

The Oceans and Weather

*The sea is as important as the atmosphere
in controlling the planet's weather*

by Peter J. Webster and Judith A. Curry

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n the hierarchy of unavoidables, weather is as inevitable as death and taxes. No matter where people live, they must think about it—whether they are checking the local news in England to see if they will need an umbrella, sowing seeds in anticipation of monsoon rains in India or rebuilding in the wake of a catastrophic hurricane in the U.S. When most people ponder the weather, they instinctively look to the sky. But the atmosphere does not determine the weather by itself. It has a less obvious but essential partner: the ocean.


One demonstration of this synergy has been quite obvious of late. The disastrous El Niño of the past year increased public awareness that many unusual events all over the globe—relentless series of storms, prolonged droughts, massive floods—were directly caused by changing conditions in the tropical Pacific Ocean.

Such connections between the ocean and the atmosphere can influence, and often dominate, changes in the

weather and longer-term climate everywhere. Effects range from storms and hurricanes generated over hours and days to ice ages that develop over millennia. In between, the ocean is the engine that drives seasonal shifts in weather, such as monsoons, and sporadic events, such as El Niño. Understanding the linkages between the atmosphere and the ocean has engaged meteorologists and oceanographers for decades. Fortunately, scientists now have a reasonable understanding of how these mechanisms work.

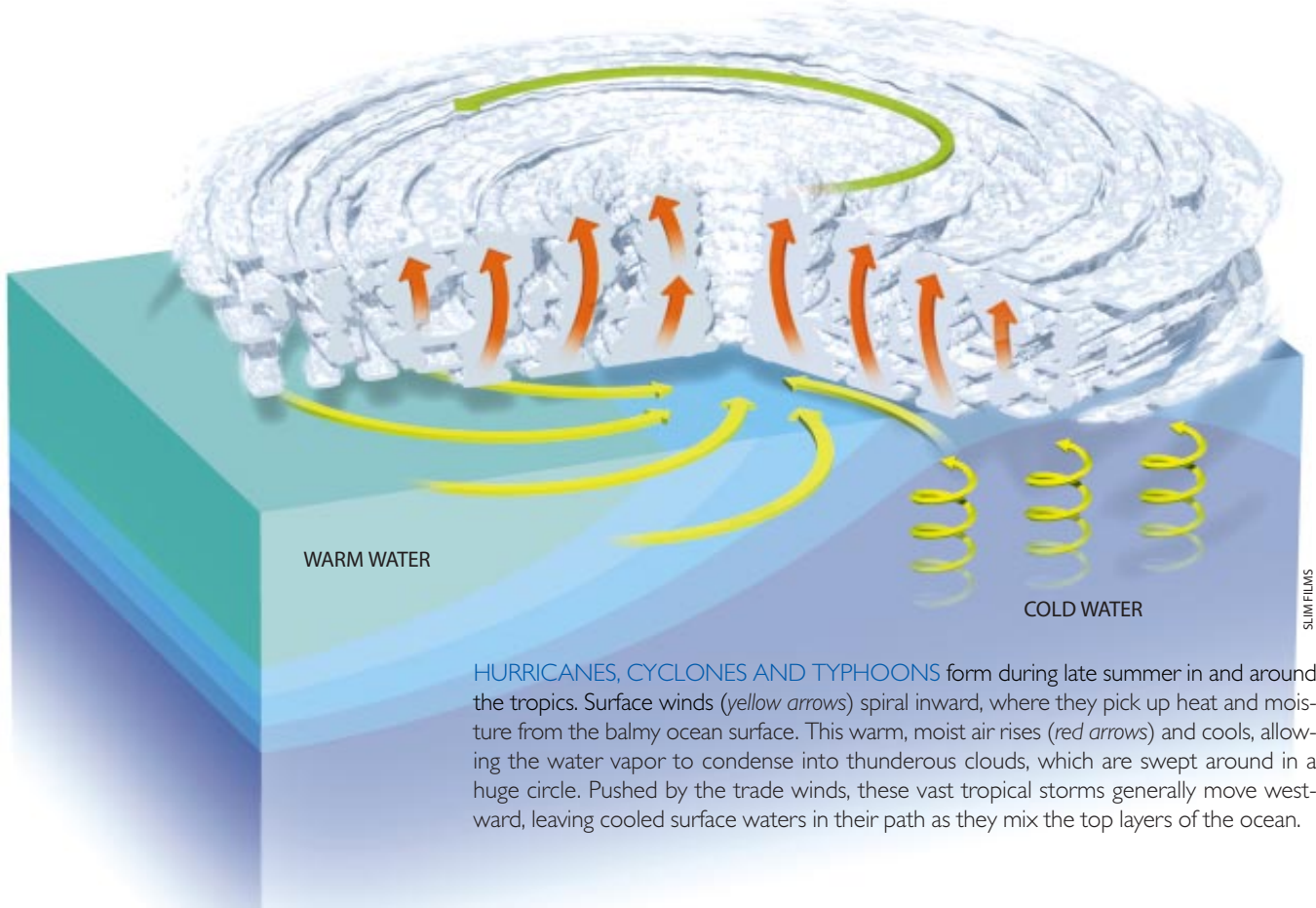
Midlatitude Battle Zone

Some of the most familiar weather systems occur at middle latitudes, although the driving forces behind this activity are oceans far away. The sea near the equator is especially warm, because solar heating is generally most intense there. To the north or south, the curvature

A satellite-style aerial photograph of a hurricane, Hurricane Elena, swirling over the Gulf of Mexico. The storm's eye is visible as a dark, circular center, surrounded by a dense, white ring of clouds. The surrounding clouds are lighter and more diffuse, showing the spiral structure of the storm. The ocean surface is visible as a darker blue area at the bottom of the frame.

HURRICANE ELENA swirls over the Gulf of Mexico in August 1985, collecting energy from the warm sea below it.

NASA Corbis



HURRICANES, CYCLONES AND TYPHOONS form during late summer in and around the tropics. Surface winds (*yellow arrows*) spiral inward, where they pick up heat and moisture from the balmy ocean surface. This warm, moist air rises (*red arrows*) and cools, allowing the water vapor to condense into thunderous clouds, which are swept around in a huge circle. Pushed by the trade winds, these vast tropical storms generally move westward, leaving cooled surface waters in their path as they mix the top layers of the ocean.

of the planet causes the sun's rays to spread out over a greater area. Solar heating at high latitudes is reduced even further in winter, when the axis of the planet tilts away from the sun. Also, like all objects immersed in a colder medium, the earth constantly loses heat to space. Near the equator the energy gained from the sun exceeds the amount lost in this way, but at higher latitudes the reverse occurs. If nothing intervened, the low latitudes would fry while the high latitudes froze.

The ocean and the atmosphere work together like a planetary thermostat, sharing nearly equally the task of exporting heat from equatorial regions toward the poles. Some of this heat is carried in warm currents such as the Gulf Stream. But the tropical ocean also passes large amounts of heat to the atmosphere. The warm, moist air created in this way rises because it is less dense than the surrounding atmosphere. If the earth did not rotate, this heated air would travel directly toward the poles. In addition, cold, dry air originating over the polar oceans and high-latitude landmasses would pass unhindered toward the equator, slipping under the warmer air and moving near the surface of the earth.

But the rotation of the earth deflects air masses into ribbons of air that spiral around the globe, westward in polar and equatorial regions and eastward in the midlatitudes. This pattern inhibits a clean transfer of heat

between north and south. Instead cold and warm air masses collide in midlatitudes, where they often mix in huge swirlings, creating powerful storms.

Within these storms, the warm air rises up and over the incursion of cold, denser air. Pushed aloft, the warm air cools, and its water vapor condenses into clouds and rain. In the process the air releases large amounts of so-called latent heat—the energy difference between water in its vapor and liquid forms. Thus, copious amounts of heat, along with moisture and wind energy, flow across the borders between the air masses. Over a period of four to six days, this stormy boundary drifts from west to east, producing much of the rain that falls at midlatitudes—in the U.S., for instance. Finally, the thunderclouds dissipate, the battling air masses achieve a new equilibrium, and the temperature difference between the tropical and polar regions decreases for a time—only to build again under the constant barrage of the equatorial sun and the intense cooling at the poles.

Sometimes the link between oceans and storms can be more explosive. For example, outpourings of frigid Arctic air frequently sweep down across North America and Asia during winter. When these air masses arrive over the warm Gulf Stream and the Kuroshio (Japan Current), which flow northward from the tropics along the western side of the Atlantic and Pacific

oceans, respectively, warmth and moisture rise from the sea, fueling the development of intense storms called bombs.

Bombs develop extremely quickly, taxing the ability of weather forecasters and often causing death and destruction. The storms have central pressures that are as low as many hurricanes, sometimes as little as 960 millibars. About two of these storms form in both the western Pacific and western Atlantic each winter. They last for days, migrating eastward and northward, thus crossing some of the busiest shipping lanes in the world. The winds can be so strong (more than 100 kilometers per hour) and the surface ocean waves so powerful that large ships can be easily lost. For instance, in September 1978 the fishing trawler *Captain Cosmo* sank in the North Atlantic, and the passenger liner *Queen Elizabeth II* suffered severe damage. In 1987 a bomb with wind speeds exceeding 160 kilometers per hour hit the coasts of Britain and France, killing 25 people, injuring 120 more and destroying 45 million trees.

Stormy Tropics

The ocean also generates intense storms at lower latitudes, in or around certain tropical regions. In the western Atlantic and eastern Pacific off Mexico and California, these storms are called hurricanes after the Mayan god of winds, Hunraken. In

the Indian Ocean and near northern Australia, they are known as cyclones, a variation of the Greek word for “coiled serpent.” In the northwestern Pacific, they are called typhoons, from the Chinese phrase for “great wind,” *tai fung*.

Despite their different names and locations, the mechanics of all these immense circular storms are much the same. Hurricanes form only in places where the ocean-surface temperature exceeds 27 degrees Celsius (81 degrees Fahrenheit), which is why they usually form in late summer, when the ocean surface is the warmest. The storms occur somewhat away from the equator, where the rotation of the earth causes the tropical trade winds to bend poleward, a force needed to initiate the characteristic spiral of these storms.

Each hurricane develops from some original eddy in the wind that causes a low-pressure center to form. Such disturbances may initially be small and innocuous. But if conditions in the ocean and the upper atmosphere are right, about 10 percent of them intensify into full-fledged hurricanes.

Air moves inward from all directions toward the low-pressure center of the developing hurricane, picking up moisture evaporating from the warm ocean. As more and more air converges toward the central low-pressure void, or the “eye,” of the storm, it has no place to go but upward, where it creates clusters of thunderstorms and releases large amounts of rain and latent heat. The density of the superheated air then decreases markedly, forcing it to rise even more and to spread outward in the upper atmosphere. This movement causes the atmospheric pressure at the surface of the ocean to drop significantly.

At this stage, winds near sea level begin to circle (counterclock-

wise in the Northern Hemisphere and clockwise in the Southern Hemisphere) at ever-increasing speeds around the eye. Friction with the ocean surface causes these winds to spiral even more quickly inward and toward the warm center of the storm.

The temperature at the surface of the sea now becomes the critical factor. The exceptional warmth of the tropical ocean boosts the amount of evaporation, allowing the converging winds to pick up more moisture and to release more latent heat when the water vapor condenses into

thunderstorm clouds. Air flowing along the ocean surface toward a low-pressure center might be expected to cool and dampen the storm. But in a hurricane, direct heating from the ocean surface offsets this effect, further intensifying the tempest. The rotating storm sustains itself by picking up as much energy from the surface of the ocean as it releases in its many thunderous clouds.

But that equilibrium does not last forever. The turbulence created by the strong winds mixes the upper ocean and brings colder water from below up to the sur-



STEVE McCURRY/Magnum



MONSOON RAINS deluge Varanasi, India, during the summer months there (*photograph*), because the prevailing winds (*blue arrows*) from May to September (*top map*) soak up moisture from the ocean and bring heavy rains to large parts of Africa and Asia (*shaded regions*). Between November and March (*bottom map*), the pattern reverses, drenching more southerly lands in Africa, Indonesia and Australia.



LAURIE GRACE (maps)

EL NIÑO of 1997 and 1998 caused extreme weather in many places, including flooding and landslides in California (*photograph*). Such conditions occur when the normal trade winds ebb or reverse direction, allowing a warm layer to cover the tropical Pacific (*far right, top*). More usually, and under a regime dubbed “La Niña,” the westward-directed trade winds are strong enough to push surface waters toward Indonesia, forming the western Pacific warm pool (*far right, bottom*).

face. That change cuts off the source of energy to the storm and leads ultimately to its demise. This mixing is why hurricanes can develop only where the layer of warm water at the surface of the sea is sufficiently thick—at least 60 meters. Otherwise cold water reaches the surface too easily. In that case, just as when a hurricane moves over cooler water or over land, its supply of heat and moisture disappears and the great storm dissipates.

Reversals of Fortune

When the ocean provides a more stable source of moisture to the atmosphere, it can create weather patterns that affect society even more than hurricanes do—the monsoons. The term “monsoon” comes from the Arabic *mausim*, which means “season.” It refers to a circulation pattern that brings especially wet weather for part of the year.

During summer in the Northern Hemisphere, Asian and north African lands heat up considerably. Warm air rises over the Himalayas, the Plateau of Tibet and the mountains of central Africa, drawing in air from south of the equator. The resultant northward-moving winds pick up considerable moisture as the rotation of the earth deflects them to the east over the warm Arabian Sea, and the South Atlantic and Indian oceans. These surging air masses rise over the heated land areas and release their moisture in the form of monsoon rains in Asia and in central Africa north of the equator. Asians celebrate the onset of this “southwest monsoon” (named for the prevailing winds, which come from the southwest) because it marks the end of a period of intense heat and because the rainfall is essential for their crops.

The rains continue roughly until winter returns to the Northern Hemisphere and the lands there begin to cool. Air masses now reverse direction, with northeasterly winds moving across the equator, picking up moisture from the oceans before they reach southern Africa and northern Australia. Weaker versions of this same process



VINCE STRIENANO Corbis

also occur in the tropical Americas, bringing wet seasons to northern South America and southern Central America in Northern Hemisphere summer and to central South America in Northern Hemisphere winter.

It is a mistake, however, to think of the monsoon simply as a period of continuous rainfall. Within the rainy season are periods of intense precipitation, called active monsoon periods, and 20- to 30-day mini-droughts, called monsoon breaks. Climatologists hypothesize that these oscillations occur because the soil becomes saturated and cools considerably; warm air then no longer rises more over land than sea. So the moisture-laden air from the ocean ceases to rush in over the continents. When the land dries out, warm air rises once again over land with vigor, moist air advances from the sea and the rains begin again.

Not surprisingly, the overall amount of moisture carried across the coastline to interior regions depends on the temperature of the adjacent ocean. Thus, a warm Arabian Sea in springtime portends a strong summer monsoon, and vice versa. But perhaps the greatest effect on the monsoons—accounting for about a 35 percent difference in the monsoon rains over India, for example—comes from the climatic phenomenon that is second only to the seasons themselves in driving worldwide weather patterns: El Niño.

The Christ Child

The ocean and the atmosphere in the Pacific perform an intricate, delicately poised pas de deux. The dance begins with the vast tropical Pacific Ocean, which under the glare of the intense tropical sun re-

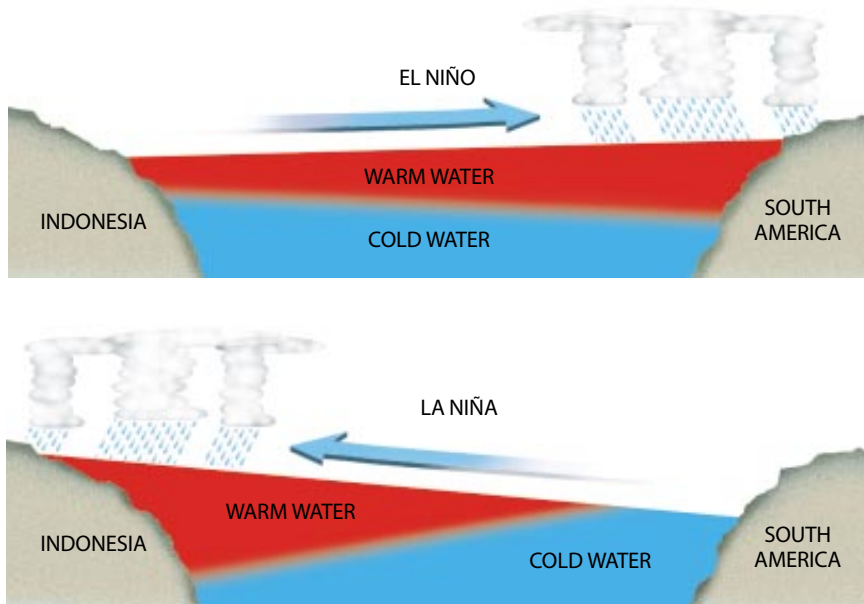
ceives more solar energy than any other ocean on the earth. Ordinarily, the trade winds push the warmed Pacific surface waters westward so that they accumulate in a large, deep “pool” near Indonesia. In the eastern Pacific, off the west coast of South America, relatively cold waters rise from depth to replace the warm waters blown west.

As springtime arrives in the Northern Hemisphere, the trade winds lose strength. Surface temperatures in the central and eastern Pacific rise by a few degrees, and the east-west temperature difference diminishes. But this warming of the central Pacific is usually transitory: the onset of the Asian summer monsoon brings freshening winds, which create turbulence that mixes cold water up from below. All in all, the winds and waters form a dynamic, delicately balanced mechanism.

But like most machines with many moving parts, this system can break down. Every three to seven years the trade winds fail to pick up in summer. The warming of the central Pacific that begins in the spring continues to intensify and spreads eastward through the summer and fall.

Below the surface, invisible “internal waves,” thousands of kilometers in length, propagate eastward along the interface between the warm layer at the top of the ocean and colder water at depth. These waves do not actually transport water eastward from the western Pacific warm pool. Rather, they serve as a cap to reduce the upwelling of cold water in the eastern Pacific. So the warm pool grows eastward across the entire Pacific.

The many schools of anchovy that thrive in the cold, nutrient-rich waters that normally rise to the surface off the Peruvian



coast then disappear. Because this warming of the eastern Pacific occurs around Christmastime, Peruvian fishermen have long called it El Niño, literally “the boy child,” after the infant Christ. The opposite extreme of the cycle, in which eastern Pacific waters become especially cold, has more recently been christened La Niña, “the girl child.”

If the effects of El Niño were restricted to the ocean, it probably would have remained a concern only of Peruvian fishers. But as the warm pool migrates eastward, it injects heat and moisture into the overlying air. This shift of the warm pool profoundly rearranges atmospheric circulation all around the globe and changes the locations where rain falls on the planet.

El Niño can, for instance, cause severe droughts over Australia and Indonesia, with accompanying forest fires and haze. It weakens the summer monsoon rains over southern Asia, but it often causes heavy rainfall and catastrophic flooding along the Pacific coast of South America. El Niño also affects the frequency, severity and paths of storms, lowering the probability of hurricanes in the Atlantic but increasing the chances of cyclones and typhoons in the Pacific.

In more circuitous but no less dramatic ways, El Niño alters the probability of certain weather regimes outside the tropics. It can intensify the western Pacific jet stream and shift it eastward, for example, increasing the chances of stronger winter storms over California and the southern U.S., with accompanying floods and mudslides.

El Niño can thus have dire consequences for society and the global economy. Indeed, it affects nearly everyone: farmers, relief workers, transportation experts, water resource and utilities managers, commodities traders, insurance brokers—even people searching for vegetables at the market. In many parts of the world, El Niño sparks the spread of waterborne diseases such as typhoid, cholera, dysentery and hepatitis as well as vector-borne diseases such as malaria, yellow fever, dengue, encephalitis, plague, hantavirus and schistosomiasis.

During the past two decades, several major warmings have occurred. In 1982 and 1983 El Niño caused thousands of deaths and over \$13 billion in damage worldwide. In 1986 and 1987 a less dramatic El Niño transpired, and a far weaker event developed in 1992. The latter was unusual because it continued for two full

years, albeit with relatively low intensity.

In the spring of last year, the tropical eastern Pacific Ocean warmed to an unprecedented extent. The surge in ocean temperatures continued at a much faster rate than usual: by October 1997 the surface temperature of the eastern Pacific had risen by more than six degrees C from its state a year before. Although temperatures there have since dropped from their peak, nearly everyone on the earth has felt the effects of this recent El Niño in some way.

Looking over the Horizon

The devastation wrought by the El Niño of 1982 and 1983 spurred meteorologists to look beyond the typical one-week range of most forecasts and to try to predict the weather a season, or perhaps a year or more, in advance. To accomplish that feat, scientists turned to the ocean, whose influence on the climate increases as the time span in question lengthens.

One manifestation of this focus on the ocean came in 1985, when researchers from many countries established a network of oceanographic sensors across the tropical Pacific. With warning from this array, meteorologists knew months in advance that the El Niño of 1997 was approaching and that it would be strong. Forewarned, some farmers planted more rice and less cotton in anticipation of especially heavy rains. Others took steps to start conserving water in preparation for the coming drought.

With a better understanding of the ocean, scientists may yet be able to forecast climate changes from year to year or even from one decade to the next. For example, they might be able to predict shifts in the frequency, duration or severity of hurricanes, monsoons and El Niño in the face of global warming. For such long-term forecasts, Bob Dylan may have been right when he sang, “You don’t need a weatherman to know which way the wind blows.” You need both a weatherman and an oceanographer. 54

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Further Reading

MONSOONS. J. S. Fein and P. L. Stephens. John Wiley & Sons, 1987.
 AN INTRODUCTION TO THE WORLD’S OCEANS. Alyn C. Duxbury and Alison B. Duxbury. William C. Brown Publishers, 1994.
 CURRENTS OF CHANGE: EL NIÑO’S IMPACT ON CLIMATE AND SOCIETY. Michael H. Glantz. Cambridge University Press, 1996.