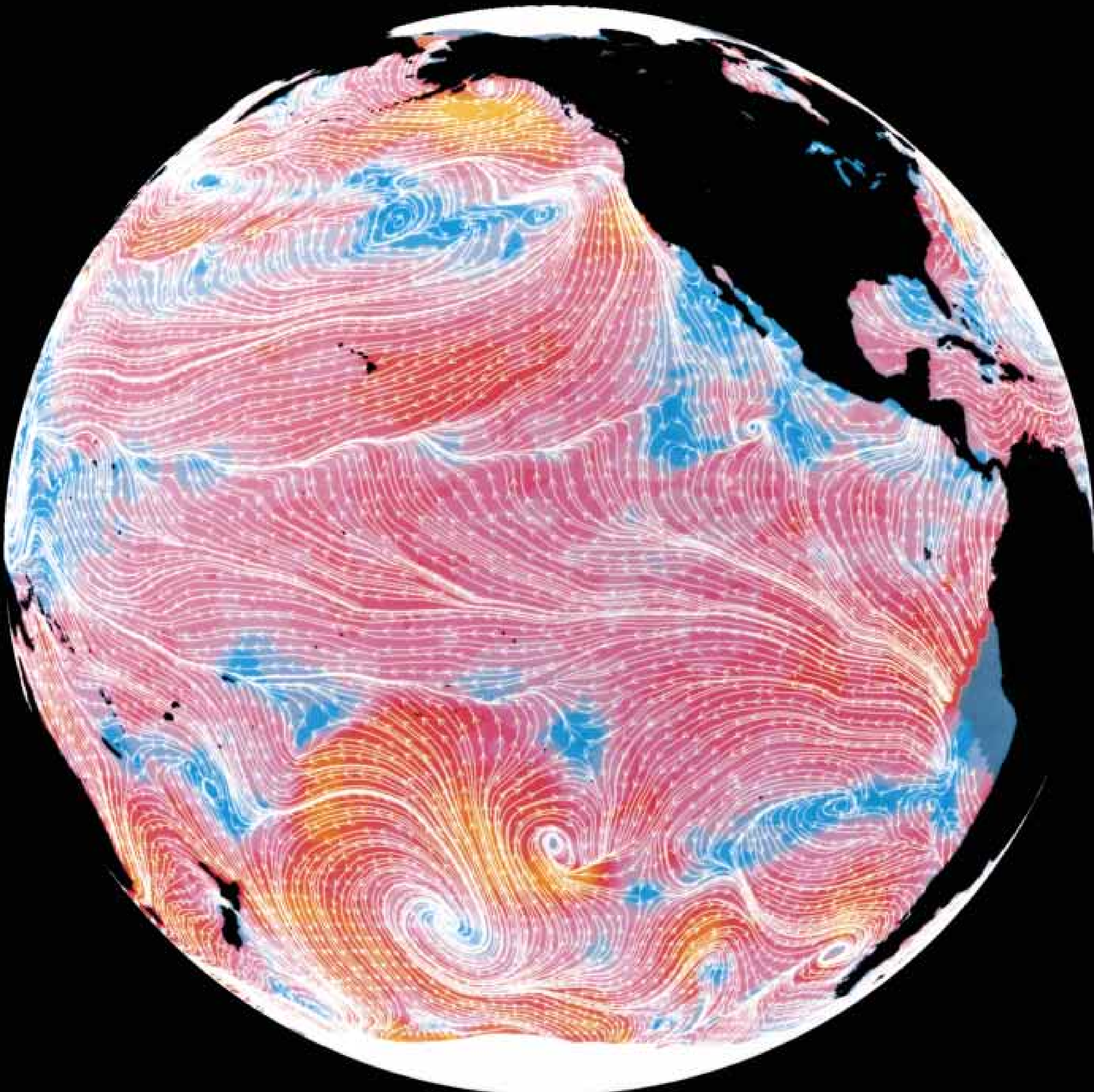


BEYOND El Niño

El Niño is not the only oceanic and atmospheric event that profoundly affects climate. Several other seesawing conditions have also been uncovered

by LAURENCE LIPPSETT

Long before anyone ever heard of the Pacific warming called El Niño, a guy named Joseph demonstrated the enormous value of a reliable climate forecast. His discovery wasn't published in a scientific journal but rather in a book called Genesis.

The pharaoh of Egypt had a disturbing dream: seven cows, sleek and fat, emerged from the Nile River. Seven gaunt and thin cows followed and ate the fat ones. Joseph interpreted the dream, warning that Egypt would have seven years of plenty followed by seven years of famine. He urged the pharaoh to take advantage of the good years to store surplus grain. So it was done. After seven years of bumper crops throughout the region, "there was famine in all lands; but in all the land of Egypt there was bread."

All human endeavor hinges on the vicissitudes of climate, and it is deep within the human race to defend itself against nature and to seek some sign, divine or otherwise, of next season's weather. Sacrifices to the rain gods notwithstanding, until recently climate forecasting hadn't advanced much in the millennia since Joseph's time. Only 17 years ago one of this century's most powerful El Niños took us completely by surprise.

In 1982 scientific experts had come to a consensus that no El Niño was forming, even as waters in the eastern tropical Pacific Ocean near Peru were already heating with inevitable and catastrophic momentum. It sparked a host of climate changes: devastating droughts and fires in Australia, flooding in normally arid regions of Peru and Ecuador, unusual storms that rearranged California beaches, and widespread mortality of fish and birds. All told, the El Niño that wasn't going to happen led to thousands of deaths and an estimated $13 billion in damage.

But from the ashes of that El Niño, which persisted from the winter of 1982 into the spring of 1983, emerged a scientific breakthrough. Caught off guard, scientists renewed efforts to figure out the riddle of El Niño. They began to see how the ocean and atmosphere are intimately linked in an oscillating rhythm. Like two people going up and down on each side of a seesaw, the ocean and atmosphere continuously shift in response to each other. The two never achieve equilibrium; one side of the seesaw is either up or down. Each "position" creates its own distinct set of climate conditions. The rhythm is complex—but it isn't random. If you could decipher it, you could anticipate

NASA

WIND EVERYWHERE: Arrows indicate wind direction at the surface of the Pacific Ocean as detected by a satellite on a single day; colors denote speed, which rises as the underlying colors shift from blue to pink, orange and yellow. Swirls reflect storms. Scientists are learning that the atmosphere and the oceans continuously interact to generate recurring patterns that influence weather and climate around the globe.

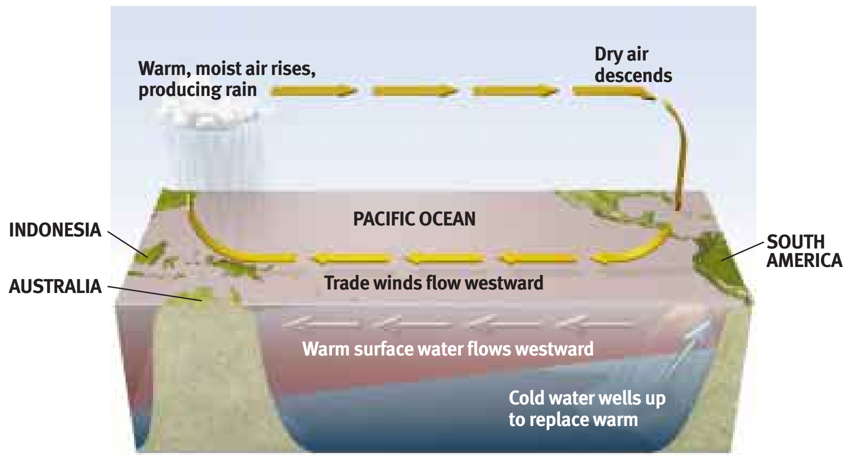
where the climate was headed. At a breathtaking pace, researchers did just that, predicting the next El Niño: 1986–87.

"That marked the beginning of the modern era of climate forecasting," says Nathan J. Mantua, a scientist at the University of Washington. Initial success with El Niño has inspired a feverish search for other oscillations. And sure enough, amid the apparent cacophony of Earth's everchanging climate, more patterns are materializing. Shifting over months or decades, these newly identified patterns may spawn different climate changes in different parts of the globe.

"People in the field realized that El Niño was just the loudest and most obvious oscillation," Mantua says. Persuaded that the oceans help to regulate our climate in quasiperiodic but potentially predictable ways, scientists around the world are mobilizing to deploy a global network of instruments—including a flotilla of several thousand buoys—that can monitor oceanic conditions. Much the way networks of land-based meteorological observatories track atmospheric conditions to give us five-day forecasts, this ocean-based array promises to give us Joseph-like warnings that next winter may be colder and snowier than usual, that next year's hurricane season may be fierce, that we should look for fish in this part of the ocean and prepare for disease outbreaks in that part of the world or that rains will not return in the spring to water our crops.

THE EL NIÑO/SOUTHERN OSCILLATION

NORMAL CONDITION



DAVID FIERSTEIN

Oceanic and atmospheric conditions in the equatorial Pacific generally flip-flop between two states: a normal condition (*left*) and an El Niño condition (*center*), which brings extra rain to parts of South

The Search for Patterns

The annual monsoon rains that farmers in India depended on never came in 1877 and 1899, each time resulting in devastating famine. In 1904 Gilbert Walker was charged with finding a way to predict the monsoon fluctuations that made life in India such a lottery. In his 30-year quest, he collected and analyzed meteorological observations from stations all over the globe. He found that the air pressure at sea level in the Pacific seesawed up and down across a region ranging from Australia to South America. Most notably, when it was high in Darwin, Australia, in the western Pacific, and low in Tahiti, in the central Pacific, there was heavy rain in the central equatorial Pacific, drought in India, a warm winter in southwestern Canada and a cold one in the southeastern U.S. Every few years the air pressures in Darwin and Tahiti reversed, and so did climate conditions in various regions in the world.

Walker called this atmospheric pattern the Southern Oscillation, but critics derided his theory, doubting that such far-flung climate changes could be linked. It didn't help that Walker had no scientific explanation for his pattern. Despite his zealous data gathering, he took no account of the ocean and made no connection with El Niño, which had been documented as early as the 16th century.

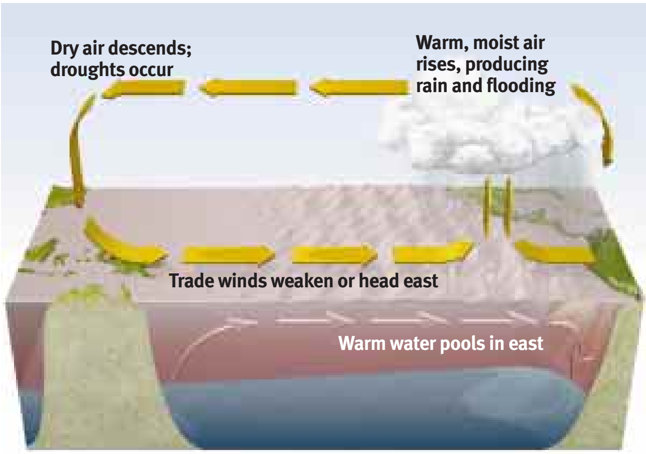
Originally, the term "El Niño" referred specifically to a warming of coastal waters off Ecuador and Peru that arrived around Christmas—the celebration of El Niño, the Christ child. In most years the warming was mild and benign, but then as now, occasionally severe warmings led to heavy rains, catastrophic flooding and the disappearance of fish from local waters.

It was not until the 1960s that anyone realized El Niño and the Southern Oscillation were related. (Today they are collectively referred to as the El Niño/Southern Oscillation, or ENSO.) Using measurements of the atmosphere and the tropical Pacific gathered during 1957–58, Jacob Bjerknes of the University of California at Los Angeles discovered that El Niño warming of sea-surface temperatures was not confined to the western coast of South America but extended thousands of miles into the central Pacific. Moreover, it was accompanied by all the atmospheric changes observed in Walker's Southern Oscillation.

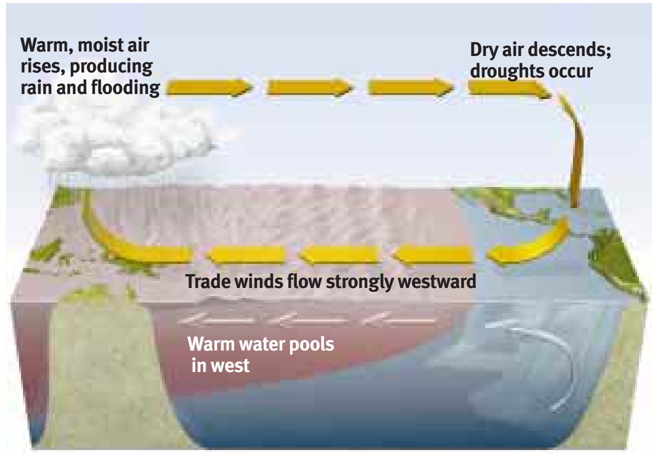
In non–El Niño years, Bjerknes noticed, sea-surface temperatures in the eastern, South American end of the Pacific are remarkably cold for such a sun-drenched equatorial region and contrast sharply with the great warmth in the western Pacific. Nature moves to even out the temperature gradient. In the west, the ocean heats the air above it. The heated air rises and draws in beneath it cooler and denser air that flows along the sea surface from the cooler eastern Pacific. These are the trade winds. (The readily evaporating waters in the west also supply moisture to the air, yielding rainfall.) Bjerknes called this equatorial circulation system—generated by the temperature and air-pressure gradients between the eastern and western Pacific—the Walker Circulation.

At the same time, Bjerknes said, the prevailing trade winds drive tropical Pacific

EL NIÑO CONDITION



LA NIÑA CONDITION



America and dry conditions to Indonesia and Australia. Sometimes, instead of returning to normal after an El Niño, the eastern Pacific cools excessively, signaling the onset of La Niña (*right*), which is accompanied by excessive rain in the west and abnormally dry conditions in the east. The shifting conditions in the Pacific also affect weather elsewhere in the world.

waters westward as well as northward and southward toward Earth's two poles. To replace those departing waters, deeper (and colder) waters upwell in the eastern Pacific. These cold, nutrient-rich waters not only allow fish to thrive, they also reinforce the east-west temperature gradient, keeping the winds blowing westward and warm waters pooled in the west.

But this air-sea interaction could flip-flop, as it does in El Niño years. If the trade winds diminished, warm waters could migrate eastward, reducing the east-west temperature gradient, which would reduce the trade winds further, and so on in a chain reaction.

Thus, Bjerknes married the circulation of the ocean and the atmosphere together in a continuous feedback loop with two alternative modes. Every few years, for reasons Bjerknes didn't figure out, the loop reverses. Warm surface waters that usually pool in the western Pacific expand dramatically throughout the tropical Pacific until they gird a quarter of Earth's circumference. Rain clouds that accompany the warm waters migrate eastward, taking rain from places where it is expected and dropping it unexpectedly in other areas. Prevailing trade winds diminish, thus rearranging global atmospheric circulation patterns and worldwide weather.

On average, an El Niño occurs about every four years, but the cycle is irregular. Sometimes there are only two years between events, sometimes almost a decade. In the early 1990s an El Niño seemed to last two years. The intensity of the events and their climatic effects vary considerably. Sometimes, in an El Niño's wake, eastern Pacific waters not only return to a cool state but also become unusually cold—a condition called La Niña, which packs its own climatic repercussions.

Only in the past decade have researchers gotten a tentative handle on why the system flips back and forth. The upper few hundred feet of the ocean stores 1,000 times more of the sun's heat than the atmosphere does. Huge masses of heat-storing water move through the depths at their own sluggish pace, uninfluenced by the much faster-moving interactions described by Bjerknes that transfer heat near the surface. The two heat-transferring processes are perpetually out of sync—continuously seeking but never achieving equilibrium.

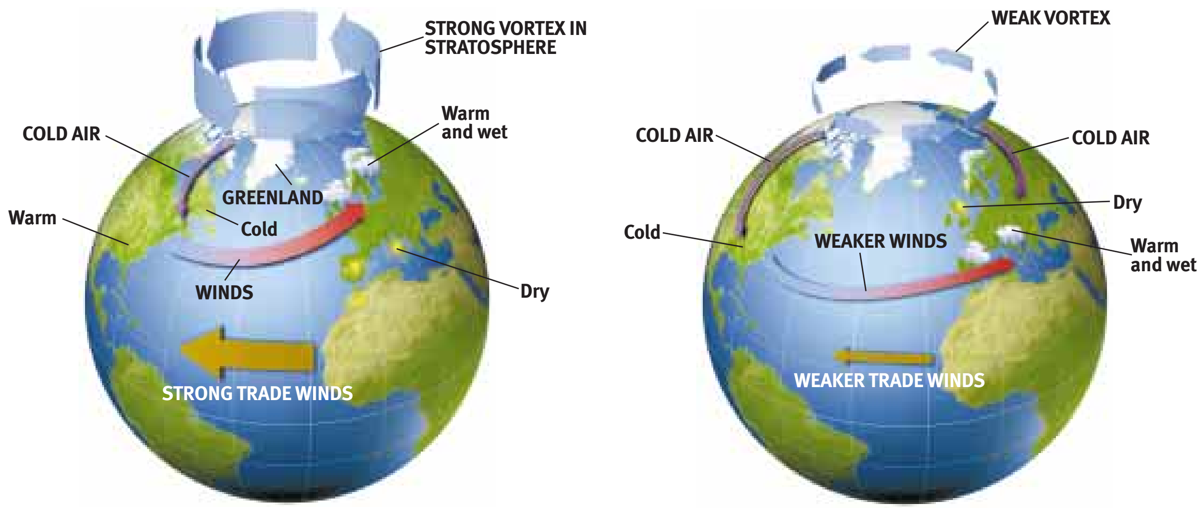
In the atmosphere, even a small change in wind direction, air pressure or temperature could launch an unpredictable sequence of events that would doom reliable weather forecasts beyond two weeks. But the oceans transfer heat around the globe in less ephemeral pulses, setting the stage to make one kind of climate condition more or less likely than another. By about 10 years ago the search was on for other oscillations—perhaps driven by many of the same air-sea dynamics that had been uncovered by studying ENSO. Scientists have only begun to explore the mechanisms driving these newly recognized oscillations. "The science right now is more like our understanding of El Niño 15 to 20 years ago," Mantua says.

The North Atlantic Oscillation

Early in the 1990s investigators revisited with a vengeance another climate pattern first identified decades ago by Walker: the North Atlantic Oscillation (NAO). Like ENSO, the NAO flip-flops between two modes, but unlike ENSO, its defining signals are primarily atmospheric.

In the "positive" mode, a huge low-pressure system sits over Iceland, circulating winds counterclockwise around it. A high-pressure system with clockwise-circulating winds lodges near the Azores off Portugal. Like interconnecting gears, the two systems steer strong winds through

THE ARCTIC OSCILLATION



STRONG VORTEX CONDITION **WEAK VORTEX CONDITION**

The Arctic Oscillation is a shift between two patterns of wind flow. In one state (*left*), a strong stratospheric vortex swirls over the North Pole, increasing the flow of surface winds across the Atlantic. The winds warm as they cross the ocean to Scandinavia and Siberia, which become warmer and wetter. When the vortex weakens (*right*), cold air seeps out across the northern lands. Meanwhile the winds originating over North America take a more southern track over the ocean, bringing some warmth and wetness to the Mediterranean.

DAVID FIERSTEIN; SOURCE: DAVID THOMPSON AND JOHN M. WALLACE *University of Washington* AND FRITZ HEIDE AND JACK COOK *Woods Hole Oceanographic Institution*

the lane where they intersect—eastward across the North Atlantic toward Europe. In winter, when northern air temperatures go down, the air-pressure contrast between the two systems increases, creating stronger winds. The winds bring polar air down through the eastern U.S. and Canada, making winters colder on average there, but then they pick up heat and moisture from ocean waters warmed by the Gulf Stream, making European winters wetter and milder.

When the NAO flips into its "negative" mode, the low-pressure system moves down over the Azores. The warm, moisture-laden winds are diverted southward, making northern European winters cooler but bringing warmth and rain across the Mediterranean region all the way to the Middle East. Winters are generally warmer in the eastern U.S. and Canada but colder in the southeastern U.S.

The NAO can switch modes over days, weeks or months, but viewed over years or decades, it essentially stays one way or the other. With the exception of 1995, the NAO has been in the positive position since 1980. The effects have been pervasive. Strong winter winds have whipped North Sea oil rigs with higher waves, for example. But they have brought more rain, increasing Scandinavia's hydroelectric output. Warmer temperatures have lengthened growing seasons but hurt the ski industry in Scandinavia and other parts of northern Eurasia.

Farther south, lack of rain has disrupted grape and olive harvests on the Iberian Peninsula and diminished stream flow in the Tigris and Euphrates rivers, which bring coveted water to the Middle East. Less rainfall in the Sahel region of Africa has brought famine to Ethiopia, Sudan and Somalia, causing starvation, expensive disaster relief, wars and mass migrations of populations (not unlike the Israelites' migration, in search of food, to Egypt following Joseph's prediction and their subsequent exodus). Interestingly, Heidi Cullen and Peter deMenocal of Columbia University's Lamont-Doherty Earth Observatory have suggested that the NAO, locked in the positive mode about 4,200 years ago, may have been at the root of the history-changing drought that archaeologists believe caused the collapse of the great Akkadian civilization of Mesopotamia.

Researchers haven't figured out what causes the NAO to switch modes, but Michael S. McCartney, an oceanographer at Woods Hole Oceanographic Institution, believes the ocean plays a critical role. Measuring ocean temperatures in the North Atlantic, he and his colleagues found large, persistent masses, or "pockets," of unusually warm or cold waters that flow in a ring of currents up the western coast of Ireland and Scotland, west to Iceland and Greenland, on to the Labrador Sea and eastward again with the Gulf Stream to Ireland. As these pockets are transported along this oceanic pathway over decades, they release more or less heat to the overlying atmosphere. McCartney found a good correlation between the fluctuations of the NAO and the heat moving through the ocean.

Arctic and Antarctic Oscillation

The NAO, however, may be encompassed by a more fundamental phenomenon—the Arctic Oscillation—that affects climate over the entire Northern Hemisphere, as John M. Wallace and David Thompson of the University of Washington pointed out in 1998. In general, winds a mile or more above Earth's surface spin counterclockwise around the polar cap. In winter, frigid air temperatures greatly strengthen the winds in the stratosphere 10 to 20 miles high, creating a powerful polar vortex that extends all the way down to Earth's surface over the North Atlantic region. When the vortex strengthens, it increases the flow of winds that bring warm, wet Atlantic Ocean air eastward toward Europe and Siberia, making winters warmer and wetter on average in those regions, say Wallace and Thompson. Those are precisely the conditions ascribed to the warm phase of the NAO.

Periodically, though, the stratosphere above the pole warms, sometimes by 50 to 60 degrees in a week. When that happens, the great swirling wall of stratospheric winds surrounding the pole partially or completely breaks down. Polar air leaks out and penetrates southward into parts of North America, Europe and Asia, making winters chillier in the affected areas. Meanwhile, eastward-blowing winds closer to the surface often weaken or shift southward, bringing rain to the Mediterranean region.

"The NAO and AO are different names for the same phenomenon," Wallace asserts. "The NAO represents a 'bottom-up' perspective that presumes that the ocean is the key player, whereas the AO is a more 'top-down' perspective," which assumes the phenomenon is driven by atmospheric changes that occur independently of the ocean.

Interestingly, the AO has an identical twin operating around the South Pole called the Antarctic Oscillation, although fewer people live within range of its climatic effects. The AO and the Antarctic Oscillation shift over weeks, months and years, but overall they seem to have become "stuck" over the past decade or two in the mode that favors strong polar vortices. But scientists have only just begun exploring in detail the long-term patterns, underlying causes and far-flung climatic impacts of these polar oscillations.

Investigators are also looking into evidence that the AO may be getting stuck because of the buildup of industrial greenhouse gases. High in the stratosphere, the gases are not trapping heat in but are radiating it out to space. The colder stratospheric temperatures may also be doing other damage: stimulating chemical reactions that destroy the ozone layer, which shields Earth from dangerous ultraviolet solar rays.

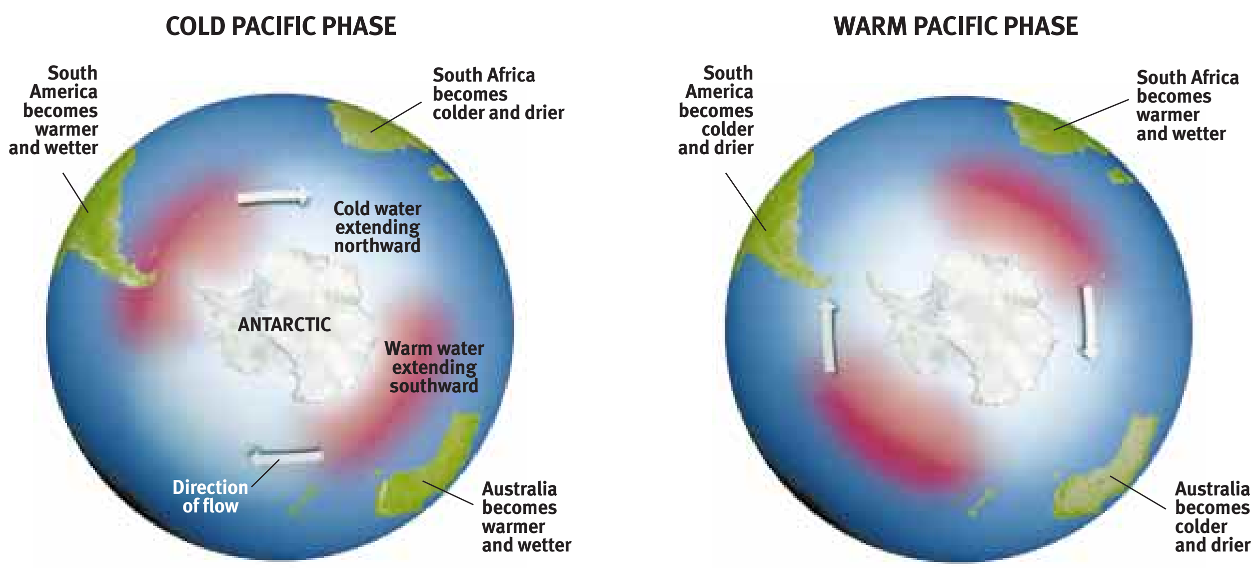
The Pacific Decadal Oscillation

In the mid-1990s Wallace and his University of Washington colleague Yuan Zhang began to notice a climate pattern over the Pacific. This pattern seemed to shift in 20- to 30-year cycles. At the same time, Steven R. Hare and Robert L. Francis, also at the University of Washington, discerned similarly timed boom-and-bust cycles in Alaska salmon. In 1997 these teams realized that they were looking at the same phenomenon and labeled it the Pacific Decadal Oscillation (PDO).

In the PDO's "warm" mode, the vast central interior of the North Pacific is colder than usual, while a narrow band of warmer than average sea-surface temperatures hugs the coastlines of Alaska and the western U.S. and Canada. In the PDO's "cold" mode, ocean temperatures are warmer in the interior and colder along the coast.

When the PDO is warm, a low-pressure system forms with a bull's-eye over the

THE ANTARCTIC CIRCUMPOLAR WAVE



The Antarctic Circumpolar Wave, shown highly schematically, is composed of alternating masses of cold polar waters (that have spread northward) and warm subtropical waters (that have spread southward) propagating slowly around Antarctica. When the wave, which takes about eight years to go full circle, is in its cold Pacific phase (*left*), South Africa has colder and drier weather, whereas South America and Australia become warmer and wetter. When the wave is in its warm Pacific phase (*right*), weather conditions reverse.

DAVID FIERSTEIN; SOURCE: WARREN B. WHITE *University of California, San Diego*

Aleutian Islands, near Alaska. It circulates strong winds that bring warm, dry air and warmer winters to the Pacific Northwest. But water supplies suffer from diminished precipitation and snowpack in the mountains. With few interruptions, the PDO has been in this mode since 1977, as it was between 1925 and 1946.

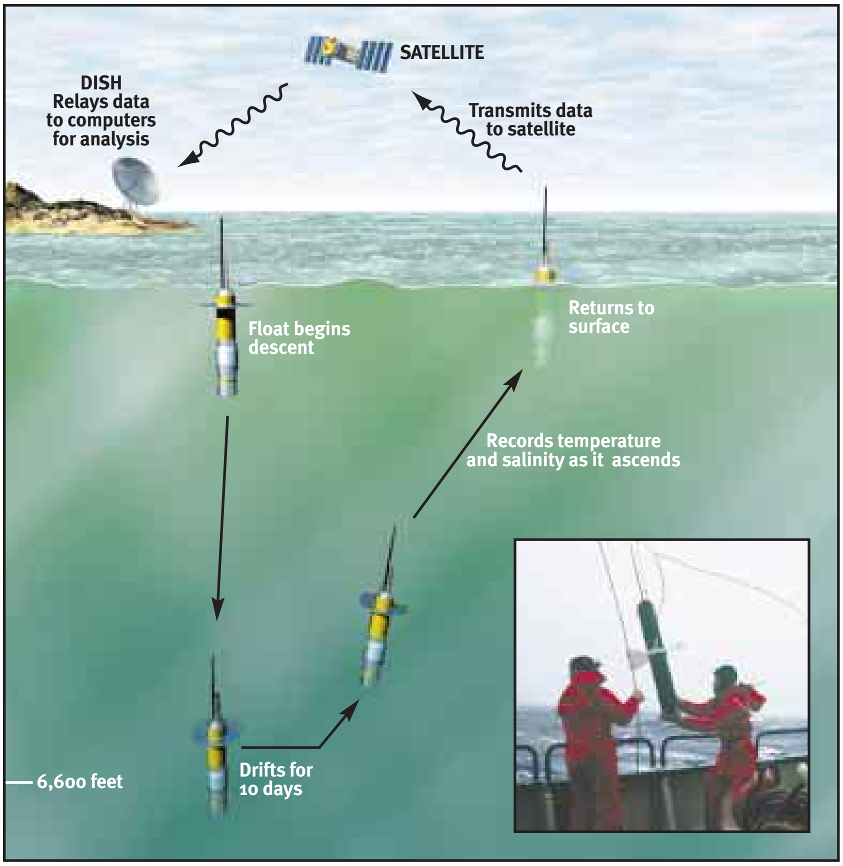
But from 1947 to 1976, water supplies were 20 percent higher on average in the Northwest. The PDO was in its cold mode, as it had been between 1890 and 1924. During that time, the Aleutian low dissipated, less warm air flowed to the Northwest, and winters were colder. But salmon fishing was terrific from California to Vancouver. "One of the most fascinating and important aspects of these oscillations is how they prompt huge reorganizations of marine ecosystems," says the University of Washington's Mantua.

Mantua, Hare and Francis found that PDO warming of coastal waters creates detrimental conditions for West Coast salmon (except in Alaska, where they thrive). The warmer, buoyant waters lay atop the ocean surface, creating a boundary between deeper, colder, nutrient-rich waters. The upper layer is no longer replenished by upwelling nutrient-rich waters. Phytoplankton and zooplankton populations crash. Juvenile salmon migrating from streams into the coastal ocean either starve or become easy prey for hungry predators.

Up in Alaska, the same changes benefit phytoplankton. The northern waters, though warmer, are still cold enough to be nutrient-rich. The more stratified waters keep phytoplankton near the surface and near the life-giving sunlight that is limited in Alaskan winters. Alaskan salmon have a banquet. Similar PDO-related boom-and-bust cycles also affect important fisheries across the Pacific in Japan, Korea and Russia.

On the lookout for possible oscillations in other oceans, scientists are also exploring the tropical Atlantic Ocean and the Indian Ocean, where a still fuzzy pattern tentatively dubbed the Indian Ocean Dipole may shift warm pools of water in a smaller version of ENSO. Down under, workers are excited about a newly discovered oscillation in the Southern Ocean,

THE ARGO FLOAT SYSTEM



DAVID FIERSTEIN (*diagrams*); GEORGE TUPPER WHOI (*photograph*); SOURCES: JACK COOK WHOI; JEFF SHERMAN U.C.S.D. (*detail*)

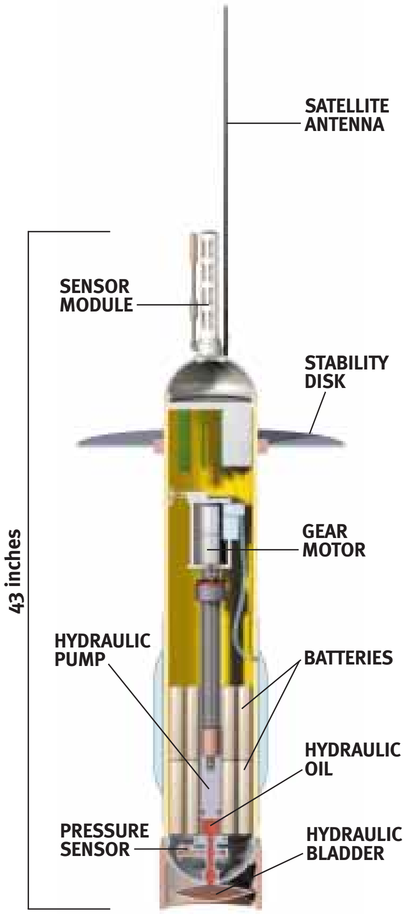
Hoping to improve weather prediction, an international collaboration is launching Argo, an array of 3,000 floats. The devices will measure the temperature and salinity of the ocean, two features that influence atmospheric conditions, and will relay the results every 10 days to a satellite for analysis (*cycle above, starting at left of center*). The floats (*shown in cutaway view*

which surrounds Antarctica. Called the Antarctic Circumpolar Wave (ACW), this pattern was unveiled in 1996 by Warren B. White and Ray G. Peterson of the Scripps Institution of Oceanography.

The Antarctic Circumpolar Wave

Analyzing measurements of sea-surface temperatures and sea-level pressure in the Southern Ocean, the two researchers found something rather curious: you can draw a wavy line, with two peaks and two troughs, completely around Antarctica between latitudes 40 and 70 degrees south; ocean temperatures are warmer above the line and colder below it. Warm tropical waters flow southward into the troughs, and polar waters flow northward in the peaks. This pattern results in four alternating regions (two each) of relatively warm or cool ocean waters that span thousands of miles. These regions are embedded in the Antarctic Circumpolar Current, which moves clockwise around Antarctica, completing one circumnavigation every eight to nine years.

Every four years or so (with a frequency similar to ENSO's, oddly enough), a peak or trough passes over a given region in the Southern Ocean, shifting winds and rainfall accordingly as it progresses—in much the same way that ENSO's shifting warm and cold pools do. When a warm trough nears Australia, winds coming off the ocean bring warm, moist air and warmer and wetter than average winters, says Peter Baines of the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia. Cold peaks



***above*) can be launched over the rail of a ship (*inset photograph on opposite page*) and, in remote areas, might be deployed from aircraft.**

passing along this traveling wave make Australian winters cooler and drier.

"Soon everyone in Australia will know about the ACW," White predicts. "It will be common knowledge on the street, just as ENSO is now." The ACW may also prove helpful for forecasts in New Zealand, South Africa and southern South America. And because it encircles the globe unimpeded by continents, it could be acting as a link to transmit climate patterns around the world, White and Peterson say. The ramifications and importance of the ACW remain untested, however.

More evidence that Earth's climate tends to oscillate between two different states arrived last November. Lamont-Doherty geochemist Wallace S. Broecker and his colleagues revealed telltale clues that the circulation of the entire world ocean oscillates in a regular pattern that produces centuries-long cold spells every 1,500 years. The most recent one was the "Little Ice Age"—a well-documented period between 1350 and 1880 of generally colder European winters that expanded alpine glaciers, froze rivers and harbors, and disrupted farming.

Today warm Gulf Stream waters flow into the North Atlantic, where they release their heat and keep Europe noticeably warmer in winter than comparable latitudes in North America. The warm waters are "pulled" from tropical latitudes into the north to replace cold, salty, dense waters that sink to the ocean bottom. Like a hand pushing downward in a bathtub, the sinking cold water propels a conveyor belt of deep-ocean currents throughout the world's oceans and eventually back to the Atlantic. When this "Great Ocean Conveyor" is pumping strongly, it draws more tropical waters northward and warms Europe. Conversely, when a smaller amount of cold North Atlantic waters sinks, less tropical water is pulled northward, and Europe receives less heat.

The conveyor receives a boost near Antarctica, the only other place on Earth where the ocean is cold and salty enough to sink. Until now, cold waters were assumed to sink at the same rates in both the North Atlantic and Antarctica. But Broecker's new study suggests that when one site revs up, the other one slows down—in a 1,500-year oscillation that generates worldwide climatic consequences.

"Wiring" the Ocean

Over the next decade, scientists should be quite busy figuring out the validity and significance of all these newly recognized oscillations. "One of our big challenges is determining the extent to which all these phenomena are linked, and how," says Stan W. Wilson, deputy chief scientist of the National Oceanic and Atmospheric Administration.

But whether the ocean drives or is driven by the atmosphere, it plays a critical role in creating our climate. Consequently, in the aftermath of the disastrous 1982–83 El Niño, NOAA, the National Science Foundation and scientific agencies of other nations deployed a string of moored buoys to monitor oceanic conditions spanning 10,000 miles of the equatorial Pacific. Satellites operated by NOAA and the National Aeronautics and Space Administration also track shifting winds and sea levels. Together these instruments provide a continuous stream of observations that feed climate forecasting models and have allowed forecasters, for instance, to give plenty of warning of the powerful 1997–98 El Niño, as well as the La Niña that followed it.

"The time is ripe to take the next obvious step," Wilson notes. With international partners, NOAA plans to cast 3,000 buoys throughout the oceans, dropped overboard from ships or parachuted by airplanes in remote regions. Each four-foot-long torpedo-shaped buoy will sink about a mile deep, drift with ocean currents for 10 days and then rise, measuring water temperature and salinity along the way. On the surface, each so-called Argo float will radio its data and position to orbiting satellites before sinking again and continuing another cycle. The satellites will relay buoy data to help make "weather maps" of the ocean, along with other satellites that will continuously measure sea levels and wind speeds and directions. The buoys are built to last five years, says W. Brechner Owens of Woods Hole, who helped to design them. "Because the ocean is so incompressible, the buoys won't clump," he adds.

"Once fully deployed, Argo will give us for the oceans what meteorologists have had for the atmosphere—a worldwide observing network," Wilson exclaims. "If we can observe and understand the oceans, we have the potential to forecast six to 12 months in advance." Forecasters will not be able to say that it will snow on Christmas in New York, but they may be able to predict that the Northeast will probably have more snow than usual next winter and give people a chance to prepare for it. The old saying—that everyone complains about the weather but nobody does anything about it—may not be quite so true anymore. W

LAURENCE LIPPSETT is science editor at the Woods Hole Oceanographic Institution.