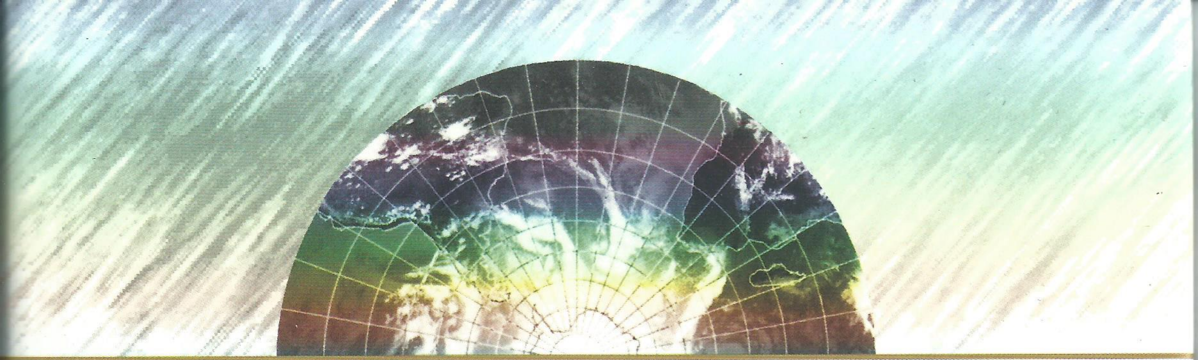
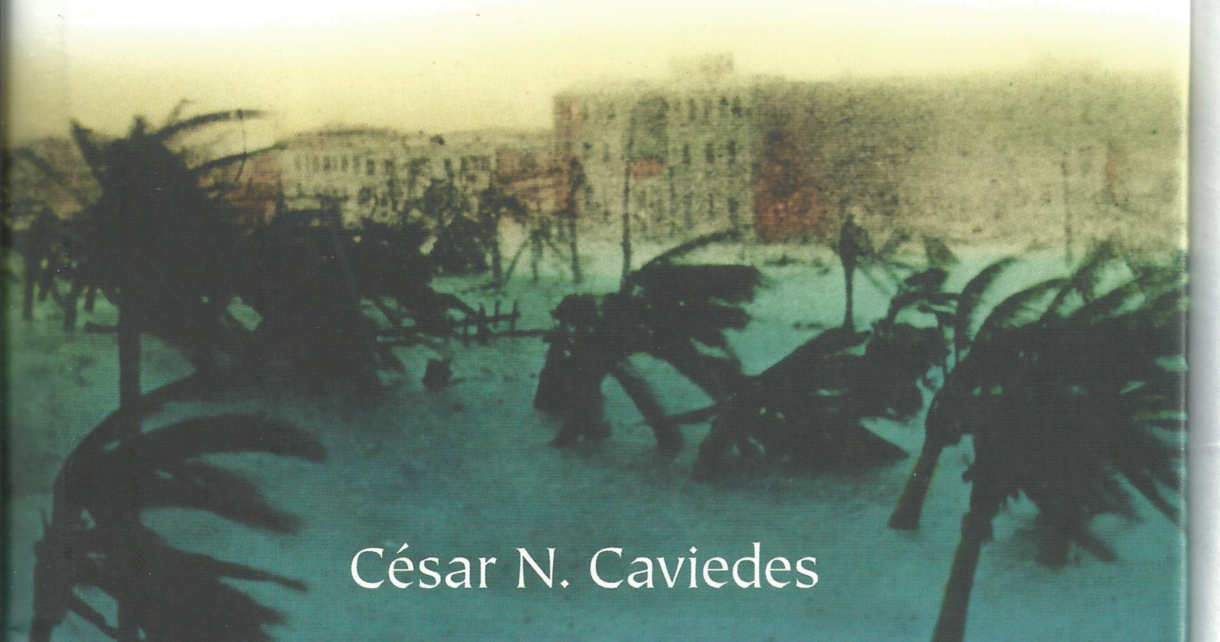


EL NIÑO IN HISTORY

Storming Through the Ages



César N. Caviedes

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Contents

to my pet subject. I also thank Michael Binford for volunteering chronological information and Jim Sloan for his excellent illustrations. Finally, I must mention my thirty-year relationship with the Hispanic Division of the U.S. Library of Congress through *The Handbook of Latin American Studies*, a relationship that provided me access to rare publications and other research materials in this incomparable facility.

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Grasping the Basic Concepts

Even though the earth is referred to as the "blue planet," we often fail to appreciate the implications of the fact that three-fourths of its surface is covered by water. The huge bodies of water are largely responsible for supplying our atmosphere with humidity: 419,000 cubic kilometers of water evaporate annually from the oceans, of which 106,000 cubic kilometers fall on continents as rain or snow. The oceans are also the main storage areas of carbon dioxide, the most important chemical compound for maintaining a balanced atmospheric temperature. Given that a quarter of the water provided by the oceans falls on continental surfaces, where it feeds the rivers, lakes, snow fields, ice masses, and vegetation that allow the existence of human settlements and the cultivation of fields, we can appreciate the oceans' importance for our survival.

Further, oceans have the physical ability to capture solar radiation and convert it into caloric energy (heat), which is distributed all over the globe. The Gulf Stream, as an example, exports to the British Isles and western Europe the caloric energy it has acquired while meandering

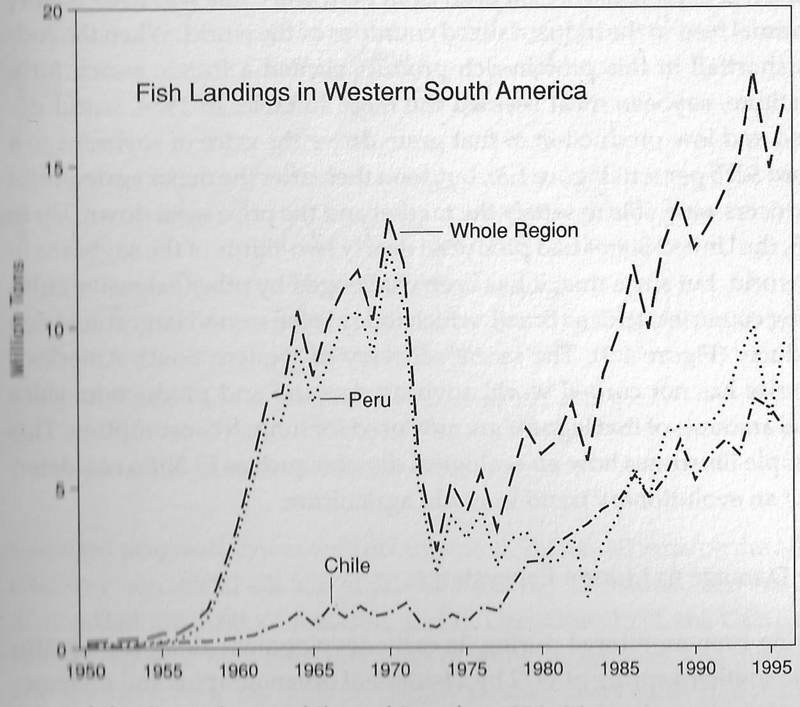
In those years Peru was the major fishing nation of the world (with Japan and the Soviet Union close behind). Its catches consisted mostly of anchovies (*Engraulis ringens*), a cold water fish that lives in voluminous shoals in the plankton-rich waters of the Peru Current. In 1970, Peru harvested nearly 10 million metric tons of that fish, and marine biologists warned that if these high harvesting levels were to coincide with the occurrence of an El Niño, the survival of the species would be threatened. The call was not heeded, as the exports of fish meal and fish oil derived from the anchovies provided a fiscal bonanza for the Peruvian government.

Then, El Niño 1972–73 struck. Although this event was not one of the most intense ENSO episodes of the century, it hit the coastal waters of Peru with particular ferocity. In 1971, the anchovy catches had reached a whopping 12 million metric tons, and when the west coast of South America was invaded by the warm waters, the anchovy stocks, weakened by overfishing, were unable to spawn at normal rates; fishing trawlers started to return empty to their ports of origin, seabirds began to starve, and the rookeries of seabirds and mammals that abound along the arid coast dwindled. Traveling down the coast of Peru in 1973, I witnessed scenes of misery: processing plants that produced fish meal were paralyzed, fishing trawlers lay idle in bays and coves, and the beaches were littered with bird and seal carcasses.

Of the estimated 27.5 million seabirds in 1970, only 1.8 million survived the crisis. By 1982, numbers were up to 8 million, but in the course of the 1990s, they never rose above the 10-million mark. Among these birds, the *guanay* (cormorant) is particularly noteworthy. It nests in large colonies on rocky islets off the coast, and its droppings, known as *guano*, are a coveted natural fertilizer. While guano was one of Peru's main exports in the middle of the nineteenth century, its exploitation today is negligible.

For the first time since the collapse of the Pacific sardines of California in the 1940s and the depletion of the Sakhalin sardines in the 1920s, a major world fishery was crumbling before the very eyes of the alarmed world fishery authorities. The catches for the year 1973 show the magnitude of the anchovy catastrophe: Peru landed only 2.3 million tons that year, and Chile as little as 668,000 tons (Figure 1.7). From 1973 to 1983 (another El Niño year), Peru endured an unstable fishing period, with catches hovering around 2 million tons per year. Chile chose a different path. In those years of military rulers, the Chilean general Augusto Pinochet ordered all industrial fishing operations to stop immediately, and after the 1972–73 low, he changed the focus from anchovies to jack mackerel (*Trachurus murphii*)—a larger subtropical fish—and sardines (*Sardinops sagax*), which thrive in temperate waters. With this change Chile moved ahead of Peru between 1979 and 1985. While Peru had its absolute lowest landings in the El Niño year of 1983, the rising trend continued in Chile thanks to species diversification. Only after 1985 did Peru start on the road to recovery, initially also by switching to sardines and jack mackerel. Since the early 1990s, a comeback of the anchovy stock has allowed the industrial fisheries to include that species in their ventures again.

During the 1990s, world fisheries underwent some interesting changes, for which El Niño acted as catalyst. The repeated oceanic warming episodes of the 1980s had led to contractions in the volume of catches, but by 1990, the combined annual landings of Peru, Chile, and Ecuador soared to a total of 14 million tons—which broke all prior records. In



1.7. Fish landings of Peru, Chile, and Ecuador, 1950–96

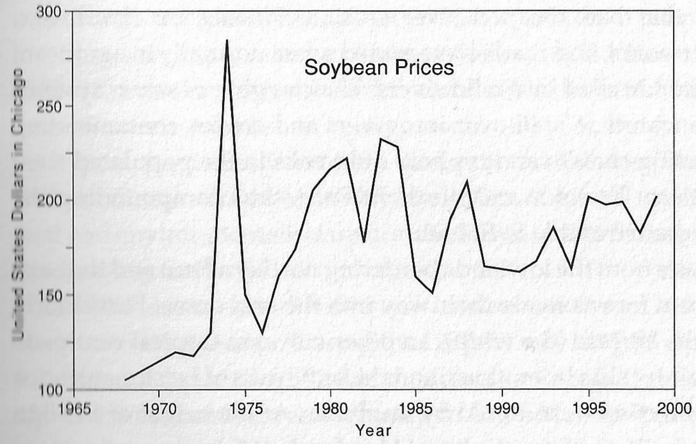
1994, landings from the cold waters of the Peru Current totaled 18 million tons, a volume that would have been unthinkable twenty years earlier and that demonstrates the resilience of the Peru Current ecosystem. In the 1990s, Peru regained the top position it had enjoyed in the 1960s, and Chile secured third place among the major fishing nations of the world. Recently, however, China has taken second place from Japan, which has slipped to fourth position. It should be pointed out in this context, though, that while Peru and Chile keep their activities in the adjacent coastal waters, Chinese and Japanese fishing vessels operate far from their territorial waters, harvesting resources that are not theirs but the patrimony of all humankind.

The changing fortunes of fisheries along the west coast of South America illustrate the impact a natural disaster, such as El Niño, can have on resources believed to be inexhaustible when it is coupled with overexploitation.

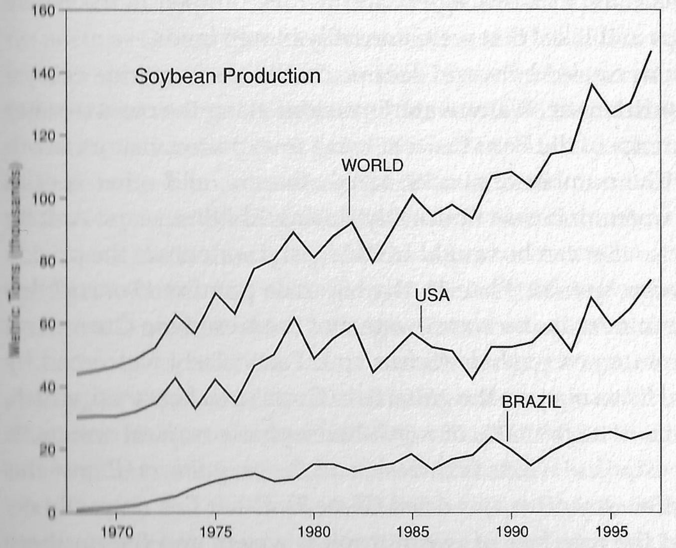
The collapse of the anchovy-based fisheries on the west coast of South America prompted an unexpected global revolution in the domain of agricultural specialization. Fish meal from Peru and Chile was used mainly as animal feed in the industrialized countries of the world. When the sudden shortfall in this protein-rich product elicited a frantic search for a substitute, soybean meal seemed the most suitable. In 1974, world demand and low production of that grain drove the price of soybeans to a record $275 per ton (Figure 1.8), but soon thereafter the major agricultural producers were able to satisfy the market and the price went down. Up to 1973, the United States had produced nearly two-thirds of the soybeans in the world, but since then it has been challenged by other extensive cultivating countries, such as Brazil, which today is the second largest soybean producer (Figure 1.9). The recent recovery of western South America's fisheries has not curbed world soybean demand and production, since equal amounts of that legume are now used for human consumption. This example illustrates how an ecological disaster such as El Niño can determine an evolutionary trend in world agriculture.

The Damage to Marine Ecosystems

Having been monitored during its early development along the equator in the southern spring of 1972 by a battery of oceanographic and meteorological devices, the devastation wrought by El Niño 1972–73 during its eastward progression was well documented. Torrential rains on the otherwise dry equatorial islands of Jarvis, Fanning, Christmas, and Malden dismantled the nests of seabirds, and in December 1972, the Galapagos Islands reported high mortality rates of seabirds, iguanas, and turtles. In arid northern Peru, the rains practically washed away cultivated fields of corn, beans, cotton, coffee, and sugarcane, depositing loads of sand and



1.8. Progression of soybean prices, 1970–99



1.9. Major world producers of soybeans, 1968–97 silt in fields that had escaped river erosion. Houses on riverbanks, bridges, waterworks, and roads were erased when normally insignificant trickles of water swelled into wild rivers. The clogging of sewer systems caused waste waters to spill over into rivers and creeks, contaminating wells and causing cholera and typhoid outbreaks in the populated river oases of southern Ecuador and northern Peru, thus compounding the general misery attributable to El Niño.

Tropical pests from the lowlands bordering northern Peru and the eastern Andean rain forests made their way into the arid oases. Particularly feared were the *latigazo* (the whip), an otherwise rare tropical centipede that causes painful skin lacerations, and the outbreaks of Leishmaniasis, a serious skin infection transmitted by sand flies. At the height of El Niño 1983, starving bullfrogs from the humid lowlands of Ecuador and eastern Peru littered the flooded streets and parks of towns in northern Peru. In 1972–73, 1982–83, and 1997–98, egrets and herons camped in the newly created swamps and lakes that were normally barren lands.

The alterations caused by warm oceanic conditions in marine ecosystems are no less dramatic. Warm water invasions along the coast that lies under the influence of the Peru Current bring unexpected visitors to offshore waters. The number of sharks, tuna, albacore, and other species from warmer waters increase noticeably during El Niño years. Among the exotic species that can be caught in the coastal waters are the prickly globe-fish (*Diodon hystrix*) (Plate 1), the big-scale pomfret (*Taractichthys steindachneri*) common in the warm waters of the Kuro Shio Current off Japan, and the humped *jorobado* (*Selene* sp.). Particularly welcomed by Peru's artisanal fishermen are the guitarfish (*Coryphaena hippurus*), which, like the dolphin, or mahimahi, of north-hemispheric tropical waters, is coveted for its exquisite white, firm flesh, and the *pez guitarra* (*Rhinobatus planicep*), an edible ray often sun-dried (Plate 2). Other fish normally occurring only at the interface of warm tropical waters and the northern edge of the cold Peru Current, such as tropical perch (*mero*) and skipjack (*Katsuwonus pelamis*), move to cooler waters farther south.

Also observable is the unusual southward migration of coastal mollusks and crustaceans. The *ostion*, or Pacific scallop, a tasty shellfish normally sheltered in protected bays, experiences explosive population growth during El Niño years, so that millions of scallops litter Peru's beaches during warm water episodes (Arntz and Fahrbach 1991). On the shallow, silty shores of Ecuador and Colombia also affected by the waters of El Niño, crabs and shrimp—otherwise confined to propitious coastal locations—multiply in large numbers. Following El Niños of 1972–73 and 1982–83, a new industry started in the shallow bays of Ecuador: shrimp nurseries were established in huge ponds (Plate 3), the product destined for export, particularly to North America and Europe. The competition with small scale shrimpers and the pollution of coastal waters by artificial feed had environmentalists up in arms, so today this industry is operating in a low-key mode.

El Niño also causes alterations in marine ecosystems along the Pacific coast of North America. During the 1982–83 and 1997–98 events, the California coast experienced visible modification in sea life between San Diego and San Francisco, and even up to Cape Mendocino. Not far off the coast, commercial fishermen were able to catch exotic yellowfin tuna, mahimahi, skipjack, marlin, albacore, and yellowtail during those years. The black durgeon (*Melichtys niger*) and similar species were sighted as far north as Queen Charlotte Islands, Canada (lat. 53°N), while other Californian species, such as the lizardfish (*Synodious lucioceps*) and tonguefish (*Symphurius atricauda*), advanced far north of their habitual temperate grounds, and crabs (*Nyctiphanes simplex*) expanded to the northern sector of Vancouver Island. Inversely, there was a marked contraction in salmon all the way from northern California to British Columbia.

A particularly damaging El Niño effect besets the coral populations in the Pacific basin. The colonies of these invertebrate organisms are very sensitive to environmental change. Since their survival depends on clear water, good circulation, and a narrow range of temperatures, a slight change in these conditions stunts their development or causes death. Thus oceanic fluctuations of El Niño or La Niña signature obviously have an enormous and immediate effect on corals of the Pacific Ocean, the Indian Ocean, and the tropical Atlantic. One of the main effects of ocean warming is coral bleaching—whitening of the coral surfaces due to the loss of a microorganism called zooxanthellae, which has a symbiotic relationship with growing corals. The absence of the temperature-sensitive zooxanthellae precipitates coral mortality and hampers the rapid rebuilding of young colonies. In addition, unusual warming of the waters leads to the disappearance of assorted crustaceans that feed on sea snails and sea urchins, the common predators of growing coral sprouts. Above all, coastal waters are polluted by abnormally high discharges of clays and silts from the copious runoffs of islands and continental margins, so that the resulting turbidity accelerates coral destruction. Glyn and Colgan (1992) estimate that the ENSO event of 1982–83 caused the extermination of nearly 95 percent of the Galapagos Islands' corals and resulted in a 70 to 95 percent reduction in the corals on the coasts of Costa Rica, Panama, Colombia, and Ecuador, all of them in the eastern Pacific Ocean. Fortunately, corals have a remarkable regenerative ability by recruiting larvae from nearby sound colonies; however, when disturbed marine conditions persist—as they did during the prolonged but mild El Niño of 1991–94—the regeneration process can be dangerously retarded.

Of the organisms living in tropical waters, corals are also the most prone to reflect environmental alterations in their biological development. The body of an individual coral grows radially by means of carbonate secretion, the growth phases being indicated in the latticed skeletal structures in the form of annual bands. The carbonate compound that constitutes the coral skeleton is aragonite, a mineral that incorporates into the calcium some trace metals such as cadmium, barium, and manganese, as well as oxygen isotopes (δ18 oxygen). Cadmium and barium are regarded as indicators of cool upwelling water conditions, with barium being very sensitive to sea temperature changes. Manganese, which indicates fine sediments of continental origin, also tends to decrease during warm ENSO episodes due to increases of coarse particles. The δ18 oxygen component of coral skeletal aragonite is precipitated by seawater and diminishes as water temperature and rainfall increase during El Niño episodes (Cole, Shen, Fairbanks, and Moore 1992). By analyzing thin coral sections, marine biologists and sediment geologists have established that deficits in δ18 oxygen, calcium/cadmium, barium/calcium, and manganese/calcium are caused by warm ENSO phases (Evans, Fairbanks, and Rubenstone 1998). Today, chemical analyses of contemporary and fossil corals offer insights into climatic variations that neither instrumental nor historical series are able to provide and are considered one of the key tools for verifying disturbed oceanic conditions of El Niño signature in the past.

Bugs and Mice of Humid Years

Some astounding ecological responses to El Niño occur on land in various corners of the world. For example, in the forests of the Amazon, the German zoologist Arim Adis noticed that spiders and other insects seem to possess a sensorial mechanism that detects rising environmental humidity and prompts them to start crawling up tree trunks well before the onset of the rainy season or to move higher as the rains arrive. The vast expanses of the Amazon lowlands are crisscrossed by streams and side channels of the Amazon River, which at the height of the rainy season—March through August—are extensively flooded. Not only insects, but terrestrial reptiles and rodents as well, are forced to move to higher grounds. Early studies of precipitation in the South American continent showed that El Niño is coupled with reduced rains in the central Amazon basin and that the rainy season—if not failing altogether—is shortened to April, May, and June. Over the course of years of observation, Adis noted that the upward movement of insects started later than usual and did not go as high during years with lowered precipitation, or El Niño years, establishing a startling "distant ecological connection" with that anomaly in the Pacific Ocean.

Another fascinating connection between a biological crisis and El Niño gained notoriety in 1993, when in the Four Corners region of the United States (New Mexico, Colorado, Arizona, and Utah) the aggressive Hanta virus broke out in the Navajo reservation with that name. The virus—harboring in the desiccated feces of the deer mouse, a small rodent that lives in abandoned dwellings—attacks the respiratory tract and leads to death within a few days. As it happened, the deer mouse population (as well as the number of rodents that feed on grasses and succulents) had exploded in 1993, in the wake of the El Niño rains that fell over the southwest part of the United States during the 1992–93 winter. Thereafter, the fatal disease—also associated with rainy winters—surfaced in other parts of the nation and even made its way into South America in the aftermath of El Niño 1997–98. Hanta pulmonary deaths were recorded in northern Chile, the highlands of southern Bolivia, and northwestern Argentina, all of them arid regions like the Four Corners where rodents might multiply twentyfold during rainy El Niño years. The Hanta virus, whose sole transmitter is mice, has been known in eastern Europe and also in the cold steppes of Asia since the Middle Ages, but the strains that developed in North and South America are new and probably unrelated to those of the Old World. The outbreak of the Hanta virus in the Americas appears to be a case of biological convergence triggered by this climatic variability that we call El Niño.

through the Gulf of Mexico and the Caribbean Sea. Inversely, cold from subpolar latitudes is exported to lower latitudes by cold water flows, such as the California or Peru currents. Thus the oceans play a crucial role as major suppliers of humidity and regulators of our global temperature.

As you can observe in any kitchen when you heat a pot of water on the stove, the water begins to pass into the air as steam before it reaches the boiling point; water that is kept at room temperature, however, takes much longer to be converted into water vapor and in some cases may not even become a vapor at all. This basic observation—that the transformation of water from a liquid to a vapor state depends on temperature conditions—helps us understand that warm ocean surfaces transfer more humidity and heat into the atmosphere than do cold ocean surfaces.

Not only are water masses slower than continental masses to absorb energy from the sun, they are also slower to release it. This means that regions in the vicinity of the sea enjoy milder temperatures in the summer months, while regions in the heart of continents get very hot in the summer but their temperatures drop drastically with the arrival of autumn. Referring to the diverse pace of temperature transfers, climatologists speak of oceans having a "long thermal memory" and continental masses having a "short thermal memory."

Of all the oceans of the earth, the Pacific Ocean is the uncontested giant, accounting for three-fifths of all water masses. This fact alone explains the Pacific's dominant influence over the continental masses that surround it—North America, Asia, Australia, and South America—and over regions that are farther removed, such as the Caribbean basin, the islands of Indonesia, and even the Malayan Peninsula and the Indian Subcontinent. To put the huge dimensions of this body of water into perspective, let's compare it with the Atlantic Ocean: at its widest extension (from the Gulf of Panama to the Celebes Sea), the Pacific spans 11,447 miles, or 45 percent of the earth's circumference; by contrast, the widest part of the Atlantic (from the littorals of Georgia to the coast of Morocco) is roughly 4,200 miles.

Another important difference is that the widest part of the Pacific coincides roughly with the equator line, whereas the widest part of the Atlantic lies within the middle latitudes. Therefore, the Pacific Ocean possesses a much larger surface for collecting solar energy in equatorial latitudes, and passes much more humidity and heat into the atmosphere, than the other oceans. On top of this, when an ocean of the dimensions of the Pacific undergoes inter-annual variations of sea temperatures due to solar inputs or by virtue of some non-annual cycles that affect its "memory," these *variations* are also reflected in proportionally higher humidity and temperature exports to contiguous and distant lands. One of these variations, and perhaps the most important climatic oscillation of our times, is El Niño.

Oceanic and Climatological Aspects of El Niño

The coastal communities of northern Peru have traditionally been highly dependent on the sea. Farming was practiced in the few river oases of that desertic region, but the main source of animal protein was the abundant fish in the cool Peru Current. Cold water fish differ from warm water fish in that they are lean, streamlined, firm, and live in shoals. Warm water fish have a rounder shape, their meat is softer and lighter, and—with the exception of tuna—they do not commonly swim in schools.

These distinctions have been well known to north Peruvian fishing villagers since precolonial times. They observed that in December—the beginning of the southern summer—tepid waters began to move into the domain between the Gulf of Guayaquil and Pariñas Point. This annual invasion of warmer-than-usual waters caused not only changes in fish populations (a decline in the species they commonly caught and an increase in tropical fish) but also a surge in air humidity in this arid coastal region, leading to frequent summer showers. Since this set of changes happened around Christmastime, the fishermen called it *El Niño*, meaning the Child Jesus.

Erwin Schweigger, a German marine biologist who spent most of his professional life in Peru, observed that in certain years this annual occurrence—called *minor El Niño*—was supplanted by extensive invasions of equatorial warm waters that would expand much farther south than Pariñas Point and last throughout the southern summer. He also noticed that these events were accompanied by considerable variations in the weather—dense cloudiness, high air humidity, frequent thunderstorms, and heavy rains—and posited that these changes had to do with sizable alterations in the behavior of water and air masses across the entire tropical Pacific, and not with the short-lived El Niño episodes of early summer. These severe events he called *major El Niños.*

For quite a while, the regionally restricted phenomenon did not arouse the curiosity of the scientific community, although some dramatic El Niño events, such as those of 1911, 1925, and 1953, made it into the pages of reputable journals. It was only with the 1957 occurrence—coinciding with the International Geophysical Year in which particular attention was paid to global geophysical phenomena—that earth scientists turned their attention toward this oddity on the west coast of South America.

In the 1960s, Hermann Flohn, of the University of Bonn, suspected that this phenomenon had an impact on the climate of South America and directed his students Rolf Doberitz and Karin Schütte to investigate the rain patterns and wind frequencies on Pacific islands located along the equator and to correlate their findings with weather events on the Galapagos Islands and in coastal Ecuador and Peru. Also in the 1960s, Professor Jacob Bjerknes, at the University of California–Los Angeles, began to investigate the coupling of sea-surface temperatures with dry and rainy episodes on several tropical islands in the Pacific. In their studies, both men and their disciples pointedly identified El Niño as the major catalyst for climate variations in the Pacific and in western South America. Concurrently, Klaus Wyrtki, an oceanographer at the University of Hawaii, was studying the dynamics that explain the circulation of water masses in the Pacific. These three scientists laid the foundations for our present knowledge of the oceanic and climatic peculiarities of the El Niño phenomenon.

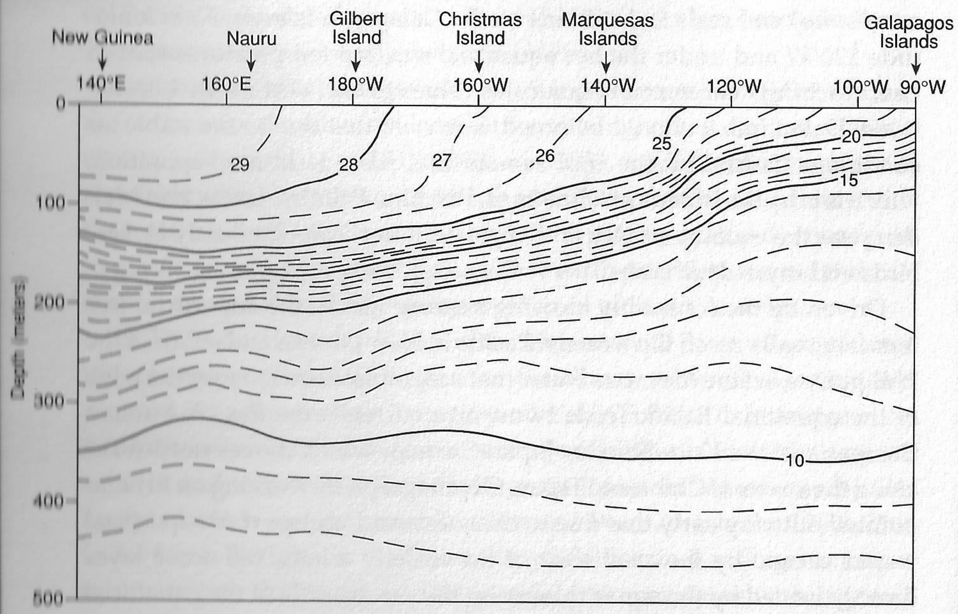
The early investigations indicated that there were two aspects to this recurring event: the *oceanic aspect,* which related to anomalies of sea temperatures across the tropical Pacific, and the *meteorological aspect,* which had to do with variations in the atmosphere above.

The Oceanic Aspect

Under normal conditions, the segment of the tropical Pacific from the coast of Ecuador/Peru to longitude 120°W is dominated by westward-flowing cold waters that are the prolongation of the Peru, or Humboldt, Current. Off the north Peruvian coast, the current turns away from the continent and forms a flow that is abnormally cold for equatorial latitudes; the cold water makes both the Galapagos penguin (*Sphoenicus mendiculus*) and seals feel at home on the Galapagos Islands. Near longitude 120°W and under the hot equatorial sun, sea temperatures start to rise, reaching near-normal equatorial values to the west of the International Date Line. It should be noted, however, that due to the stable air conditions caused by the cool sea surface, there is little evaporation, which is why the islands of Christmas, Fanning, Palmira, Jarvis, and Malden near the equator are dry and vegetation free, colonized only by seabirds and myriads of crabs.

Driven by the constantly blowing easterly winds, the superficial waters eventually reach the western Pacific in New Guinea and south of the Philippines, where the *excess* water that accumulates on the western edge of the equatorial Pacific feeds two warm currents: the East Australian Current and the Kuro Shio, or Japan Current, which moves northward along the coasts of China and Japan. Oceanographers working on El Niño pointed out very early that due to this westward transport of superficial waters caused by the *wind shear* of the easterly winds, the ocean layer directly heated by the sun is thinner on the eastern side of the equatorial Pacific and thicker on the western side, where the warm waters, driven by the easterlies, tend to pile up. The "thickness" of the superficial layer is determined by the *thermocline,* or lower boundary of the sun-heated upper layer that around 20°C marks the beginning of cooler water temperatures underneath. Under normal oceanic conditions, the thermocline between Peru and the Galapagos Islands runs at a depth of some 40 meters, while on the Asian side of the Pacific, it dips as low as 120 meters, revealing a marked asymmetry in the thickness of the sun-heated layer across the Pacific (Figure 1.1).

During abnormal warm years—synonymous with El Niño years—many of the above-mentioned conditions are drastically altered. First, the westward flow of cooler waters weakens or ceases to exist; second, there is less or no wind shear from the easterly winds; third, the thermocline in the eastern half of the equatorial Pacific may reach depths of up to 80 meters; fourth, there is horizontal transport (*advection*) of warm waters from west to east, which is caused by the development of Kelvin waves (explained later in this chapter) in the upper 100 meters of the tropical Pacific. This eastward movement, originally believed to be a massive outflow, prompted coinage of the term *El Niño current,* in use into the late 1950s. Today, the invasion of warm waters from the west Pacific is pic-



1.1. The thermocline across the equatorial Pacific Ocean. Arrows indicate the location of Pacific equatorial islands mentioned in the text.

tured as an oil slick pouring out of a damaged tanker, that is, as oil patches constantly changing shape and direction under the influence of the variable winds and the Kelvin waves.

During El Niño years, these events begin at the onset of the southern spring, that is, in September and October, and during the following months the warm waters proceed eastward, reaching the area between the Galapagos Islands and the Ecuadorian/Peruvian coast in the month of December. The eastward migration of warm water can start earlier, as it did in 1997, when advection in the western Pacific began in May, or in other instances the warm waters may stall before reaching the Galapagos Islands, which results in an "aborted" El Niño, as happened in 1976.

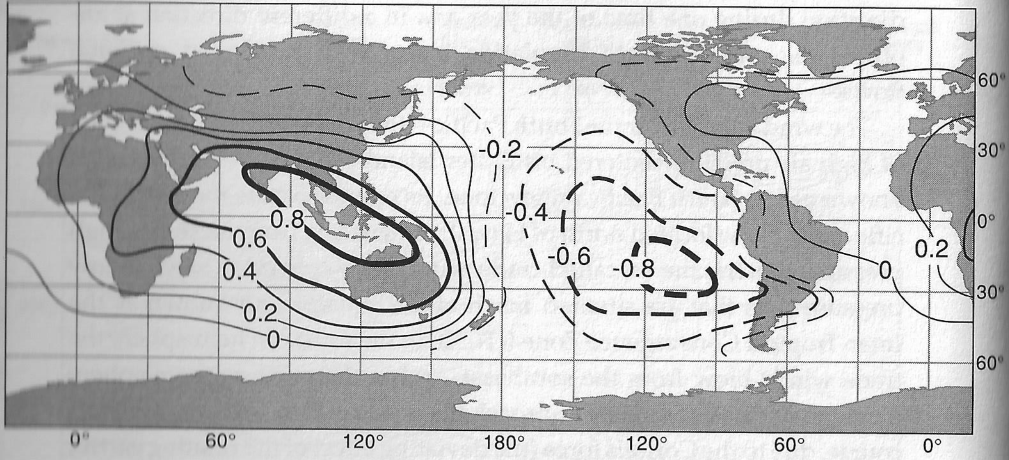
The Meteorological Aspect

Before proceeding any farther, we need to understand that the superficial circulations of the sea are prompted by the winds blowing above it. Surely, the water's response to episodic winds is the formation of waves and swells, but with winds of seasonal character—that is, blowing in one direction during one time of the year and in a different direction at another—the entire surface circulation reacts with prolonged seasonal flows.

The wind source over the South Pacific—the cradle of El Niño—is a cell of high air pressure centered on Easter Island (27°S, 110°W); this cell is known as the South Pacific anticyclone. Its counterpart is the North Pacific anticyclone located north of Hawaii. Emanating from these two high pressure centers, the so-called trade winds flow toward a band of low pressure cells that are situated north of the equator and known as the Inter-Tropical Convergence Zone (ITCZ). In the southern hemisphere the trade winds blow from the southeast, and in the northern hemisphere from the northeast. As they approach the equator, they take an east-west course, due to the Coriolis force (the deviating effect of the rotating earth), and are henceforth known as equatorial easterlies. Trade winds, equatorial easterlies, and the westward water transport intensify when the two high pressure cells are strong. In those years, the waters of the eastern Pacific are moderately cold, and the thermocline runs not far below the ocean surface.

However, when—for reasons still not well understood—the South Pacific anticyclone loses intensity, the whole wind system that it supports collapses. The trade winds slacken or cease altogether, the thermocline thickens in the eastern tropical Pacific, and westerly winds replace the easterlies in the tropical belt. Coupled with these changes is the onset of the eastward advection of warm waters, described in the previous section. In addition, a phenomenon occurs that may be even more important: hot and humid air masses—uncommon in the tropical Pacific—glide on top of the warm waters and begin their progression to the east, dumping along the way torrential rains on the dry equatorial islands mentioned above, as well as on the arid coasts of Ecuador and northern Peru, which are not accustomed to such downpours.

These highly visible oceanic and atmospheric changes in the eastern Pacific during El Niño years are some of the indicators of large-scale climate variations in progress. As early as 1924, Sir Gilbert Walker, working with the Indian Meteorological Service, noticed a counterbalancing tendency between air pressures at Djakarta (Indonesia) and those measured at Tahiti (French Polynesia), which suggested an interrelation between the pressure cells over the two locations notwithstanding the distance



1.2. The two hemispheres of the Southern Oscillation. Solid lines show positive correlations of air pressures with Darwin/Djakarta in the "eastern hemisphere," and broken lines show negative correlations with Tahiti in the "western hemisphere," during El Niño years.

involved. Thirty years later, the Dutch climatologist H. P. Berlage proposed the concept *Southern Oscillation* to refer to the counterbalancing of pressures within the southern half of the tropics. The Southern Oscillation expresses the difference between the high pressure cell of the South Pacific and the low pressure cell over Indonesia. Meteorologists use an index to quantify this difference. A high Southern Oscillation Index (SOI) signifies dominance of easterly winds and cooler sea conditions in the Pacific, while a low (or negative) SOI means weakness or absence of easterlies, high humidity in the tropical atmosphere, and warm ocean conditions. Walker and Berlage were the first to realize that the pressure field of the South Pacific was interlocked with the pressures over Indonesia in a way that fitted the development of El Niño. That is, during El Niño events, the South Pacific anticyclone is weak while the Indonesia low is strong—triggering a series of anomalies in the Indian and Pacific Oceans.

The Southern Oscillation Index has become the established yardstick against which most climate variations in the tropics and middle latitudes are gauged. Knowing how to interpret these variations allows predictions of the degree to which El Niño conditions in the tropical Pacific will affect other world regions within a few months. During major El Niño events, when the whole tropical belt is engulfed by atmospheric and oceanic anomalies, the areas influenced by the Southern Oscillation are so vast that one can clearly identify two hemispheres (Figure 1.2): a western hemisphere that comprises the Pacific basin, western South America, Central America, and the western half of North America, where abnormally low air pressures, warm coastal waters, and unusually heavy rains occur; and an eastern hemisphere centered on Indonesia, where air pressures are high, ocean waters are cooler than normal, and severe droughts are visited upon certain regions. Included in this eastern hemisphere are Southeast Asia, Australia, India, Africa, the Atlantic basin, and northeast Brazil. Readers should now understand why, when El Niño makes it into the news for pounding California with rainstorms and wreaking havoc in the islands of the Pacific or in Peru, they also hear about wildfires in Indonesia, livestock mortality in Australia and South Africa, drought, starvation, and death in sub-Saharan Africa, and—more so in the past than lately—famine in India and northeast Brazil. The long-distance implications, or teleconnections, of El Niño and other climatic developments are covered in the next section.

Any study of El Niño and the Southern Oscillation, or ENSO—to use the acronym—should address the frequency of occurrence of such events. Table 1.1 lists El Niños since the early 1800s, and La Niñas from 1870 onward, for it was not until the nineteenth century that air and sea temperatures, pressures, and precipitation began to be systematically recorded in reliable and continuous series. Sporadic observations and unreliable measurements from earlier times do not permit comparisons with the existing series from developed parts of the world.

Early observations seemed to indicate that ENSO events occurred at intervals of about eleven years, a circumstance that led to speculation that these flare-ups of heat and humidity in the Pacific were prompted by "sunspots" that tend to peak at eleven-year intervals. However, the surge in frequency of ENSO events after 1970 and their occurrence also in years of low sunspot activity have forced researchers to look for other explanations. Today, accurate studies of the frequency of ENSO events show that they occur at intervals of about three and a half years, and that the major events tend to repeat themselves every six years. What processes are responsible for these return intervals is a question that still keeps geophysicists busy and that we will return to in the final chapter of this book.

Table 1.1
Warm (El Niño) and cold (La Niña) Pacific episodes since 1800

El Niño	La Niña	El Niño	La Niña
	1802*	1900	1903
1803			1904
1804			1908
		1911	1910
		1912	
1812			
1814			1917
		1919	
1817			
1819	1822*		1924
	1825*	1925	192?
1828		1926	
	1832*	1932	1933
			1938
1844		1940	1939
1845		1941	1945
			1950
1850		1953	1955
	1857*	1957	
		1958	1960
1864	1863*		
		1965	1964
			1968
1871	1872	1972	
	1873	1973	1974
	1875		
	1876	1976	
1877			
1878		1982	
1884		1983	1984
	1886		
	1887	1986	1988
	1890		
1891		1992	
	1893	1993	1994
1897	1898	1997	
		1998	1999

* Estimated from dry periods in western South America. All others inferred from low sea surface temperatures in the eastern tropical Pacific.

The Distant Effects: Teleconnections

We rarely stop to think about the fact that the weather we are experiencing locally may be the result of climatic developments in a distant region of the globe. If we were to tell a man in Buffalo who shovels the snow from yet another winter storm that this "white stuff" is actually coming from the Pacific, he would probably reply that he could not care less, for all he wants is this miserable winter to end. Of similar irrelevance to him would be the fact that the earth rotates from west to east and that, dragged by the momentum of this rotation, most of the weather systems that travel over North America, or across South America, and Europe follow a distinct *west-east* trajectory. However, these points are central to understanding how the effects of El Niños in the Pacific can be "exported" to distant regions.

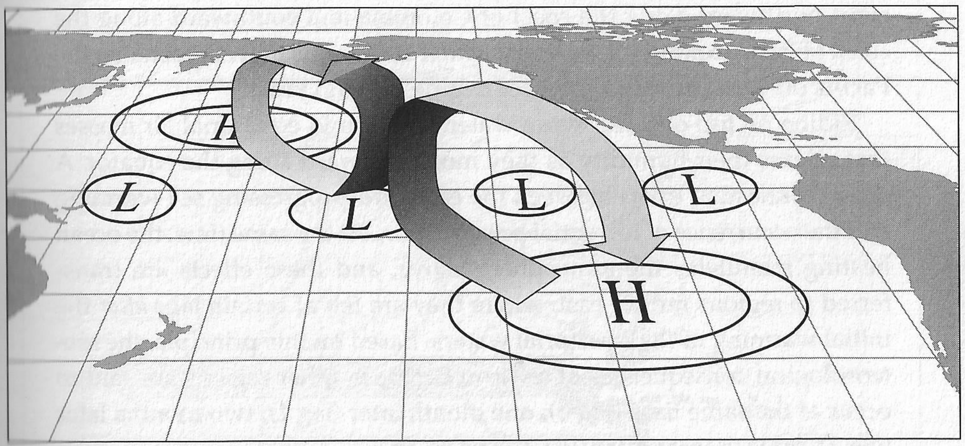
Nevertheless, the workings of these processes were difficult to visualize before the advent of satellites that could track and transmit images of weather systems. Unlike static weather maps, contemporary satellite images actually show movements of clouds, storms, and fronts. On the screen we see how white streaks (cloud bands) or rotating swirls (traveling cyclones or depressions) make their way across the oceans and onto continental North America or Europe, and we begin to understand how dependent local daily weather is on the events occurring over oceans.

In the early decades of El Niño research, climatologists did not have the tools we work with today. My initial investigations of rainfall variations in temperate central Chile were conducted at a time when satellite imagery was affordable only in the industrialized countries of the northern hemisphere. So when I explained to my countrymen in Chile that the precipitation they received depended on the sea temperatures in the eastern Pacific Ocean, more than a few eyebrows were raised in disbelief. However, subsequent research proved that El Niño had important implications for regions beyond the restricted realm of northern Peru and Ecuador. Finally, the informed public grasped the large areal involvement of the Southern Oscillation and was ready to accept the notion that weather developing over the South Pacific not only bore upon the circum-Pacific regions but involved Indonesia, India, Africa, and Europe. The distant relations between local weather and the vagaries of ENSO (that is, El Niño and the Southern Oscillation) are known as *teleconnections*.

To understand how teleconnections operate, it is necessary to consider the different circulations that drive the movement of air masses on the globe. Circulations consist of "circuits" that are fueled by heat engines and pressure differences scattered over continents and water masses. The main circuit is the thermal-driven Hadley circulation, which involves warm air rising in equatorial latitudes due to surface heating and descending in subtropical latitudes once the air has cooled in higher elevations (Figure 1.3). Thus the warm equatorial belt constantly provides heat to other latitudes and feeds the subtropical high pressure cells from which the trade winds emanate. Another circuit, known as Walker circulation, entails the less dramatic but equally effective exchange of air from warm oceans or continents to cooler waters and land masses. While the Hadley circulation activates movement of air away from the equator, the Walker circulation propels air masses along the equator, as seen in Figure 1.4. Ascending branches are located over heated waters and superheated continental interiors—such as the Amazon and Congo basins; descending branches sit over cooler waters and dry continental margins—such as those of coastal Peru and Chile, and of Angola.

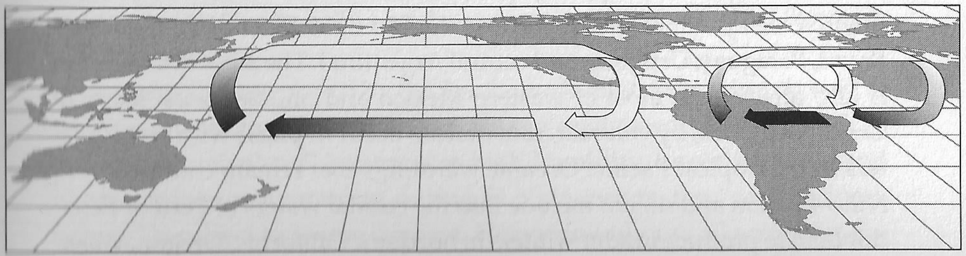
Complicating this picture are other interactions between pressure cells. We have already discussed the Southern Oscillation (SO), which interlaces the centers of the South Pacific and Indonesia. There is also the North Atlantic Oscillation (NAO), which expresses the differences between the Azores high and the low pressure over Iceland and influences air masses circulating over the tropical or midlatitudinal Atlantic Ocean and conterminous lands. NAO closely reflects the strength or weakness of the trade winds in the North Atlantic and controls, to a certain degree, the passage of hurricanes during the summer and fall seasons. While the Southern Oscillation rules air circulation in the direction of the parallels, the North Atlantic Oscillation runs along the meridians and across the parallels, thereby fostering exchanges between cold and warm air masses in the northern Atlantic basin.

The interactions between these circuits can be compared to the communications between computer nodes whose impulses cause varied responses depending on the nature of the intervening systems. Included in this cacaphony of communications are warm and cold oceans, rising or descending circuit branches, dry and humid air masses, warm continental interiors and cool coastal margins whose various circulation circuits can be greatly upset by oceanic El Niños or La Niñas. Obviously, the energy input into different latitudes and longitudes also varies from case to case.



1.3. The Hadley circulation. Air from the subtropical highs converges to the equatorial lows, or doldrums.

Let us now look at the teleconnections triggered by El Niño. The warming anomalies that indicate the onset of an El Niño are first felt over the western half of the equatorial Pacific, usually at the beginning of the southern spring. It takes two to three months for the warm surface water to flow into the intervening space between the Galapagos Islands and the northern coast of Peru. The movement of this superficial water mass occurs in the form of Kelvin waves, pulsating advances of warm waters that were pooled in the western Pacific during the preceding period of dominating easterlies. Under slackening easterlies that normally keep these waters confined to the west Pacific, they begin to spread from west to east along the equator, temporarily raising sea levels by as much as two feet (seventy centimeters). Upon reaching South America, the Kelvin waves



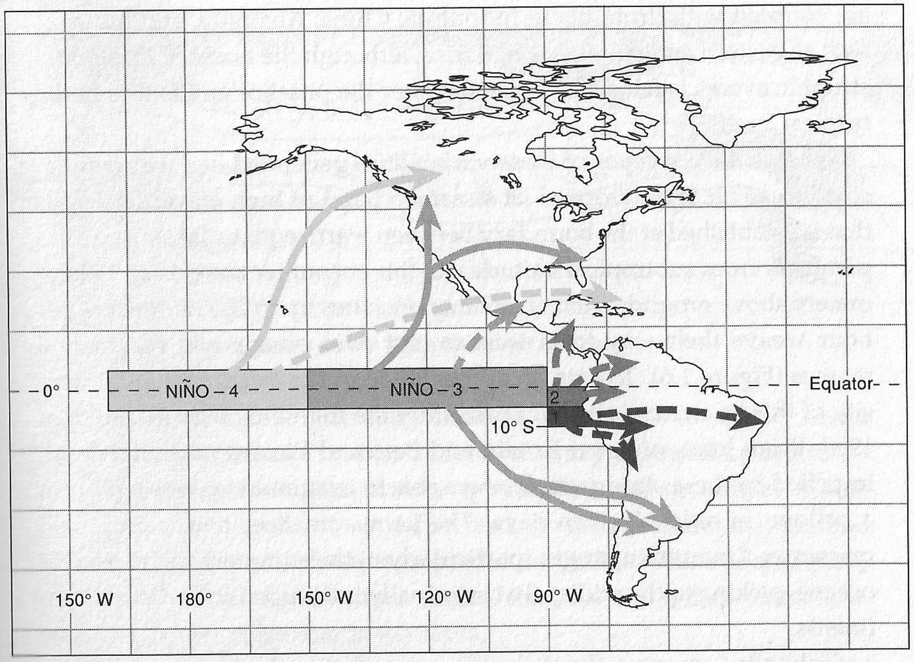
1.4. The Walker circulation. Surface air along the equator flows from east to west and returns east at high elevations.

swirl northward along the coast of Colombia and southward along the coast of Peru, expanding the warm water conditions that characterize the Pacific off western South America during El Niño years.

Riding on top of these warm waters are humid equatorial air masses that release their humidity as they move eastward along the equator. A direct connection exists between the eastward-progressing sea warming and the occurrence of torrential precipitation. At the same time, the ocean heating stimulates the atmosphere above, and these effects are transferred to regions farther east, where they are felt at certain lags *after* the initial warming of the equatorial waters. Based on this principle, the meteorological consequences of a warm Pacific in other regions are said to occur at the same time (lag 0), one month later (lag 1), two months later (lag 2), three months later (lag 3), and so on.

After decades of studying the thermal behavior of the tropical Pacific, as well as related precipitation and temperature conditions in distant regions, oceanographers discerned a distinct pattern of El Niño manifestations and divided the tropical Pacific into four major quadrants, or "regions" (Figure 1.5). El Niño 1 region comprises the coastal waters off Peru, which heat up only during major oceanic warming events. High water temperatures in this quadrant correlate with simultaneous torrential rains in the conterminous countries and with severe droughts in the Peruvian Andes and on the Altiplano of Bolivia. Across the continent, in northeastern Brazil, these El Niño episodes are associated with devastating droughts.

Warm waters in El Niño 2 region, comprising the ocean between the Galapagos Islands and the coast of Ecuador, correlate closely with increased rainfall in the Pacific lowlands and the Andes of Ecuador and decreased precipitation in the interior Amazon basin. When the waters in El Niño 3 region heat up, high precipitation occurs—after two or three months' delay—in central Chile and the Rio de la Plata basin (southern Brazil, Paraguay, Uruguay, and central Argentina). The coast of California is also affected. In most of western Mexico and on the Pacific slope of Central America, by contrast, rain deficits occur in phase with warm waters in the tropical Pacific. Oceanic warmings that remain confined to El Niño 4 region and do not intrude into the coastal waters of Peru or Ecuador tend to produce milder winters in northern California, Oregon, Washington, British Columbia, and the U.S.-Canadian prairies. Inverse relations between this El Niño region and lowered precipitation are



1.5. The four quadrants of El Niño in the tropical Pacific Ocean and relationships with rain in the Americas.

experienced in most of the Antilles, as well as along the Caribbean coasts of Colombia and Venezuela.

However, since sea temperature changes of the tropical Pacific are the result of atmospheric forcing, that is, pressure variations and resulting winds in the southern hemisphere, these precipitation and temperature anomalies are also related to the Southern Oscillation Index (SOI), since the latter is an accurate expression of the atmospheric variabilities affecting the circulation over tropical oceans. In fact, most of the studies on teleconnections with ENSO-related anomalies use the SOI as the main scale of reference.

Keeping the role played by the Southern Oscillation in mind, as well as its division into two distinct halves, we can easily see that while the SO's "western hemisphere" experiences high humidity, torrential rains, and above-average temperatures during El Niño events, the "eastern hemisphere" is subject to severe dryness. Heavy downpours all across the Pacific, catastrophic rains and river flooding in Ecuador and Peru, and heightened rains and winter storms on the Pacific coast of North America are coupled with droughts in Indonesia, China, Australia, and India, as well as eastern and sub-Saharan Africa, although the brunt of these catastrophic events is felt several months after the onset of an El Niño in the tropical Pacific.

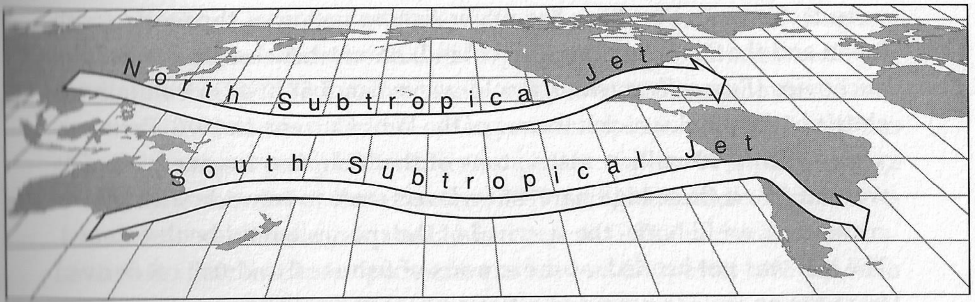
What is the conveyor of these variabilities generated in a warmed Pacific Ocean? It is the tropical jet stream, a band of high-elevation winds that is established at the boundary between warm equatorial air and temperate air from subtropical latitudes. In this encounter zone, 12 to 15 kilometers above ground, winds reaching velocities up to 200 kilometers per hour weave their way from west to east over oceans and continental masses (Figure 1.6). To gain an appreciation of the steadiness and intensity of this jet stream, one might consider the following feat: in March of 1999, Brian Jones of Great Britain and Bertrand Piccard of Switzerland, impelled by these strong winds, were able to circumnavigate the globe in a balloon in only nineteen days. The jet stream rises over continental masses and mountain ranges (particularly in the summer) and dips over oceans, picking up humidity that eventually is dropped over distant continents.

Only after grasping the dynamics operating in the high troposphere (12,000 to 15,000 meters up) can one understand how stimuli generated in the distant tropical Pacific can be responsible for unusually mild winters in western Canada, rainy springs in the southeastern United States, and cold, snowy winters in western Europe during El Niño events.

Nature's Reactions to El Niño and La Niña

So far we have reviewed a series of disturbances that characterize the atmospheric and oceanic aspects of El Niño and its counterpart, La Niña. Since these changes represent brisk departures from normal conditions, they exert enormous stress on natural environments through high humidity and heavy rains in certain regions and severe droughts in others.

A sudden surplus of water in dry areas may bring dormant vegetation to bloom and cause an explosive multiplication of insects, reptiles, and small mammals, which, in normal years, stay within controlled population levels. Lack of water in other regions has the opposite effect: not only does the usual vegetation dry up or go dormant, but animal life that consumes it is drastically reduced. The fact that El Niño is basically an alteration of oceanic conditions makes its impact on the oceans even more serious. Ocean warming usually involves an increase in salinity and a reduction in oxygen and carbon, a life-threatening change for plankton—microorganisms of vegetal nature (phytoplankton) or animal nature (zooplankton)—on which many fish feed. A reaction in the marine food chain follows: not only the oceans' predators, but also seabirds and mammals (seals, sea otters, and small whales) that feed on the fish, suffer famine and a severe reduction in numbers.



1.6. The meandering paths of the subtropical jet streams

Let us now turn to a selection of ecological crises caused by El Niño and La Niña in natural systems and their effect on human activities that depend on these resources.

The Collapse of the Peruvian Fisheries

Not until the occurrence of El Niño in 1972–73 did the industrialized world become aware of this phenomenon, which was affecting the distant country of Peru in South America, and have to start dealing with the consequences. Peru had moved into the limelight toward the end of the 1950s, when Peruvian gunboats began harassing or seizing fishing trawlers from San Diego for entering their "territorial waters" in pursuit of tuna. The "tuna war" between the United States and Peru was still simmering in 1968, when Juan Velasco-Alvarado, a general of nationalist leanings who had seized power in a military coup, confiscated the U.S.-owned oil wells on the northern coast of the country. The escalating friction became a cause of concern for the Americans, especially when Peru called on the Soviet Union for support. The Soviets were only too eager to oblige, thereby gaining access to the rich fishing grounds of the eastern Pacific and strengthening their geopolitical presence in Latin America.

tive not available to the native communities in the interior. Findings from the even drier environments of northern Colombia attest to the severe effects of mega-Niños around 1000, 700, and 500 years B.P. that caused devastating droughts, site abandonments, and reoccupations by groups with new ceramic traditions as on the San Jorge River and at Carrizal in the swampy lowlands south of the Caribbean coast.

As further evidence for these distant effects of past El Niños, Meggers mentions pollen profiles that document climatic changes as far back as 4000 years B.P., indicating brief but change-inducing periods of dryness in 1500, 1200, 700, and 400 B.P. Residues of catastrophic conflagrations are also interpreted as evidence of strong El Niño episodes. Recent examples of the ecological effects of forest burnings are the fires that broke out in the Rio Negro area in 1912—at the end of the ENSO episode of 1911—claiming the lives of hundreds of rubber collectors; the forest fire of 1926, which burned out of control for a full month during the decaying phase of the 1925 El Niño; and the wildfires of the early 1940s in concurrence with the extended ENSO of 1940–42. In the course of the 1972 El Niño event, the cultivation plots of Yanomama Indians were destroyed by fires, and the natives were forced to leave their villages and revert to gathering-and-hunting activities for their survival. Charcoal residues in the soil at San Carlos in southern Venezuela—the site of a widespread conflagration at the height of the major 1982–83 El Niño—are also related by Meggers to droughts caused by prehistoric El Niños which in the Casma Valley, northern Peru are reflected by mighty river sediments from catastrophic floods. Close temporal proximity between catastrophic events of different natures in these two distant places appear again around A.D. 500, 1330, 1460, 1628, and 1750, with the first two events fitting well the archeological discontinuities already mentioned and lending more support to the argument that the occurrence of severe droughts in the eastern lowlands of South America can be inferred from linguistic fragmentations, cultural differentiation, pollen profiles, and catastrophic fires.

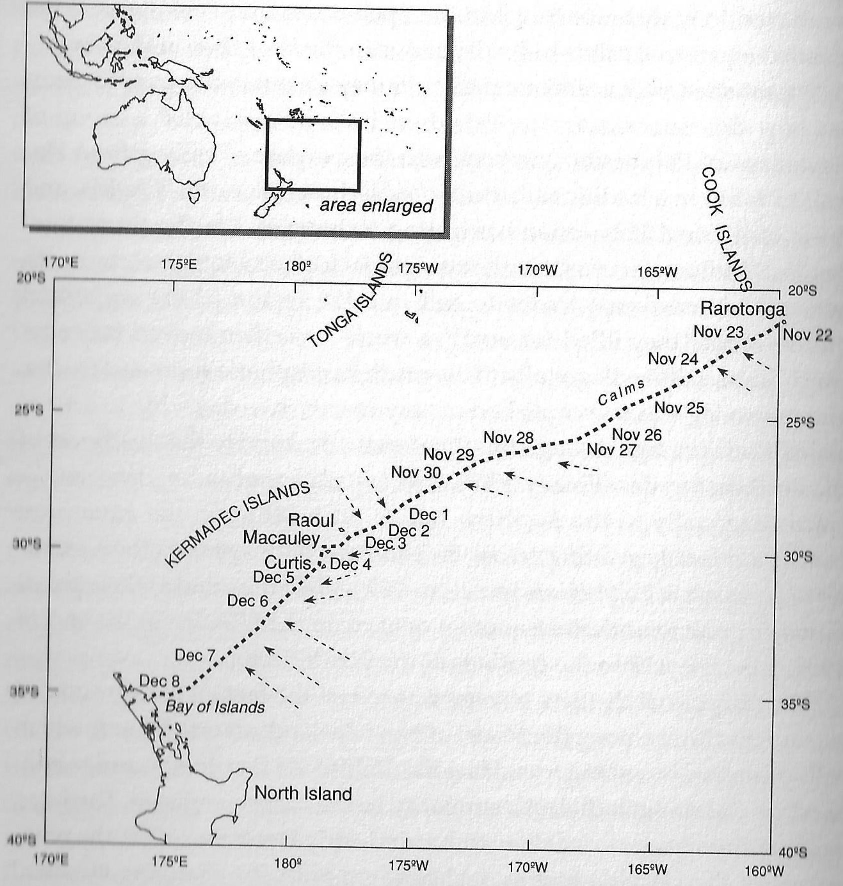
West Winds Sweep Polynesians toward New Lands

Ben Finney loves his profession and is very resolute in his research. An anthropologist at the University of Hawaii, he wanted to find out how prehistoric navigators from the ancestral home of the Polynesian culture conducted long-distance travel in the open ocean and even crossed the dreaded equatorial calms to finally arrive in the Hawaiian archipelago.

Not satisfied with academic theory, Finney set out to discover for himself how this feat was accomplished. In 1976, he assembled a group of Hawaiians of Polynesian ancestry with the purpose of sailing from Hawaii to Tahiti in a traditionally built double-hull canoe, the *Hŏkūle′a,* and using traditional Polynesian navigating techniques. On the thirty-two-day (5,370 kilometer) voyage, the navigators took advantage of the north hemispheric northeast trades to sail into the region of the equatorial calms—where they idled for nearly a week—and then moved faster toward Tahiti, sailing diagonally to the south hemispheric southeast trades. The return leg was accomplished in only twenty-two days due to a more expeditious passage through the equatorial calms and to the steadiness of the northeast trades (Finney 1977). The experience of sailing first southward diagonally to the northern trades, then idling in the equatorial calms, and finally slanting across the southern trades proved the feasibility of prehistoric Polynesian vessels to sail against the wind and prepared Finney's crew to undertake another venture in the *Hŏkūle′a* at the end of 1985, this time within the confines of the South Pacific.

The purpose of the new voyage was to test the factual background of an oral tradition among the Maori of New Zealand's North Island, which tells of ancestors coming from Hawaiki (Tahiti) via Rarotonga, and to confirm the Rarotongan dialect's similarity to the Maori language. During a sixteen-day voyage in late November and early December 1985, the navigators of the *Hŏkūle′a* had to deal head-on with the changing seasonal winds and storms that arise over the warm ocean during the southern summer (Figure 8.6); still, on December 8, they sailed into the Bay of Islands on New Zealand's North Island (Bayaban et al. 1987).

Before proceeding any farther, we should have some knowledge of the process by which the islands throughout the vast expanses of the Pacific were populated. The first inhabitants arrived on the western Pacific islands in the third millennium B.C. probably from the Malayan peninsula. Around 1500 B.C. these Proto-Polynesians—the ancestors of today's South Seas inhabitants—were established on the string of islands east of New Guinea called Melanesia, and around 1300 B.C. they seem to have reached Fiji. In successive "hops" they proceeded to the Tonga archipelago and colonized the islands of Samoa probably at the beginning of the first millennium B.C. Larger in size and richer in resources, Samoa



8.6. Route of the *Hōkūle'a* from Rarotonga to North Island. Arrows indicate the wind direction. Adapted from Bayaban et al. 1987.

became the cradle of this now genuine "Polynesian" civilization. From Vava'u (Samoa), audacious seafarers undertook further voyages of discovery and colonization to the north, where they eventually happened upon the Hawaiian Islands; to the southeast to Rarotonga and Aotearoa (the North Island of New Zealand); and westward to Tahiti and the Marquesas Islands.

At the beginning of our era, population pressures seem to have sent Polynesian navigators roaming the Central Pacific in search of new lands. Their vessels were now bigger: double canoes more than sixty feet long, equipped at times with double decks, fit with large sails, and amazingly

maneuverable. Early European explorers of the South Pacific, like François La Pérouse and James Cook, report seeing fleets of these vessels transporting large groups of people. François La Pérouse describes in detail the circuslike performances that the "religious" entertainers of the Arioi fraternity performed on most inhabited places of the Society Islands.

In view of the Polynesians' societal and navigational advancements, it is obvious that the search for and colonization of new islands were deliberate acts and not the result of some unlucky fishermen's being swept away from their home islands. The incentives are also easily understandable: rapidly expanding populations on islands with limited resources sparked internecine struggles for survival, the losers being forced to leave. For these one-way scouting and colonization voyages, young people of both sexes were chosen, their canoes (double as well as single) well provisioned with taro, yams, coconuts, breadfruit, gourds (used as canteens), chickens, and South Asian pigs.

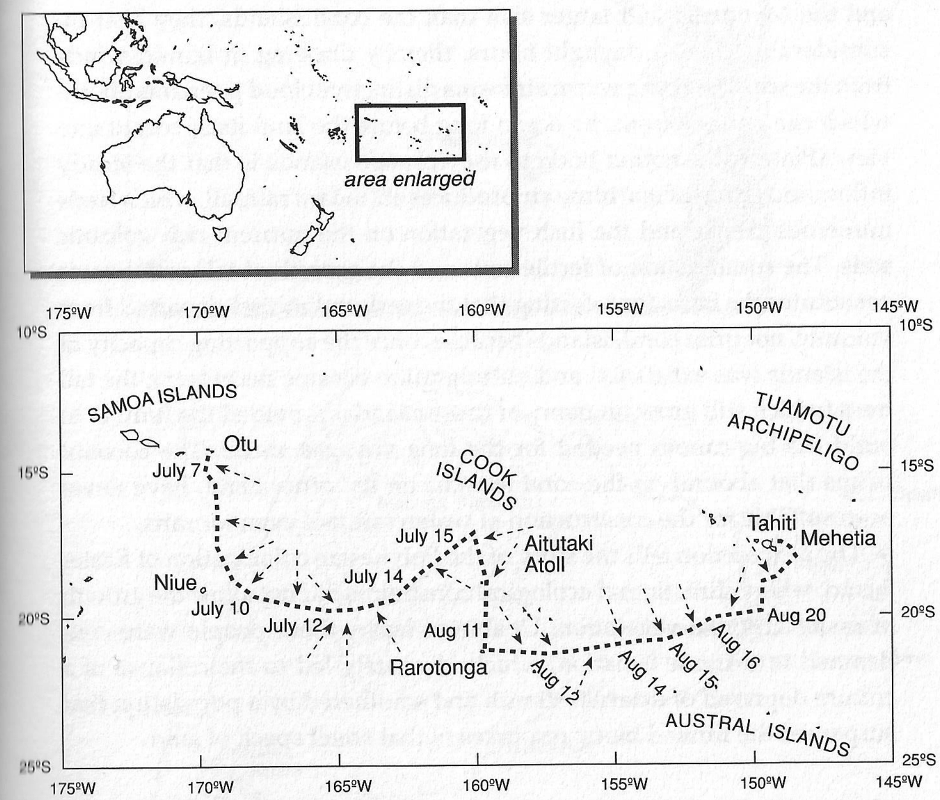
Early European as well as contemporary travelers extol the Polynesians' expertise in reading the stars, in inferring from waves and swells the locations of reefs and islands, and in foreseeing weather and climate changes based on their observations of seabird-, fish-, turtle-, and sea mammal-behavior, and on the general aspect of the ocean. While sailing downwind expedited navigation toward a known destination, the Polynesian seafarers were also expert at tacking against the wind, but—as Ben Finney experienced—it took twice as much time and effort as in a modern yacht. In view of such accomplished mastery of the sea, it can be posited that the Polynesians were limited in their search for new lands only by the number of islands and not by the vastness of the ocean.

During his 1,650-mile voyage from Rarotonga to New Zealand's North Island in the early summer of 1985, Finney experienced firsthand the strength of the steady easterlies in that part of the South Pacific and wondered how prehistoric navigators could have sailed against the winds when they left Samoa or Tahiti in search of new lands to the east. Faced with the reality that most of the inhabited Polynesian islands east of Samoa and the Society Islands are located in regions of the eastern Pacific where the dominating trade winds or easterly winds are stronger and steadier than between Rarotonga and New Zealand, Finney decided to tackle this problem also. In two articles published in 1985 and 1989, he argued that during certain years the southern trades and the equatorial easterlies are interrupted by anomalous flows from *west* to *east* that could have facilitated the discovery and colonization of the easternmost islands of Polynesia, the Marquesas Islands, and the Tuamotu archipelago. These special years, he wrote, were those in which a phenomenon called El Niño affected the coast of distant South America.

To prove his contention, Finney took the *Hŏkūle'a* on yet another trip, this time from Samoa to Tahiti, during the southern winter of 1986 when a moderate El Niño was in progress. Even though the southern winter is not the season when this condition manifests itself strongly, navigators can rely on some breaks in the normally steady southeast trades caused by transient depressions, to facilitate sailing eastward with the help of temporary westerly flows.

The first 650 nautical miles, between Samoa and Aitutaki in the Cook Islands, were covered in only nine days due to occasional westerly winds associated with the passing of winter depressions (Figure 8.7). The second leg, from Aitutaki to Rarotonga, was undertaken in early August when the temporary resumption of the southeast trades allowed the *Hŏkūle'a* to sail southward to Rarotonga. The final 720 miles, from Rarotonga to Tahiti, were to be completed around mid-August. The strategy was again to wait for disruptions in the easterlies and southeast trades to take advantage of the strong westerly winds that would push the watercraft eastward. It could not be helped, though, that the stars would be hidden behind clouds and prevent the navigators from ascertaining their progress. The expected disruptions occurred during the final days of the southern winter: several low pressure cells and troughs developed in the South Pacific, spawning westerly flows so powerful that after eight days, Finney's crew found themselves near the island of Mehetia, 80 miles southeast of their destination, and had to take a northwesterly course—now helped by the southeast trades—to reach Tahiti. Still, sailing 720 miles in unknown open seas in merely eight and a half days had been a record performance.

During the voyage, the modern Polynesian seafarers encountered situations that their ancestors had probably exploited. Several times when there was no land in sight, they noticed seaweed floating past, which indicated the proximity of an island or reef. Or they sighted boobies and white terns, which, like other marine birds of the Pacific, make long daily excursions from coastal nesting places, their morning and evening routes also providing clues about the location of land to those who could "read" these signs. In addition, contemporary fishermen and seafarers of Micronesia have preserved the skill of inferring from wave and swell deflections in the open seas the location of atolls or reefs that cannot be seen from the low decks of their watercraft or of islands beyond the horizon.



8.7. Route of the *Hŏkūle'a* from Samoa to Tahiti. Arrows indicate the wind direction. From Finney et al. 1989

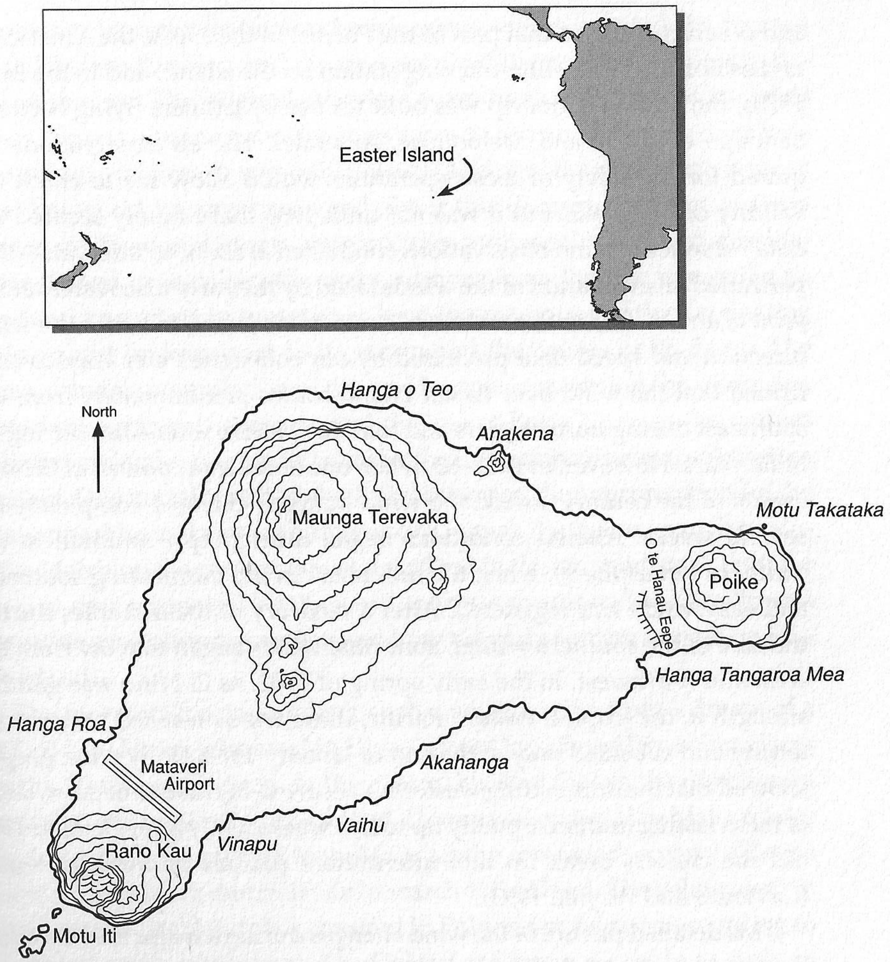
Yet another contributing factor helped ancient Polynesian seafarers in their discovery quests. According to their geological origin, the minor islands of the Pacific are classified as volcanic islands and coral islands, or atolls. The latter consist of coral reefs ringing beautiful lagoons and rise just a few feet above sea level. Only coconut palms and undemanding tubers grow on the nutrient-poor sandy soils. Farmland is not extensive because the island center is occupied by the lagoon. Volcanic islands, on the other hand, are the tips of extinct volcanoes or lava flows, and their bizarre peaks form landscapes of unique beauty, as on Bora-Bora, Tahiti, and the Marquesas. Of larger size than the coral islands, they heat up considerably during daylight hours, thereby drawing in humid winds from the sea. The rising warm air forms distinctive cloud pennants above, which can be seen from the ocean long before the land itself comes into view (Plate 10). Another boon to the volcanic islands is that the steady inflow and rising of maritime air produces abundant rainfall, which feeds numerous creeks and the lush vegetation on the nutrient-rich volcanic soils. The combination of fertile soils and the growth of tall native trees constitutes the basis for inferring that the early colonizers departed from volcanic, not from coral, islands because, once the supporting capacity of the islands was exhausted and outmigration became neceessary, the tall trees (which still grow on many of these islands) provided the lumber to build the big canoes needed for the long voyages ahead. The coconut palms that abound on the coral islands, on the other hand, have never been suitable for the construction of watercraft, not even for rafts.

The next section tells the story of the Polynesian colonization of Easter Island, where climatic and ecological constraints did not allow the growth of major arboreal vegetation. Unable to leave, these people were condemned to extreme isolation, which ultimately led to the collapse of a culture deprived of external stimuli and smothered by a population that surpassed the limited biotic resources of that small speck of land.

The Extraordinary Discovery of Rapa Nui

Easter Island is the most isolated inhabited island of the world, 1,000 miles from unpopulated Ducie, the nearest Polynesian island in the Tuamotu archipelago to the west, and 1,800 miles from the coast of South America to the east. Triangular in shape, the island is slightly more than 8 miles at its base and 4 miles at its tip. Obtuse volcanic cones sit on each of the three corners, the Maunga Terevaka at 1350 feet above sea level being the highest (Figure 8.8). The discovery of this tiny island in the immensity of the South Pacific Ocean is a major feat of humankind. Not only the island's small size conspires against its easy finding, but its location in a part of the South Pacific where the prevailing winds and ocean currents flow from east to west must have discouraged navigators approaching from the opposite direction and sailing *against* the winds and currents.

In December 1978, aboard a Chilean jetliner en route from Easter Island to Tahiti, I was pondering these difficulties when the first atolls of the Tuamotus came into view below. More a geographer than an anthropologist and without the sailing experience of Ben Finney, I could think of only one way for navigators of the past to have come close to Easter Island: with the help of winds blowing from the west; that is, during El Niño occurrences, when the usual trades and easterlies flowing from the strong South Pacific high are temporarily reversed.



8.8. Topography of Easter Island. The volcanoes, main anchorages, and Mataveri airport are also shown.

To substantiate this hypothesis, I knew that I had to find solid proof of the interruption of the normal air circulation by a west-east flow of winds and ocean currents in that part of the Pacific. In the 1960s, the Americans had established a satellite-tracking station on the island, and in the early 1970s, the Mataveri airstrip was built for use by jetliners flying between Santiago de Chile and Melbourne, Australia. The air observations required for the safety of these operations would allow me to check the validity of my thesis, but it was not until 1986 that I finally secured the data—a series of wind observations conducted at six-hour intervals—that permitted an evaluation of the winds faced by the early discoverers at the *point of arrival*. Computer-animated wind roses generated with the wind direction and speed data processed by our colleague Peter Waylen confirmed that the wind over Easter Island comes predominately from the southeast during normal years and that this pattern intensifies during La Niña years. However, in 1982–83, when one of the most powerful El Niño events of the century struck, the wind patterns changed completely for several weeks. Altered conditions began during April (midfall in the southern hemisphere), when the first break in the dominating southeast and east winds was registered. After a recovery of the easterlies during the core of the southern winter, abnormal winds began to blow from the west and northwest. In the early spring of 1982, as El Niño was gaining strength in the tropical eastern Pacific, these winds reached unusual intensity and subsided only at the end of January 1983. Daily wind graphs showed that the dominating westerlies occurred in clusters of days, some of them lasting uninterruptedly up to five weeks. Only after October 1982 did the clusters break up into intermittent periods of westerly winds (Caviedes and Waylen 1993).

This detailed picture of the wind changes during a major El Niño event in the eastern South Pacific could now be used to check the Easter Islanders' legends pertaining to their origin. It may be due to the extreme isolation that the traditions about their provenance and the events surrounding their arrival have been so cherished and passed on to subsequent generations with other ledgendary accounts.

The first European to set foot on Easter Island was the Dutch voyager Jacob Roggenween, who arrived in 1622. The island was visited by several navigators during the eighteenth century, among them François La Pérouse and James Cook. They marveled at the huge stone statues standing and lying all over the island and were intrigued that the people they encountered appeared to be too primitive to have carved these magnificent figures (Plate 11). Sadly, postdiscovery contacts with Europeans

proved to be catastrophic for the islanders: sailors infected the women with Western diseases, and the men acquired the reputation of being devious thieves. The original islanders were further decimated by raids from Peruvian guano entrepreneurs eager to procure labor for their ventures in coastal Peru. It was only toward the end of the nineteenth century that the world became concerned about this decaying outpost of Polynesian civilization. Literary personalities, anthropologists, and missionaries rushed in to collect the oral traditions from the few remaining islanders in an effort to preserve at least the memories of this fascinating culture and find answers to its origin and the causes of its decay. The most valuable compilation of the oral legends concerning the discovery, populating, internal warfare, and decline of Rapa Nui—as the natives called the island—was undertaken by the Capuchin missionary Sebastian Englert. Due to their methodological robustness, the interpretations of the first-arrival legends by anthropologist Thomas Barthel are equally valuable. Matching the circumstances described in the oral traditions with the time of year suggested by the wind analyses mentioned above allows a plausible conjecture as to when and how the early settlers arrived on Easter Island.

The incentive for undertaking such a voyage came from a dream of a certain Hau Maka, who lived in Hiva—Hiva Oa or Fatu Hiva being places on the Marquesas Islands. In the dream, his soul flies in the direction of the rising sun until it finds new land. Upon awakening, Hau Maka relates his dream to the local chief, Hotu Matu'a, who commands a party of seven young men to leave immediately in search of that land. "Traveling east" in search of mystical lands is a constant in Polynesian folklore, according to Barthel; the title of his book *The Eighth Land* refers precisely to such an island which, in Polynesian cosmology, lies in the eastern confines of the Pacific. So the scouting party sails eastward and eventually finds the island of Hau Maka's dream. On their voyage, the scouts are followed by a mythical sea turtle, which turns out to be an evil spirit that causes the death of one of the young men.

The element of inevitability that pervades this legend of discovery was probably inserted into the account once the people were already established on the island; the dream is at the same time an omen and a command given by fate, the latter being reinforced by the presence of the sea turtle, which indicates the very special circumstances under which the voyage was made. The fear of undertaking a voyage against the prevailing winds and currents around Hiva—normally considered senseless and suicidal—is definitely overridden by the supernatural imperative of the dream. The sea turtle swimming eastward is an indication that the voyage took place at a time when the waters of the eastern Pacific were warming up, since these creatures are uncommon in the cooler waters of the eastern Pacific. The order to sail in the direction of the rising sun expresses the fateful certainty that no other than the island of Rapa Nui is awaiting discovery.

From the vantage point of the Marquesas Islands (at 10°S/140°W), Easter Island (at 27°S/110°W) lies due southeast at sunrise during the summer months. Hence it can be surmised that these events occurred at the onset of an unusual summer when the winds (the means by which Hau Maka's soul traveled) and the ocean currents (the sea turtle's medium) were flowing in an eastward direction. Chief Hotu Matu'a's peremptory order to depart immediately is consistent with our plotting of the winds on Easter Island during El Niño 1982, which showed the first signs of altered flows in the fall of that year. Hundreds of generations of experience had probably taught the Polynesians that such early deviations from the norm heralded major air and ocean alterations ahead. Thus, when they noticed the first symptoms of the abnormalities we today know as El Niño, they had time to send out scouting parties and prepare for major colonization expeditions in the upcoming spring and summer when the changes in the direction of the winds and currents would be firmly established.

According to the legends, Chief Hotu Matu'a did *not* wait for the seven scouts to return but arrived on the island in two canoes with an organized party of colonists just when the young men were about to embark on their return voyage. The fact that cultivated plants, such as taro, yams, sweet potatoes, bananas, and sugarcane, as well as chickens were supposedly in the canoes indicates that the expedition had been thoughtfully planned. Another indication that the voyage was undertaken with the intent of founding new settlements is the legendary detail that two women aboard gave birth shortly before the party landed. Had this been just an exploratory voyage, pregnant women would not have been taken along.

In his analysis of the legends about the arrival on Easter Island, Thomas Barthel found several clues concerning the time of year when this happened. The mention of Vaitu Nui (April)—the first month of agro-fishing activities in the Polynesian calendar—as the month when the scouting party departed coincides with the time when the early symptoms of a major El Niño event are manifested. Their arrival at the beach of Anakena on Rapa Nui (Plate 12) is reported to have occurred in early Maro (June), which means the journey took roughly five weeks, a period so short that even Barthel suggested that this could not have been achieved without the help of favorable winds from the west. As to April being the month of departure, this is in keeping with Easter Island's contemporary wind patterns: our studies revealed that during the onset of El Niño 1982, the first reversals in wind direction occurred in April. The legends do not mention the weather conditions when the main colonizing group landed, but it can be assumed that they arrived during one of the prolonged periods of strong winds from the northwest, which tend to occur in August and September of El Niño years, as the 1982 wind data show. Incidentally, the beach of Anakena is open to the northwest.

Many details in the Easter Island legends compiled by Father Englert and Thomas Barthel denote a preoccupation with the past that is not frequently found in the folklore of the rest of Polynesia. The details serve to embellish or sublimate actual events in order to keep alive the islanders' thoughts about the homeland and strengthen their sense of identity. They also constitute proof that the discoverers and colonizers of Easter Island were Polynesians and not Indians from South America, as Thor Heyerdahl insisted. Recently, his thesis has been definitely refuted by DNA studies proving the Easter Islanders' genetic affiliation with Polynesian peoples. As to the language spoken by the Easter Islanders, it has greater affinity to Marquesan than to the Matarevan spoken in the Tuamotu archipelago, although the Marquesas Islands lie 2,000 miles *northwest* of Easter Island.

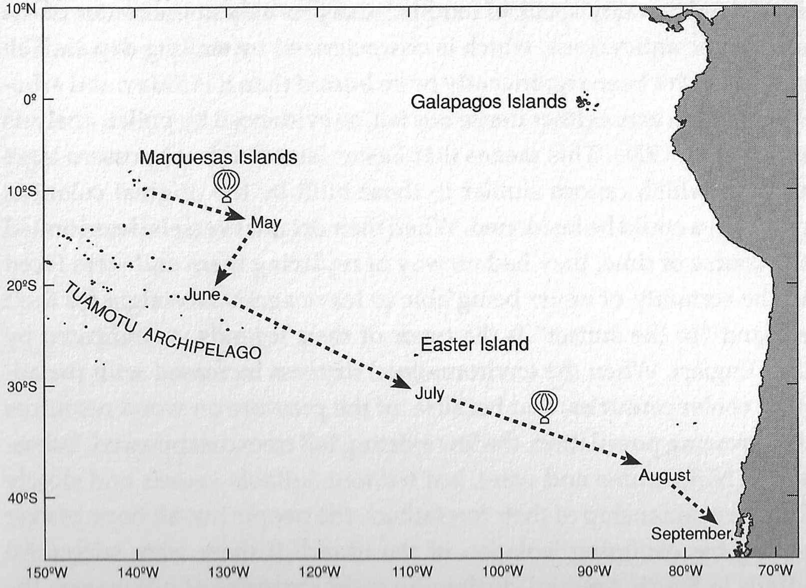
We have discussed the Polynesian origin of the Easter Islanders and prosed that their journey of discovery seems to have occurred during an El Niño event in the distant past; what remains to be clarified is the approximate date of their arrival. Based on carbon-14 datings of organic remains, Thor Heyerdahl placed that event around A.D. 380, and contemporary archeologists propose that the early settlement occurred around A.D. 400, findings which direct the search for clues about altered global climatic conditions toward the end of the fourth century. According to Hubert Lamb (1995), those were turbulent times in climatic history. In Europe, summers were becoming increasingly warmer and drier, and as polar ice melted, sea levels rose flooding vast coastal areas in both the North

Atlantic and the Mediterranean. Italy, Greece, and Asia Minor suffered pronounced drought, and the water level of the Caspian Sea dropped considerably. In northeast Africa, the Nile experienced low levels, and a Christian kingdom in Nubia (Sudan) seems to have foundered due to food scarcity. As repeatedly stated in this book, these unusual weather conditions coincide with upset conditions in the tropical Pacific, meaning that warm ENSO events occurred frequently and individual El Niño events occurred with similar or even greater intensity than at present. The repeated reversals in the direction of the winds and ocean currents probably encouraged exploratory voyages from the eastern outposts of Polynesia to an unprecedented degree—and one of these voyages resulted in the discovery of Easter Island.

There is, however, a controversial point in this story of the settlement of Easter Island. The legends collected by Sebastian Englert (1970) suggest that there was more than one wave of arrivals. At some unspecified time after the arrival of Hotu Matua's group, whose descendants called themselves Hanau Momoko (lizard men), a second group allegedly arrived—the Hanau Eepe (the heavyset men)—whose long earlobes have been perpetuated in all *moai,* Easter Island's famous stone figures. Size and prolongation of the earlobes point to their origin in the Marquesas where large earlobe rings were worn. Relations between the two groups were never good, and in the confrontation at the ditch of O te Hanau Eepe, the Hanau Eepe were totally annihilated, while the remaining victors descended to the low cultural levels that discoverers and early navigators found hard to reconcile with the monumental statuary of the island.

Of interest to us is the arrival date of this second wave of colonists. If changes in stone carving styles are an indication of new influences, the Hanau Eepe probably arrived between A.D. 1000 and 1100, the transition period from the "settlement phase" (A.D. 400 to 1100) to the "Ahu Moai phase" (A.D. 1000 to 1500), according to JoAnne Van Tilburg (1987). The period from A.D. 1000 to 1100 has been mentioned repeatedly as a time of global warming and abrupt climatic changes that peaked around A.D. 1200. As discussed in earlier sections of this chapter, it was also the time of decisive cultural turnarounds in coastal Peru, in the Bolivian altiplano, and in the Amazon basin, probably the consequence of mega-Niño events. Thus Easter Island can be included with other regions whose cultural histories were notably influenced by major changes in the climatic and oceanic circulations of the eastern Pacific. If there was a global warming trend around A.D. 1000–1100, it can be posited that reversals in the sea and airflow circulations of the South Pacific occurred just as they do today in El Niño years, and also with similar frequency, which is what probably encouraged the Polynesians to undertake more scouting missions.

The last point raises another intriguing question. If the eastern Polynesian islands were discovered during those special years, why were there no further exploratory endeavors during subsequent El Niño occurrences? Nobody can prove that there weren't. Peter Waylen conducted an enlightening experiment using the wind data of Mataveri airstrip. Sequencing the six-hour wind observations, he produced simulations of the tracks that would be taken by balloons propelled by those winds (Figure 8.9). During years of normal circulation in the southeastern Pacific (such as 1980 and 1984), the balloons drifted, as expected, from the Marquesas Islands—the Easter Islanders' assumed ancestral home—to the west and northwest into central Polynesia. However, under the wind conditions dominating in 1982, a balloon starting from the Marquesas in May would have taken a southeasterly course and would have passed slightly west of



8.9. Route followed by a simulation balloon from the Marquesas Islands to Easter Island. Adapted from Caviedes and Waylen 1993

Easter Island by the end of the month. Returning now to the actual scenario of the Polynesians' exploratory voyages: when they reached a location equivalent to that hypothetical point where the balloon had drifted, these experienced seafarers might have been alerted to the proximity of land by sightings of seabirds or of the cloud pennants that usually hover over the volcanic islands of the South Pacific.

The experiment also proved the feasibility of an assumption advanced by some specialists in transoceanic contacts: namely, that Polynesians could even have reached the South American continent at some time in the past. After passing southwest of Easter Island, the balloon in the simulation continued drifting *eastward* for several weeks and would have reached the west coast of South America by early September, provided the winds persisted. This means that if the Polynesians—once established on Easter Island—ever continued sailing to the east in search of the legendary "Eighth Land," the westerly winds prevailing during El Niño years could have taken them to the coast of southern Chile.

Then why are there no traces of Polynesians to be found in South America? Certainly the favorable winds were not lacking, for as we know, westerlies erupt frequently in the South Pacific. The reason lies elsewhere. Easter Island is a tiny speck of land located precisely at the center of the South Pacific anticyclone, which is characterized by sinking dry air. The island has never been significantly more humid than it is today, and arboreal vegetation was neither dense nor tall, as evidenced by pollen analysis (Flenley et al. 1991). This means that Easter Island did not possess large trees from which canoes similar to those built by the original colonists back on Hiva could be fashioned. When their original vessels deteriorated in the course of time, they had no way of replacing them and were faced with the certainty of never being able to leave again. Nostalgia for their homeland "to the sunset" is the tenor of their legends, as indicated by Father Englert. When the environmental dryness increased with the advent of cooler centuries, and because of the pressure on wood resources by the growing population, the few existing tall trees disappeared. Subsequent El Niños came and went, but without suitable vessels and slowly losing the seamanship of their forefathers, the people lost all hope of ever escaping the confining isolation of the island. If there were successful landfalls in South America during the early centuries of occupancy, the traces of their presence were probably erased by assimilation into the local populations. As in the case of other South Pacific islanders, those who were forced to leave because of dwindling resources, warfare, and increasing population pressures did so without a return ticket.

A team of European environmentalists recently published a study suggesting the possibility of South American Indians coming to Easter Island between A.D. 1300 and 1450 (Dumont et al. 1998). Might this event—which, interestingly enough, coincided with the end of the *moai*-carving period—have been responsible for the sudden appearance on the island of *totora* reed (*Schoenoplectus californicus*), which is widespread on the western margin of South America, and for changes in the microzoa populations of the island's few lakes? This possibility would support Thor Heyerdahl's theory that the original islanders came from that continent, but the researchers themselves concede that the islanders' DNA shows no signs of the intermixing that should have occurred with these Indians, so other explanations for these sudden changes must be explored.

These conjectures all add to the many mysteries surrounding the origin of humans on Easter Island, the emergence of its magnificent statuary, and the precipitous decay of its culture. What seems to be incontestable, however, is that the navigating feats of eastern Pacific islanders and the destiny of the people on Rapa Nui are intricately linked to the changes in ocean and wind conditions brought about by El Niño phenomena during the last two millennia.