higher latitudes. (From Enfield and Allen [16])

Public and scientific awareness of the atmospheric teleconnections proposed by Bjerknes was increased because of severe weather abnormalities that occurred in North America during the 1976–77 winter. An exaggerated circulation pattern, attributed to teleconnections from a moderate El Niño that year [17], brought a paralyzing drought to the US west coast, while the east coast suffered the numbing effects of repeated snow storms and record cold. Extensive analyses of historical data sets soon revealed that the interchange between ocean and atmosphere during one of these events is a continuous process occurring in both directions, developing in phases seemingly locked to the march of the seasons [18], and with major teleconnections to the northern hemisphere occurring during the northern winter season (figure 7).

The 1982–83 El Niño

By 1982, a certain complacency had set in amongst scientists, who felt that El Niño/Southern Oscillation episodes (ENSOs) tend to follow a repeatable pattern and that further examination of the teleconnection process could soon lead to useful forecasts of major climatic anomalies. Hence, when the first reports of anomalies in the tropical Pacific were received in mid-1982, many scientists refused to believe a true El Niño was in progress, based on the unusual time of year and the lack of antecedent conditions thought necessary (for example., a positive SO index). In spite of its nonconformity to the canonical pattern, the 1982–83 period subsequently proved to be a disastrous El Niño, more intense than any other in living memory. The last episode of comparable magnitude occurred in 1891, almost a century before. Although our basic concepts of what happens during a ENSO episode remained unchanged, our faith in the feasibility of forecasting its occurrence had been badly shaken.

There was extensive damage to the marine environment along the South American coast in 1983 [9]. Ironically, not all of the fisheries impacts were disastrous; certain commercial species, most notably shrimps, but also dolphinfish, scallops, octopus, and many others appeared in unusual numbers. Others, of course, virtually disappeared or their stocks were greatly depleted. High temperatures and low concentrations of traditional plankton varieties devastated many pelagic (mid-water) fish stocks, such as anchovies and sardines. Many bottom dwellers like shrimp and scallops fared well because of an enriched oxygen supply, while other demersal (near-bottom) species such as hake were redistributed by the environmental changes. One can speculate, of course, that the demise of some species favoured the prosperity of others, directly or indirectly, through greatly altered patterns of interdependent factors such as available food types, larval survival, predation, and so forth.

Mortality among the normally abundant guano birds and marine mammals of this coastal region was extensive, especially of their young, because their normal food supply of schooling fishes was greatly reduced and/or made unavailable to them. Since the hungry adults abandoned their nests and broods in large numbers in search of scarce food, their populations were subsequently slow to recover after environmental conditions returned to normal in 1984. A well documented microcosm of the bird mortalities occurred near the equator on Christmas Island, half-way across the Pacific [20].

By far, the most extensive damage to the South American coast came in the form of rainfall. Unheard-of amounts of rain fell on coastal Ecuador and Peru, north of Lambayeque (6°S). Flash floods roared through the desert gullies, ripping out roads and bridges and damaging the oleoducts that transport crude oil to ports of embarkation. The important coastal town of Talara, built in a canyon cut through the Sechura plateau, was inundated with mud that took more than a year to remove. Talara and other isolated communities had to be supplied by helicopter until road links could be re-established. Vast regions of the Sechura desert were revegetated by the rainfall (figure 4), and large shallow lakes appeared, often burying major highways, some remaining for almost two years. Agriculture, highly dependent on a well controlled system of irrigation, was ravaged by untimely water damage, a lack of transportation facilities and – not the least – by infestations of voracious insects spawned by the rogue vegetation. Because mean sea level had risen by as much as two feet, many low-lying beach communities were pounded by surf, streets flooded, and beachfront buildings wiped out.

Many poignant laments of human suffering emerged from the 1982–83 El Niño disaster [21]:

> In the center of the city of Sullana a whole block became an island of land on Alcedo street. Entire families were imprisoned by the water which reached four metres. A merchant committed suicide. A wall fell on a young woman and caused her death. The Navarro family prayed in front of their religious statues. La Arena, a country town, was totally inundated. In the television interview with a simple country woman: 'The water took everything, our children are hungry. Oh dear Lord. I mean to say that the rain is good but our lack of preparation to receive it is bad'.

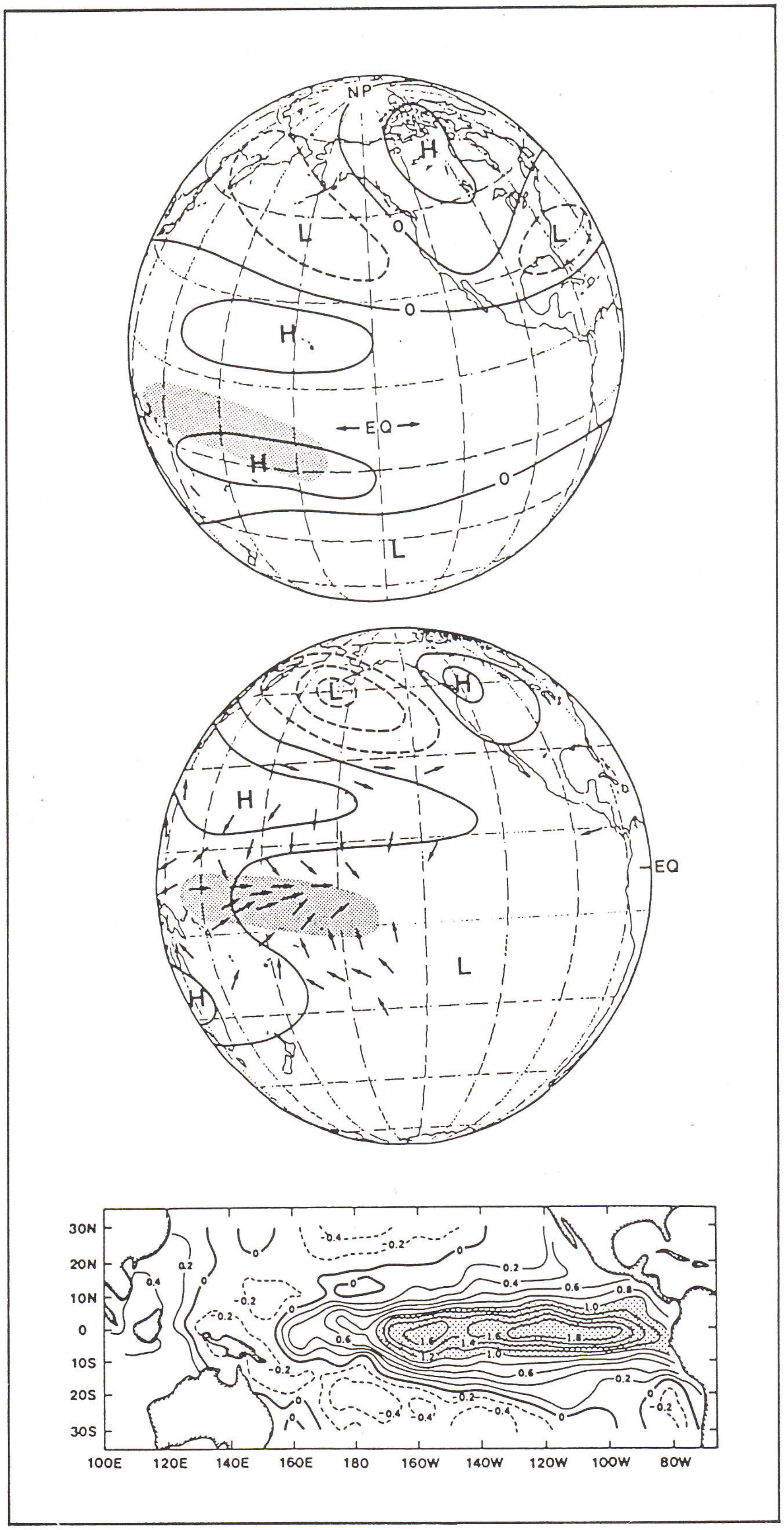

Figure 11 An illustration of the distributions of key properties involved in the teleconnection process during a typical ENSO event. (a) Upper troposphere anomalies of geopotential height for the northern hemisphere winter. (b) Contours of surface barometric pressure, with surface wind anomalies (arrows) in the tropics. Bottom: Distribution of anomalous sea surface temperature (°C). (From E. Rasmusson [14]. *Reprinted courtesy of Oceanus Magazine.*)

Figure 12 Damage due to coastal erosion by high surf at Pacifica, near San Francisco, California in 1983. *(Photo by James Sugar/Black Star.)*

The teleconnections of weather phenomena to more remote regions began in June-July 1982, when central Chile suffered the effects of record rainfall and flooding resulting from an intensified southern hemisphere winter jet stream. By December 1982 the sea surface temperatures along the equator had risen to 4–6°C above normal and were pumping energy into the subtropical jet stream of the northern hemisphere. Frequent storms moved south of their normal tracks and battered the California coast with high surf. The coastal erosion was all the more catastrophic for coastal communities due to the fact that mean sea level had risen about a foot (30 centimetres) above normal levels (figure 12). The offshore circulation of the normally southward California Current was reversed, and hundreds of marine species were carried far north of their normal ranges [22]. Some fisheries prospered; others collapsed; of these, a few have not yet recovered. And the list goes on: record drought in Australia, South Pacific hurricanes as far east as Tahiti, unusual winter rainfall in the southern USA and northern Caribbean, and so on. Certainly, the global weather disturbances were remarkable during 1982–83 [23], confirming the basic hypothesis of Bjerknes. However, the pattern of weather phenomena produced by the teleconnections turned out to be radically different from that on previous occasions. We currently fear that the details of the atmospheric response to El Niño warmings are hypersensitive to initial conditions in ways that are difficult or impossible to predict, and we need to know more about the teleconnection process.

Present and future research

The 1982–83 ENSO was a humbling experience for scientists; a comparable El Niño may not occur for another 100 years, but this one left its mark. Fortunately, the interest and funding generated from it has caused an explosion in ENSO research around the world, as well as widespread coverage in the popular press. In 1985 a decade of ENSO research was inaugurated under the aegis of an international effort called the Tropical Ocean-Global Atmosphere Program, or simply, TOGA. By the end of the 1990s, hundreds of meteorologists, oceanographers, biologists, and engineers will have been involved in TOGA, trying to unravel the many remaining mysteries of ENSO:

1. What are the mechanisms by which the oceanic relaxation produces unusual surface warming over large areas of the tropical Pacific?

2. Do the tropospheric teleconnections occur as Bjerknes explained, or does the atmosphere transmit anomalous variability through wavelike or other means?

3. Does the coastal wave propagation of oceanic disturbances to high latitudes really occur, or do the atmospheric teleconnections produce similar effects and merely make them appear wavelike (or, more likely, do both occur)?

4. What first causes the trade winds and Walker Circulation to decelerate, initiating an ENSO sequence, and can this event be predicted so as to produce reliable and useful forecasts?

The TOGA research strategy to answer these and many other questions is to foster investigations along three broad and interactive fronts [24]: long term (decadal) monitoring of key environmental variables; shorter term (several months to several years) field experiments designed to gain an understanding of the key processes that occur during ENSO; and theoretical and numerical modeling of ENSO with an aim to ultimately predicting its occurrence and time evolution.

What is the greatest obstacle to further progress? This author's worst fear is that the attention span of administrators and politicians will be too short to keep the effort funded for the full decade. Will another disaster be required to ensure final success?

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