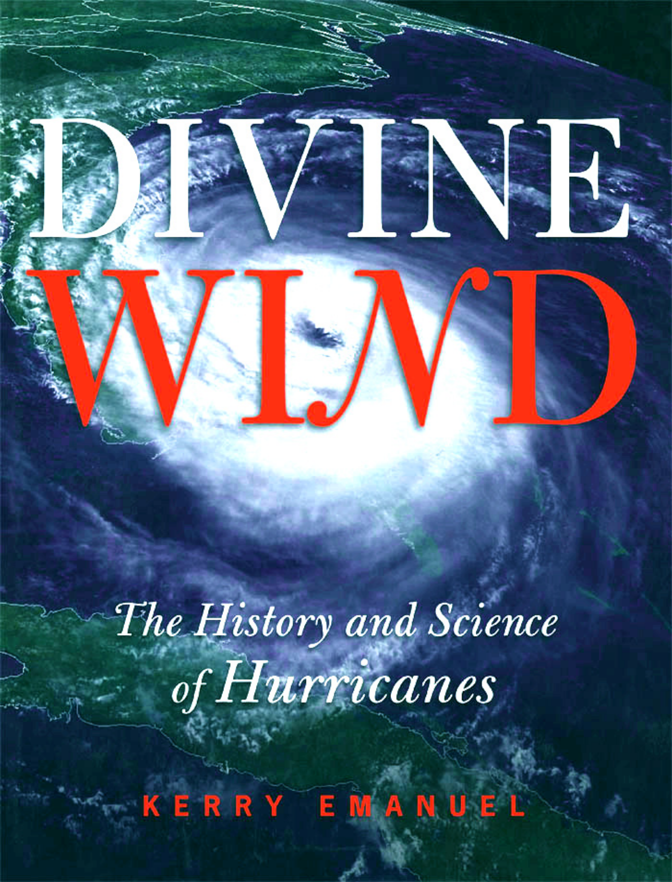

DIVINE WIND

The History and Science of Hurricanes

KERRY EMANUEL

DIVINE WIND

▲
Impending. Oil painting by American artist Amy Marx, 2002.

The Voice of the Sea is never one voice, but a tumult of many voices—voices of drowned men,—the mutterings of multitudinous dead,—the moaning of innumerable ghosts, all rising, to rage against the living, at the great Witch-call of storms....

—Lafcadio Hearn (1850–1904), *Chita: A Memory of Last Island*

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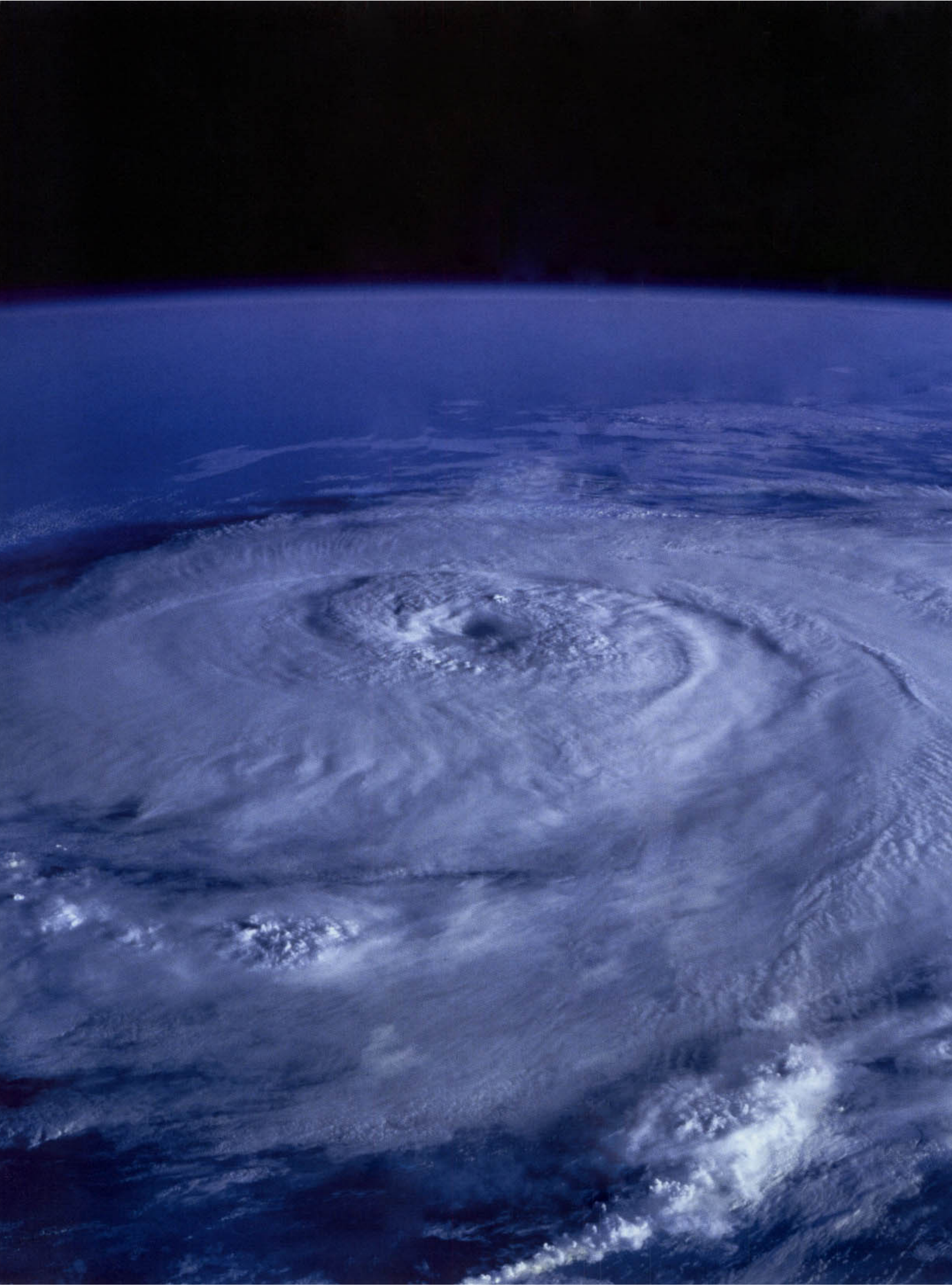

Preface

Of all the natural phenomena that affect our planet, the hurricane is among the most deadly and destructive. Hurricanes have killed more people worldwide in the last fifty years than any other natural cataclysm, and a single storm—Andrew of 1992—was the most expensive natural disaster in history. At the same time, the magnificence of these great tempests has influenced artists, writers, and naturalists through all time, inspiring works from ancient Mayan hieroglyphs to abstract renditions of recent storms, from the plays of William Shakespeare to a novel by Joseph Conrad. The terror and awe of rotating windstorms are conveyed in all of the major religious texts: the Bible, for example, contains numerous references to whirlwinds, invariably invoked as instruments of God. Hurricanes have altered both natural and political geography, cutting new inlets with the same ease with which they dispatch entire navies. As destructive of human ends as they may be, they nonetheless play a vital role in certain tropical ecosystems and may, ironically, prove essential to the comparative stability of tropical climate.

It is my ambition to portray the hurricane as it is seen from the perspectives of history, art, and science, so as to form an integrated appreciation of the phenomenon. To help accomplish this, the chapters of this book alternate between accounts of hurricanes that have played important roles in history and a scientific narrative that describes some of what has been learned about the nature of these storms. Interspersed throughout are works of art and literature that help convey the human experience of hurricanes. Some (but I suspect very few) of my scientific colleagues may complain that the sentiments expressed by the art and literature distract from what ought to be an impersonal pursuit of scientific truth. I remind them that there is not a single one of us who is not driven forward by a passion for our work, and there is no shame in admitting that. To those who feel that science need

◄ Hurricane Elena over the Gulf of Mexico in September, 1985, photographed by a crew member onboard the space shuttle Discovery.

play no role in the appreciation of nature, who feel that scientists are motivated primarily by the desire to demystify and to exercise power over nature, I ask you to remember how you felt about science when you were in third grade, when knowledge stimulated rather than extinguished wonder, and to contemplate the words of Albert Einstein, that the most beautiful experience we can have is that of the mysterious. I believe that most scientists are motivated more by the desire to find new mysteries than to solve known problems.

To one accustomed to publishing in scholarly journals, it becomes instinctive to cite all sources that were brought to bear on one's own contribution, yet to do so would considerably compromise the tone and flow of a book like this. I am left with the impossible task of summarizing in a few brief sentences the vast quantity of inspiration and help I have received from many others. I begin with two books—now quite dated—that served as models for this one. In her magnificent *Hurricane*, Marjory Stoneman Douglas presents a riveting account of the effect that tropical cyclones had on exploration and settlement of the New World, interwoven with discussion of what was then known about the physics of hurricanes. I relied on this work for much of the historical material presented here. In his Time-Life series book *Weather*, Philip Thompson showed me that historical, artistic, and scientific material can be skillfully interwoven to illustrate a complex topic in an entertaining and informative way. Other sources are given in the reference list at the back of the book. I am indebted to many for providing source material, photographs, and advice. These include Lixion Avila, Mike Black, Howie Bluestein, Ray Hennessey, Kam-Biu Liu, Frank Marks, Peter Perdue, Jim Pritchet, and Joel Sloman. This book would not have been undertaken without the encouragement of my editor, Joyce Berry of Oxford University Press. In addition to editing often unreadable drafts, she worked tirelessly to obtain many needed permissions, artwork, and works of literature while patiently enduring a steady stream of polemics about publishing. Work on this project made a virtual widow of my wife, Susan, and orphan of my son, David. To them I dedicate this book.

—Kerry Emanuel, Lexington, April 19, 2004

Supplementary material for Divine Wind and more information about hurricanes may be found at:
http://www.oup.com/us/divinewind

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The Coming Storm.
Watercolor by American artist Winslow Homer, 1901.

The summer's sun was sinking down 'neath Binion's waveless bay,
And burnishing its rippling tide with many a golden ray;
The zephyrs stayed their wanton steps, and hushed their every breath—
The scene was still, the bay was bright and undisturbed as death.
Tall Raghlin looked with queenly pride far out into the main,
And Binion threw its giant shade across the watery plain;
And fair Donaff in distance blue raised up its head on high,
And caught the sun's expiring beams, and kissed the cloudless sky—
No dark spot dimm'd the broad expanse that spann'd the silent sea;
That was fair as eastern bride, and brighter far than she!

A tiny boat, like speck of snow, on ocean's bosom hoar,
Had spread its sails at early morn, and left that lonely shore;
The noontide sun had seen it far out on the watery track,
And vesper lit her dazzling lamp to guide the wanderer back.
The idle sails now flap the mast, no breeze disturbs the sea,
And through Lagg Bar the angry tide for once steals silently;
The boatmen press the pliant oars, and raise the jocund song—
They pass the tower of Malin Head girt round by barriers strong;

And Tullagh's strand is full in view, and seen is rough Maymore—
Full well these boatmen know each spot from Doagh to Leenan Shore!

But just athwart the day-god's track a sudden gloom has passed,
As if the night her sombre veil across the day had cast;
A vivid flash lights up that gloom, the sudden thunder rolls—
It peals along the startled heavens, and roars around the poles.
The gushing rain comes dancing forth in drenching torrents wild,
And leaps the whirlwind from its throne of storms on storm-clouds piled,
It sweeps the main with tyrant might—upheaves the tranquil bay—
And dashes o'er the troubled sea like dolphin at its play;
It crests the wave with snowy foam, throws billows mountain high,
And rears up watery spires that pierce the bosom of the sky!

The storm has ceased, the night is on, and sighs the dying gale,
And quick the swollen streamlets run in murmurs down the vale;
And where's the boat—poor tiny thing—that rode the waves at morn,
And spread in pride its snowy sail like butterfly just born?
And where's the crew that mann'd that boat—Clonmany's seamen bold—
Who feared no tide, disdained all storms, felt not the winter's cold?
They've sunk beneath the billow's breast, down in the salt-sea wave—
No humble cross in hallowed spot shall mark their lonely grave.
Their shroud shall be the sea-weed green, their tomb the ocean sand,
Their epitaph—the tale which tells their fate upon the land.

The summer's sun again looks down on Binion's waveless bay,
And sees no trace which marks the storm that swept it yesterday;
But there are hearts beneath that tide cold, cold as winter's snow,
Which never more shall feel life's joys, nor taste its cup of woe.
On yester-morn those hearts were glad—their life blood bounded free—
The tempest swept across the deep, and sunk them in the sea!
There shall they sleep regarding not the storms that o'er them rave;
No sound of busy life shall break the stillness of their grave;
Eternal hurricanes may roll unheeded o'er their head—
No voice they'll hear but that which cries:—'Arise, arise ye dead!'

—J. K. O'Doherty (1833–1907), "The Hurricane"

1 Kamikaze

Behold, a whirlwind of the Lord is gone forth in fury, even a grievous whirlwind: it shall fall grievously upon the head of the wicked.
—Jeremiah 23:19

Were it not for two typhoons, Japan might be part of China today.

In the year 1259, Kublai Khan, the grandson of Genghis Khan, became emperor of Mongolia and renamed it Yuan, meaning "first beginning," reflecting his aspirations for the empire. In 1230, the Mongols had conquered northern China, and between 1231 and 1238, they overran the Korean peninsula. As the Mongols took it as their mission to conquer as much land as possible, Japan, separated by only 150 km (100 mi) from Korea, rightly feared invasion. Between 1267 and 1274, Kublai Khan sent a number of emissaries to Japan demanding that its emperor submit or face an invasion. These emissaries were usually turned back before their message reached the emperor; in any event, the Mongols never received a response.

Thus it came to pass that Kublai mounted an invasion to conquer Japan. Although the Mongols knew nothing of seafaring, the newly conquered Koreans were expert shipbuilders and navigators and were put to work assembling an impressive naval fleet.

On October 29, 1274, the invasion began. Some 40,000 men, including about 25,000 Mongolians and Chinese, 8,000 Korean troops, and 7,000 Chinese and Korean seamen, set sail from Korea in about 900 ships. At first, the expedition went well for the Mongols. After quickly overrunning several small islands off the northwest coast of Kyūshū, the force landed at the harbors of Imazu and Hakata in Kyūshū on November 19. The Japanese defenders were horrified by the Mongol cavalry charging off the beaches, steeped as they were in the tradition of hand-to-hand combat between knightly warriors. With fewer troops and inferior weapons, the Japanese were rapidly pushed back into the interior. But at nightfall, the Korean pilots sensed an approaching storm and begged their reluctant Mongol commanders to put the invasion force back to sea lest it be trapped on the coast

Figure 1.1 Scene from the thirteenth-century Mongol invasion scrolls, based on a narrative written by the Japanese warrior Takezaki Suenaga.

▲

and its ships destroyed at anchor. The next morning, the Japanese, who had wished for nothing more than a delay in the Mongol assault to allow reinforcements to arrive, were surprised and delighted to see the last of the Mongol armada struggling to regain the open ocean in the midst of a great storm. The ships of the time were no match for the tempest, and many foundered or were dashed to bits on the rocky coast. Nearly 13,000 men perished, mostly by drowning. The Mongols had been routed by a typhoon.

Even as Kublai Khan was mounting his Japanese offensive, he was waging a bitter war of conquest against southern China, whose people had resisted him for 40 years. But finally, in 1279, the last of the southern provinces, Canton, fell to the Mongol forces, and China was united under one ruler for the first time in three hundred years. Buoyed by success, Kublai again tried to bully Japan into submission. But this time the Japanese executed his emissaries, enraging him and thereby paving the way for a second invasion. Knowing this was inevitable, the Japanese went to work building coastal fortifications, including a massive dike around Hakozaki Bay, which encompasses the site of the first invasion.

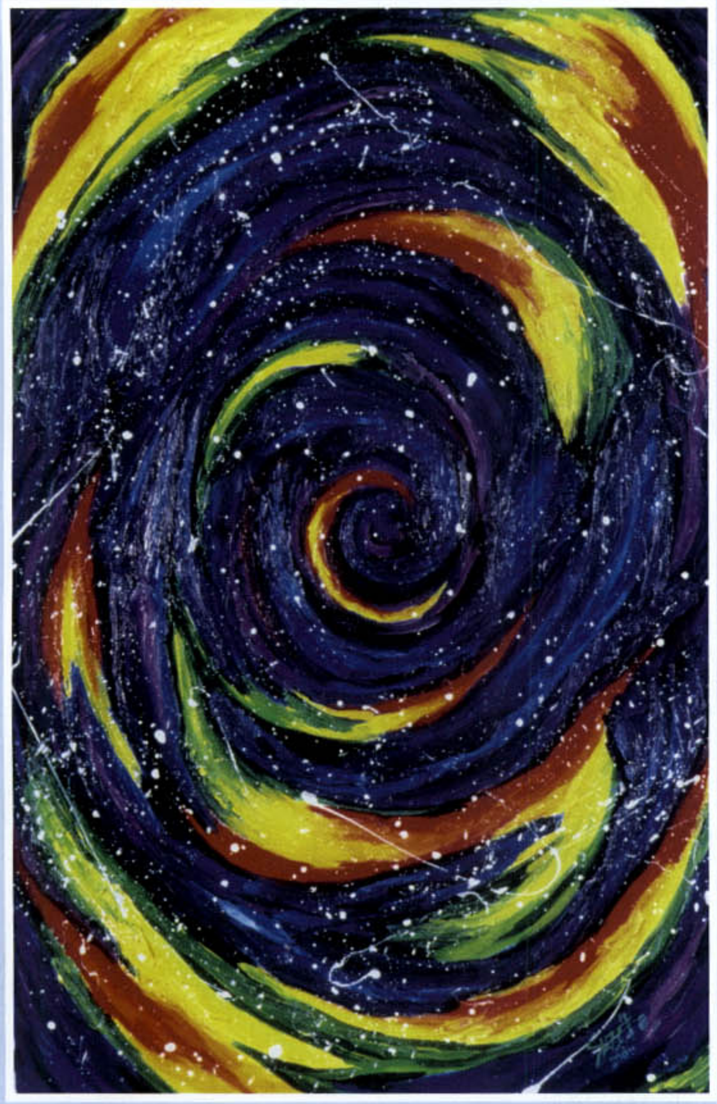
The second Mongol invasion of Japan assumed staggering proportions. One armada consisting of 40,000 Mongols, Koreans, and north Chinese was to sail from Korea, while a second, larger force of some 100,000 men was to set out from various ports in south China. To gauge the size of this expeditionary force, consider that the Norman conquest of Britain in 1066 engaged 5,000 men.

The invasion plan called for the two armadas to join forces in the spring, before the summer typhoon season, but the southern force was late, delaying the invasion until late June 1281. When they arrived along the coast of Kyūshū, they met fierce resistance from Japan's samurai warriors, who were better prepared and now knew what to expect from the Mongols. The defenders held back the invading forces for six weeks, until, on the fifteenth and sixteenth of August, history repeated itself. Once again, the Korean and south Chinese mariners sensed the approach of a typhoon and attempted to put to sea. But the fleet was so unwieldy and poorly coordinated that many of the ships collided at the entrance of Imari Bay and were smashed by the typhoon, as were most of those that made it to the open ocean. Kublai managed to escape on an undamaged ship, but left his men to die at the hands of the storm and the samurai. The wreckage and loss of life was staggering. Once again, Kublai Khan's designs on Japan were defeated by a typhoon, and never again did he attempt such an invasion.

As a direct result of these famous routs, the Japanese came to think of the typhoon as a "divine wind," or *kamikaze*, sent by their gods to deliver their land from invaders.

Seven hundred years later, in 1981, Torao Mozai, a Tokyo University engineering professor, conducted sonar-aided digs in Japan's Imari Bay and turned up numerous artifacts from the Mongol invasions, including spearheads, war helmets, a cavalry officer's iron sword, and stone anchor stocks. Fisherman came forward with other objects they had pulled up in their nets. Excavations continue to this day and have yielded many more treasures from these ancient invasions, including ceramic pots and ship anchors.

Six hundred and sixty-three years after Kublai Khan's last defeat on the shores of Japan, another naval commander, facing the same enemy, made the same mistake twice in succession. Aircraft, weather maps, and steel ships were not enough to prevent Admiral William F. "Bull" Halsey, commander of the U.S. Third Fleet in World War II, from meeting disaster in the form of two typhoons. We shall return to Admiral Halsey's plight in Chapter 23.



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Storm II The Hurricane. Acrylic painting by American artist Suzette Barton Chandler.

Lo, Lord, Thou ridest!
Lord, Lord, Thy swifting heart

Naught stayeth, naught now bideth
But's smithereened apart!

Ay! Scripture flee'th stone!
Milk-bright, Thy chisel wind

Rescindeth flesh from bone
To quivering whittlings thinned—

Swept-whistling straw! Battered,
Lord, e'en boulders now out-leap

Rock sockets, levin-lathered!
Nor, Lord, may worm out-creep

Thy drum's gambade, its plunge abscond!
Lord God, while summits crashing

Whip sea-kelp screaming on blond
Sky-seethe, high heaven dashing—

Thou ridest to the door, Lord!
Thou bidest wall nor floor, Lord!

—Hart Crane (1899–1932), "The Hurricane"

2 Anatomy of a Meteorological Monster

The storm was in the form of a great whirlwind.

—William Redfield, 1831

The early settlers of the New World were adept at describing the effects of hurricanes, but they were not able to form any conception of their structure. It was not until the early nineteenth century that naturalists began to accept the idea that hurricanes are vast vortices, or whirlwinds. In 1821, William Redfield, a New England saddler and amateur meteorologist, traveled through Connecticut to inspect the damage wrought by a hurricane that had raced northward through the mid-Atlantic states and New England. He noticed that although trees had fallen toward the northwest in the eastern part of the state, they pointed southeastward in the western part. He then hypothesized that hurricanes are giant whirlwinds, an idea that was soon supported by observations made by the British engineer William Reid, while surveying damage done by an 1831 hurricane in Barbados. Reid supplemented his account of the damage in Barbados with wind observations recorded in ships' logs, confirming the circular nature of the wind field.

Redfield and others believed that hurricanes extend upward only about a mile or so into the atmosphere. Their reasoning was based in part on the observation that hurricanes are often severely disrupted by relatively small mountains or hills. But in Cuba, Benito Viñes, a Jesuit priest and trained physicist, argued that hurricanes extend many miles upward, since they produce large amounts of cirrus. Such clouds are composed of ice crystals that can only form in the extremely cold conditions high up in the atmosphere. This controversy about the height of hurricanes was not finally settled until the 1930s, when the laws of physics were sufficiently well-known to rule out the idea of shallow hurricanes. Today we know that most hurricanes extend through the whole depth of the troposphere and into the lower stratosphere, sometimes reaching heights of around 18 km (11 mi).

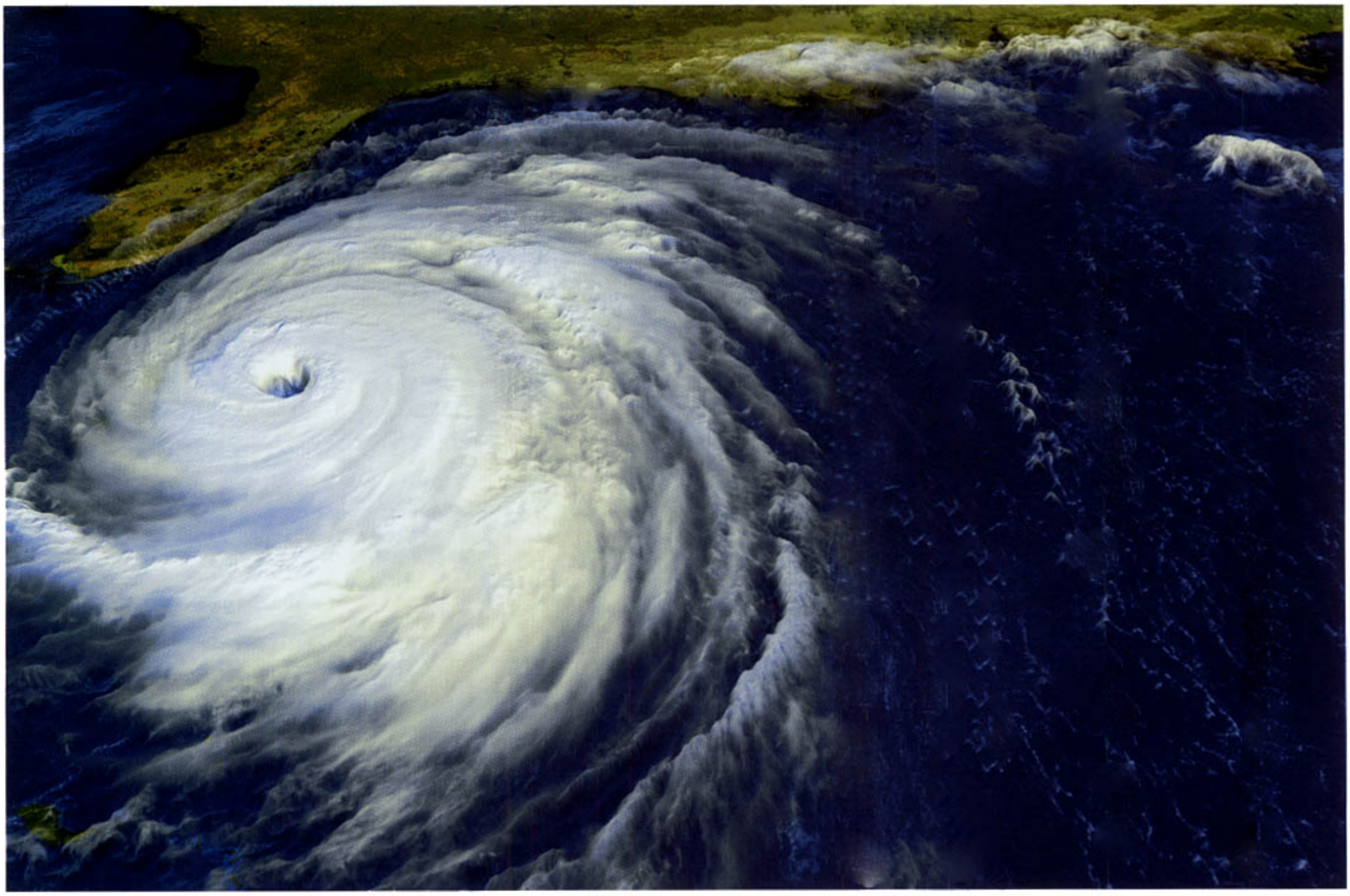


Figure 2.1: Satellite image of Hurricane Floyd approaching the east coast of Florida in 1999. The image has been digitally enhanced to lend a three-dimensional perspective. ▲

The advent of reconnaissance aircraft and radar in the 1940s, and of satellites in the 1960s, gave scientists the means to determine the detailed structure and evolution of hurricanes. Today, almost everything we know about hurricanes is based on observations by aircraft, radar, and satellites.

Figure 2.1 shows a satellite picture of Hurricane Floyd approaching the east coast of Florida in 1999. The image has been enhanced using a computer, to give a feeling for the relative heights of clouds in the storm. The swirling mass of clouds is about 300 km (180 mi) across, and Floyd's eye is about 50 km (30 mi) in diameter. Surrounding the eye is a deep ring of thick cloud called the *eyewall*. A thin veil of very high cloud covers most of the swirling mass of thicker clouds; this is the veil of cirrus, made up of tiny ice crystals, that Benito Viñes spoke of. Underneath it, and thus invisible from above, are several spiral-shaped bands of deep, thick cumulonimbus clouds, interspersed between relatively clear sky. These spiral bands produce heavy rains and gusty winds well outside the eyewall of the hurricane, where the strongest winds are found.

Let's have a closer look at the eye. Figure 2.2 shows a photo taken from a U.S. space shuttle overpass of Hurricane Emilia in the eastern North Pacific in 1994. Looking at the eye from above is like staring down the middle of a bathtub whirlpool, except that the boundaries are made of cloud and the "funnel" comes to an abrupt end at the sea surface. The eyewall is visible as the stadium of thick, white cloud surrounding the eye. This is where the strongest winds and heaviest rain are found. Unlike the

Figure 2.2: The eye of Hurricane Emilia over the eastern North Pacific, as seen from directly above by the crew of the space shuttle Columbia *on July 19, 1994, at 19:33 UT. At this time, Emilia had maximum winds of 70 m/s (155 mph).*

▶

bathtub whirlpool, the air inside the eyewall is going up, not down, as it swirls around the eye. There are spiral striations along the inner edge of the eyewall and two big, swirling eddies in the low clouds at the base of the eye.

No mere photograph can do justice to the sensation of being inside the eye of a hurricane. Imagine a Roman coliseum 20 mi wide and 10 mi high, with a cascade of ice crystals falling along the coliseum's blinding white walls. The photo displayed in Figure 2.3, taken from a reconnaissance aircraft, gives some impression of the beauty of a hurricane's eye.

However impressive a hurricane's visual appearance, it is the instruments aboard satellites and aircraft that reveal the essence of a hurricane's structure and inner workings. In the early days of aircraft reconnaissance, the crew estimated wind speeds by looking down and noting how rough the sea appeared. Today, a sophisticated array of instruments automatically collects large quantities of high-quality data, which are taken back to laboratories and analyzed.

Among the most essential equipment is the meteorological radar, which works by transmitting pulses of electromagnetic radiation and measuring the radiation that is scattered back to the radar from raindrops, snowflakes, hailstones,

Figure 2.3: The eye of Hurricane Georges in photo taken from a reconnaissance aircraft. The eyewall at right is casting a shadow across part of the eyewall ahead.

►

and other forms of precipitation. By measuring the time it takes the radiation to return, one can calculate the distance to the scattering particles, and by measuring how much radiation returns (and correcting for distance), one can establish the concentration of scatterers. Big particles, like hailstones, are much more efficient scatterers than smaller particles, like raindrops; and the tiny droplets and ice crystals that comprise what we see as cloud are too small to scatter a detectable amount of radiation. Thus what we see on a radar display is a measure of the concentration of precipitation in the air, weighted toward the bigger raindrops and ice particles. The radar antenna sweeps around in a circle, all the while transmitting and receiving pulses of radiation, and can thus in a few seconds survey a circular area several hundred kilometers in diameter.

The image displayed in Figure 2.4 was made using a radar mounted on an aircraft flying in Hurricane Floyd. It shows the distribution of precipitation-size scatterers about 1 km (3,300 ft) above the surface. The heaviest rain is indicated by yellow and orange, with progressively lighter rain indicated by greens and blues. Floyd's eye is the circular blue region near the center of the image, and it is surrounded by the intense rain of the eyewall. In this case, the eyewall is not perfectly circular but consists of several arc-shaped regions of very heavy rain. Outside the eyewall is a region of reduced precipitation, known as the *moat;* this is surrounded by another ring of heavy rain that may constitute an *outer eyewall.* Part of this ring is composed of a spiral band that is wrapping inward from the south to the east of the storm center. There is also a prominent spiral band that starts north of the outer ring and extends eastward and then southward.

Figure 2.5 shows an east-west vertical slice through the storm made about the same time as the image in Figure 2.4. The figure spans a distance of 120 km (75 mi) centered at the storm center and extends upward to 20 km (12.5 mi) altitude. Note the pronounced eyewall of high

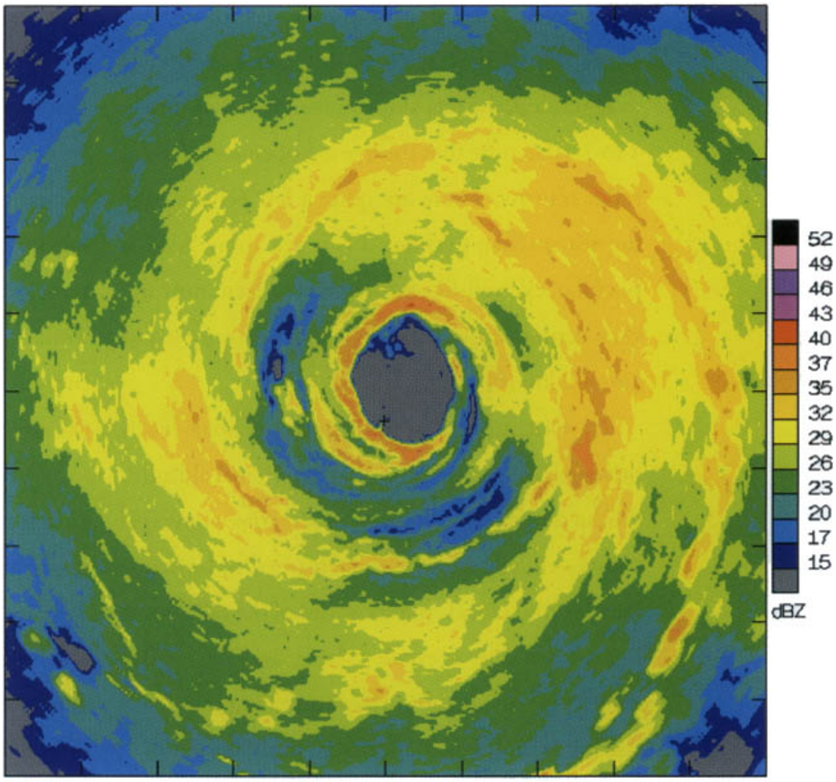


Figure 2.4: Radar reflectivity map from a hurricane reconnaissance aircraft flying in the eye of Hurricane Floyd of 1999. Map is 360 km (225 mi) square. The radar reflectivity measures roughly how much rain, snow, and hail are in the air.

▶

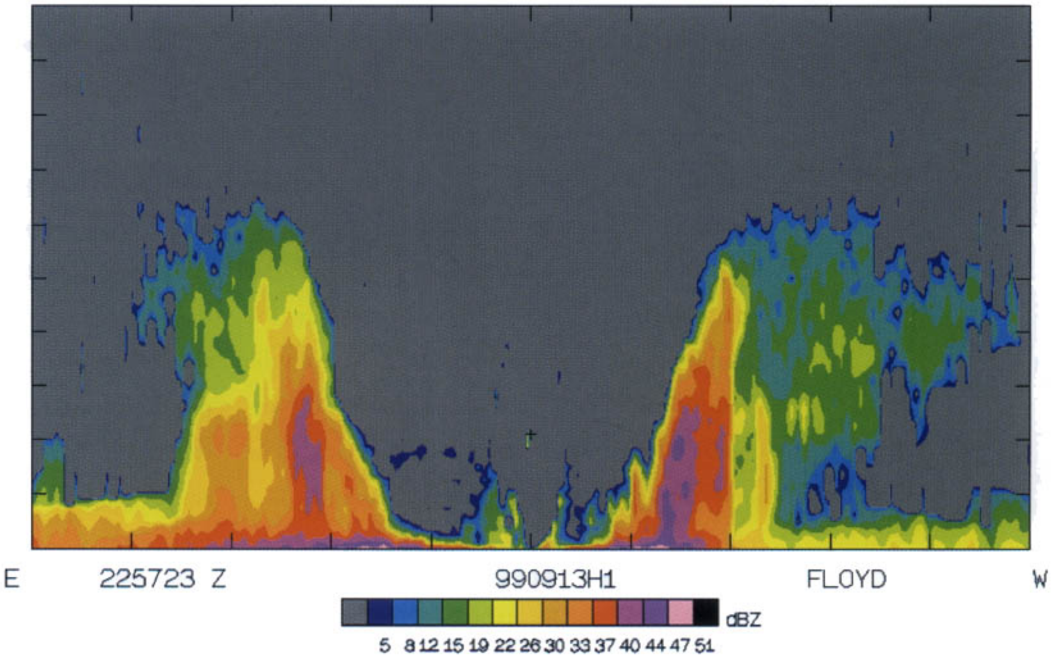


Figure 2.5: Vertical cross section of radar reflectivity in Hurricane Floyd of 1999, made from hurricane reconnaissance aircraft in the eye, located at the "+" sign. The diagram spans 20 km (12.5 mi) in height and is 120 km (75 mi) across.

▶

radar reflectivity, sloping outward with height. Since the vertical scale of this cross section is exaggerated, the real slope of the eyewall is nearly 1 to 1. Also note that the eye is not entirely free of radar returns. There are quite a few echoes near the sea surface; perhaps this is sea spray. Also, a peculiar, eyewall-like structure is present near the very center of the storm but extends only up to about 2 km (6,500 ft).

Outside the eyewall, radar echoes reach outward, centered at about 10 km (6 mi) altitude. These radar echoes represent *stratiform precipitation*—mostly snow and ice formed in horizontally layered clouds that flow out of the tall cumulonimbi of the eyewall. There are also radar returns very near the surface, revealing rain from shallower clouds and, perhaps, some sea spray.

In addition to carrying radar, aircraft are also used to directly measure meteorological quantities such as temperature, pressure, and humidity. Determining wind direction and speed requires a little more doing. Sensors on the aircraft measure its speed through the air, but to find the wind direction and speed with respect to the ground, one has to first determine the speed of the aircraft relative to the ground. Beginning in the late 1950s, this was done by pointing a radar at an angle to the ground. The radar measures the Doppler shift of the radiation reflected from the ground and thereby determines how fast the aircraft is moving with respect to the surface. (The same principle can be applied to sound. As a train goes by, the pitch of its whistle decreases; by measuring how much the pitch decreases, you can determine how fast the train is going.) The Doppler technique is not ideal: for one thing, it can be fooled by rain, sea spray, and ocean waves. Starting in the 1960s, aircraft motion was determined by a system of gyroscopes that very carefully keep track of all the accelerations experienced by the aircraft. By integrating these accelerations over time, one can find the aircraft's velocity over the ground, and by integrating these velocities in time, one can determine the aircraft's location. This system, called "inertial navigation," was used for some time to navigate aircraft. Today, the satellite-based Global Positioning System (GPS) is the method of choice for finding the aircraft's position and speed over the ground.

Figure 2.6 shows composite views of the structure of a hurricane revealed by direct measurements from research aircraft. These diagrams were made by fitting a satellite image of the top of one hurricane (Fran of 1999) to aircraft measurements of wind, temperature, and humidity from a different storm (Inez of 1966). The top panel shows the speed of the wind going counterclockwise around the center of the storm; the black dashed lines show the altitudes at which the aircraft were flying. (These lines are also displayed in the other two panels in this figure.) The darkest shade of blue indicates the lightest winds, less than 5 m/s (11 mph). Each successive color represents an increment of 5 m/s (11 mph), with the bright orange showing winds in excess of 65 m/s (145 mph). The strongest winds occur just above the ocean in a ring around the center, slightly outside the eyewall of the storm. Winds decrease rapidly inward toward the center, which is practically calm. They also decrease outward from the ring of maximum wind, but much more slowly, so that strong winds can still be found 100 km (60 mi) from the center of the storm. As we go up from the surface, the counterclockwise winds get lighter and lighter. If the highest aircraft had flown even higher, it would have actually encountered "negative" wind speed, which here means winds going the other way (clockwise) around

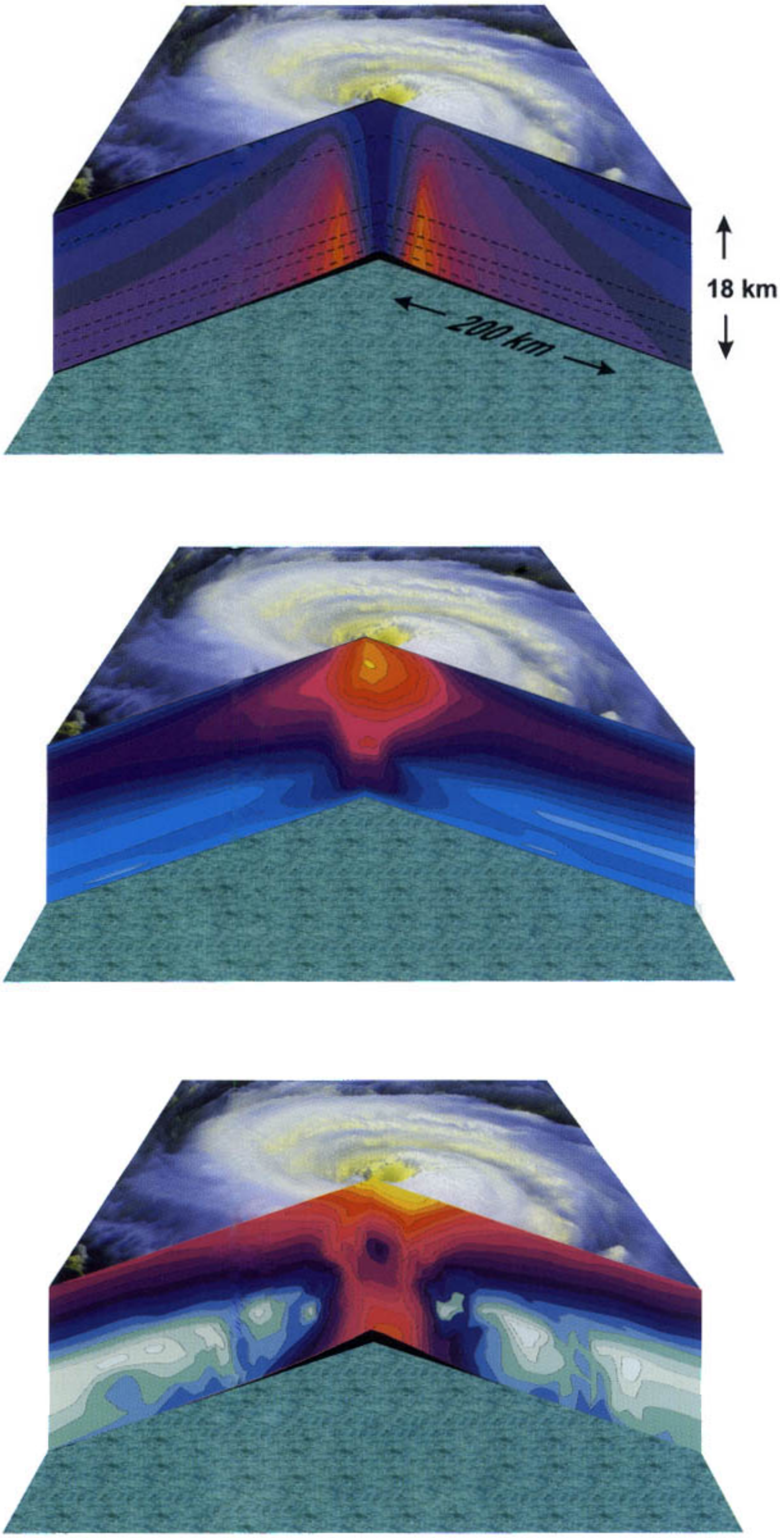


Figure 2.6: Composite views of the distribution of various quantities in a hurricane, as revealed by measurements made from research aircraft. In each panel, the center of the hurricane is in the center of the panel, and the cutaway extends outward about 200 km (125 mi) and upward to about 18 km (11 mi). Top panel: wind speed; middle panel: difference between temperature in the storm and temperature at the same altitude far away from the storm; bottom panel: entropy, a measure of the heat content of the air. ◀

the center. Near the top of the storm, the clockwise winds increase from the center, reaching maximum speeds several hundred kilometers from the eye. But whereas the actual winds are nearly circular in the lower part of the storm, the high-level clockwise flow is usually very irregular, being concentrated in a few outward-curving jets.

The middle panel shows the difference between the temperature at a given point and the temperature at the same altitude far away from the storm. The lightest shade of blue shows no temperature difference at all, while bright yellow shows air that is more than 16°C (29°F) warmer than its distant environment; each shade represents an increment of 1°C (1.8°F). Hurricanes are very hot at their centers, especially near their tops. This great warmth is one consequence of the enormous amount of heat sucked out of the ocean by the storm. On the other hand, there is very little change in temperature as you move in toward the eye along the surface of the ocean.

The distributions of temperature and wind in hurricanes are related to each other. Look carefully at the upper two panels of the figure. Notice that the rate at which the wind decreases upward is proportional to the rate at which the temperature decreases outward. This relationship is fundamental to rotating fluid flows and is called the *thermal wind relation.*

The lowest panel in the figure shows a quantity called entropy, which is a measure of how much heat has been added to the air. The smallest values of entropy are denoted by the light blue colors, while yellow represents the largest values. There are two main sources of entropy in a hurricane: heat transfer from the ocean to the atmosphere, which is accomplished mostly by evaporation, and frictional dissipation of wind energy. Heat transfer by evaporation is familiar to anyone who has ever stepped out of a swimming pool on a windy day. Even when the air is hot, you feel chilled by the wind. This is because the evaporation of water from your skin takes heat from your body. This heat does not disappear: it is added to the air in the form of *latent heat,* which is proportional to the amount of water vapor in the air. When this water vapor later condenses into cloud, the latent heat is released to the air, warming it in the process. Frictional heating is sometimes used to start campfires. When two sticks are rubbed vigorously together, some of the energy of the motion of the sticks is converted into heat energy. Similarly, the friction of air rubbing the ocean surface, or of quantities of air or water sliding past one another, converts some of the energy of motion into heat. Both the transfer of heat from the ocean and the frictional heating increase the entropy of air flowing inward toward the hurricane's eyewall in the lowest kilometer of the atmosphere. Then, as air enters the eyewall, it turns upward and slightly outward, spiraling upward through the eyewall and carrying with it the large entropy it acquired on its way into the eyewall. Near the top of the storm, the high-entropy air turns outward. Ultimately, the heat acquired from the ocean in a hurricane is exported to the distant environment, where it is finally lost by radiation to space.

Mathematical models provide another potential source of information about hurricanes. These models use computers to solve the differential equations that govern the evolution of the atmosphere. These equations are based on Newton's law applied to fluids, the first law of thermodynamics, and the conservation of water in its various phases. Unfortunately, computers are not yet powerful enough to accurately calculate certain physical processes in hurricanes, including turbulence, the formation and fall of rain, and the intricate interaction of radiation with clouds. These processes must be represented by approximations. Moreover, even today's computers can't keep track of every molecule of air and must work instead using fairly sizable chunks of air. In even the most advanced models, these chunks of air are many cubic kilometers in volume. The inaccuracies introduced by dividing up the air in this way, and by the approximations to the physics, render the models imperfect. In the end, one can only have confidence in the models to the extent that their results compare favorably to observations of hurricanes.

Yet models are good at filling in details that are difficult to observe. For example, while aircraft can make excellent measurements of the horizontal motion of air, measuring the air's vertical motion (updrafts and downdrafts) proves far more difficult. Updrafts and downdrafts tend to be widely separated, and an airplane may only sample a few on its way across a storm. The average vertical air motion calculated from such measurements is unlikely to correspond to the true

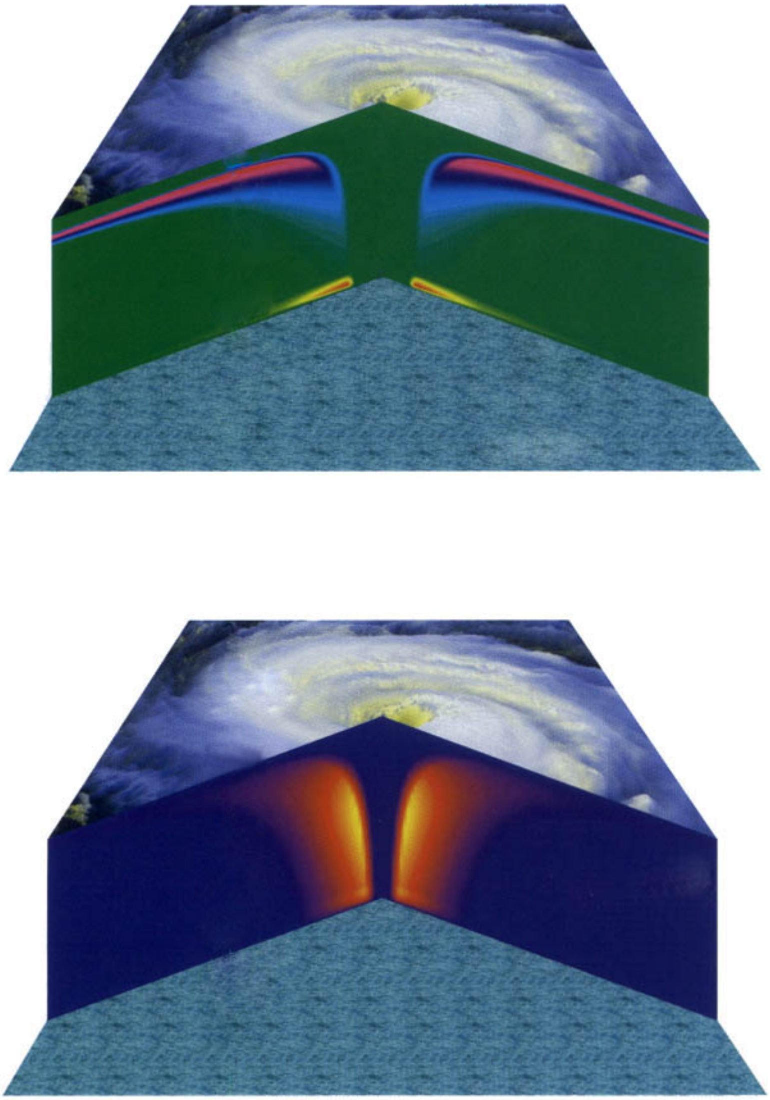


Figure 2.7: The same cross sections as in Figure 2.6, except showing quantities generated by a computer model. Top panel: radial air motion, with yellow and orange denoting inflow and blue and violet denoting outflow. Bottom panel: upward air motion. ◄

average. Here the computer model has the advantage that it can make exact "measurements" of vertical motion. So we have to choose between imperfect measurements of the real thing and perfect measurements of the fiction generated by a mathematical model.[1] The best we can do is to draw conclusions from a judicious blend of the two.

Figure 2.7 shows composite views of the vertical and radial (in-out) air motion in a hurricane, similar to Figure 2.6 but now showing the results of calculations using a mathematical model. It shows inward flow next to the sea surface (yellow and orange), strong upward motion in the eyewall, and outflow in a thin layer near the top of the storm (blue and violet). Although it is too weak to be seen in this figure, there is downward motion in the eye itself, strongest right next to the eyewall, and also in a broad region outside the eyewall. But since this figure is made by averaging the air motion along circles centered at the storm center, the strong updrafts associated with spiral rain bands are missed.

The nature of the airflow and the distribution of clouds in a typical hurricane are summarized in Figure 2.8. Air spirals in toward the eyewall in the lowest kilometer or so, counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. The spiral becomes tighter and tighter near the eyewall, as the wind speed increases to hurricane force. Some of the inward-spiraling air is drawn into the strong updrafts associated with spiral rain bands outside the core of the storm, but most of it converges into the eyewall, where it turns abruptly upward and ascends in a broadening spiral to the top of the storm. There the airflow turns progressively outward, and after spiraling out a few hundred kilometers, its rotation

[1] Or, as one wit put it, we must choose between observing the unpredictable and predicting the unobservable.

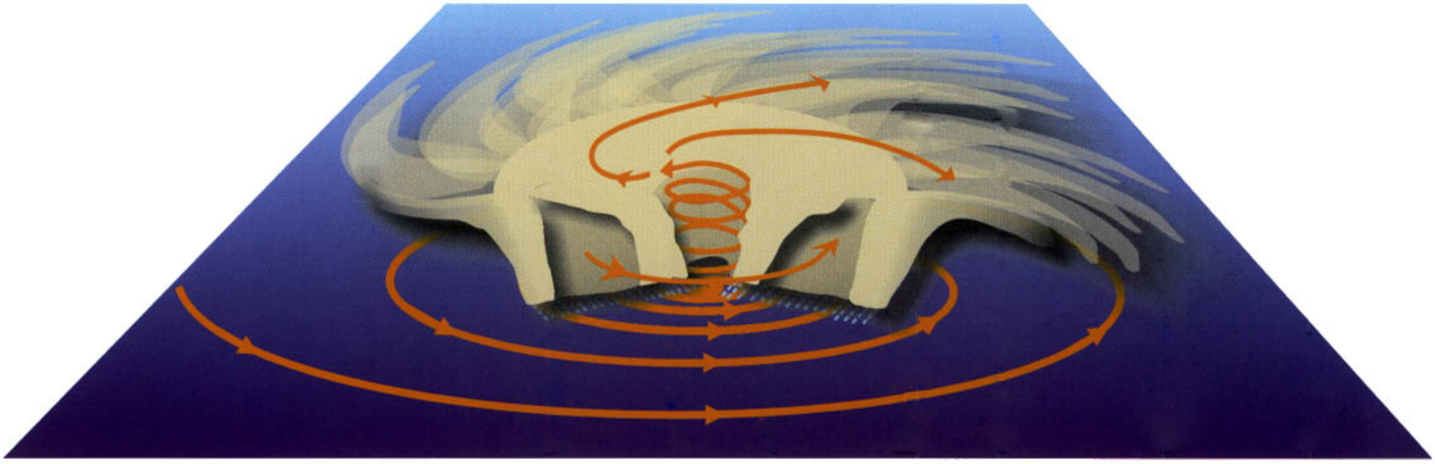
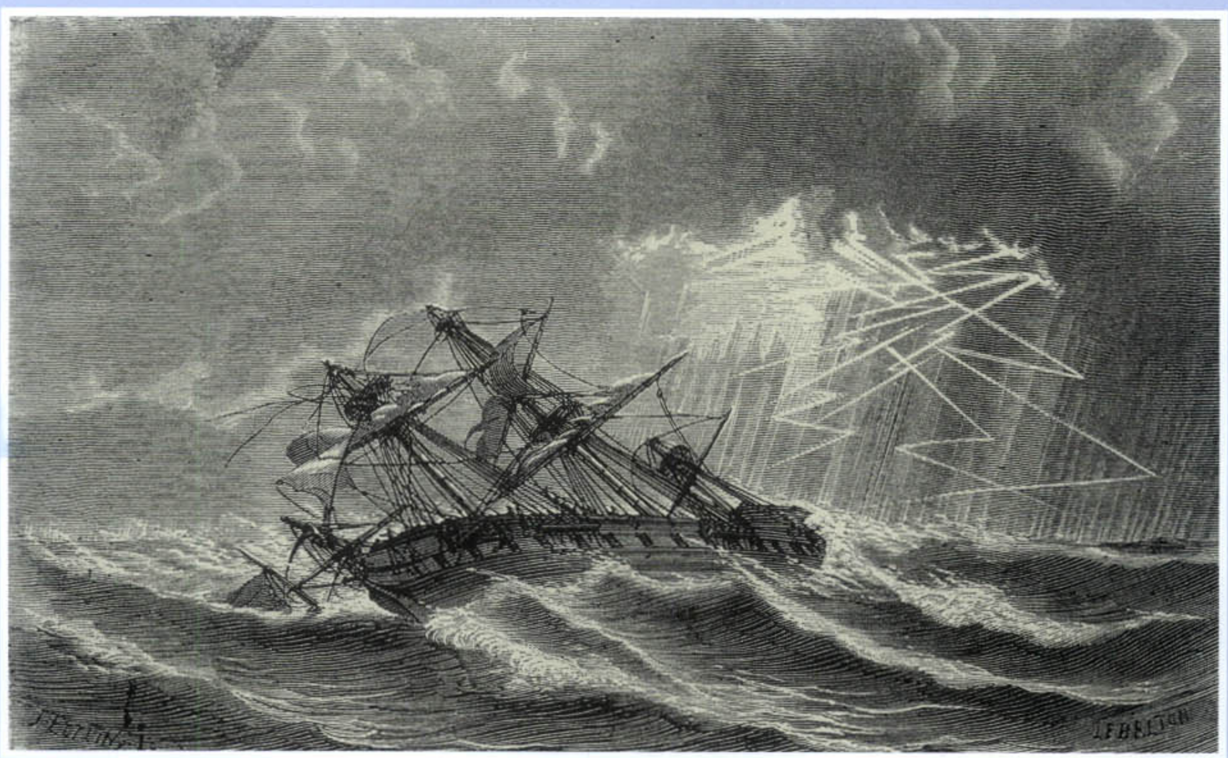


Figure 2.8: Synopsis of the airflow and cloud distribution in a mature Northern Hemisphere hurricane.

▲

reverses, turning clockwise in the Northern Hemisphere. But unlike the spiraling inflow, air coming out of the top of a hurricane seldom retains much circular symmetry. Instead, it tends to concentrate in one or more "outflow jets" that carry away the exhaust of this massive heat engine. The entire system moves as one body across the surface of the ocean, and the speed of its movement is added to winds on one side of the storm, and subtracted from them on the other side.

The hurricane, once fully developed, is among the most coherent and persistent structures that inhabit the otherwise chaotic atmosphere of our planet. However terrible its effects, one cannot help but admire the intricate beauty of its architecture.



▲ The sailing vessel *Ouragan* in a hurricane. Engraving from *Les Meteores,* Paris, 1869.

I have seen tempests, when the scolding winds
Have riv'd the knotty oaks; and I have seen
The ambitious ocean swell and rage and foam,
To be exalted with the threat'ning clouds:
But never till to-night, never till now,
Did I go through a tempest dropping fire.
Either there is a civil strife in heaven,
Or else the world, too saucy with the gods,
Incenses them to send destruction.

—William Shakespeare (1564–1616),
from *Julius Caesar,* Act I, Scene iii

3 Huracán

Hurricane: *A name given primarily to the violent wind-storms of the West Indies, which are cyclones of diameter of from 50 to 1000 miles, wherein the air moves with a velocity of from 80 to 130 miles an hour round a central calm space, which with the whole system advances in a straight or curved track; hence, any storm or tempest in which the wind blows with terrific violence.*

—Oxford English Dictionary

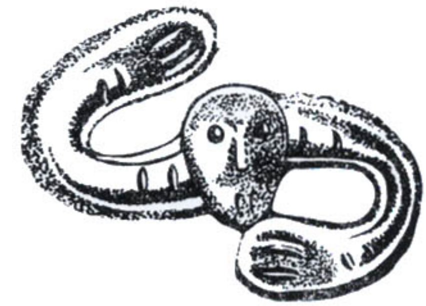
Hurricane: *(Many regional names.) A tropical cyclone with 1-min average surface (10 m) winds in excess of 32 m* s^{-1} *(64 knots) in the Western Hemisphere (North Atlantic Ocean, Caribbean Sea, Gulf of Mexico, and in the eastern and central North Pacific east of the date line). The name is derived from "huracán," a Taino and Carib god, or "hunraken," the Mayan storm god.*

—American Meteorological Society Glossary of Meteorology

The word *hurricane* comes to us via the early Spanish explorers of the New World, who were told of an evil god of winds and destruction, variously called Huracán, Hunraken, or Jurakan in the Caribbean and Mexico. In the legends of the Mayan civilizations of Central America and the Tainos of the Caribbean, this god played an important role in their Creation. According to Taino legend, the goddess Atabei first created the earth, the sky, and all the celestial bodies. To continue her work, she bore two sons, Yucaju and Guacar. Yucaju created the sun and moon to give light, and then made plants and animals to populate the earth. Seeing the beautiful fruits of Yucaju's work, Guacar became jealous and began to tear up the earth with a powerful wind, renaming himself Jurakan, the god of destruction. Yucaju then created Locuo, a being intermediate between a god and a man, to live in peaceful harmony with the world. Locuo, in turn, created the first man and woman, Guaguyona and Yaya. All three continued to suffer the powerful winds and floods inflicted by the evil Jurakan.

The natives of the Caribbean were clearly terrified of Jurakan, and would shout, beat drums, and engage in bizarre rituals in attempts to drive the god away. The early inhabitants of Cuba carved images in stone of the god they called Huracán; two such images are reproduced in Figures 3.1 and 3.3.

The various likenesses of Huracán invariably consist of a head of indeterminate gender with no torso, and two distinctive arms spiraling out from its sides. Most of these images exhibit cyclonic (counterclockwise) spirals. The Cuban ethnologist Fernando Ortiz believes that they were inspired by the tropical hurricanes that have always plagued the Caribbean. If so, the Tainos discovered the vortical nature of hurricanes many hundreds of years before the descendents of European settlers did. How they may have made this deduction remains mysterious. The spiral rain bands so well known to us from satellite pictures were not "discovered" until meteorological radar was developed during



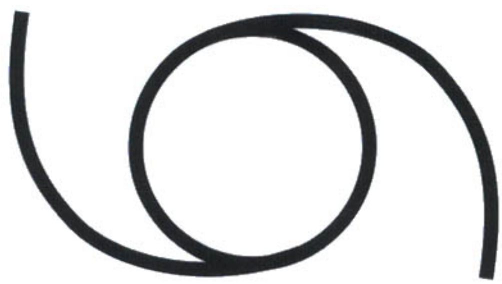


Figure 3.1: Likeness of the god Huracán, from a Cuban ceramic vase.

Figure 3.2: Universal symbol of the tropical cyclone. In the Southern Hemisphere, the arms are curved in the opposite sense.

World War II, and they are far too big to be discerned by eye from the ground. Perhaps these ancient people surveyed the damage done by Huracán and, based on the direction trees fell, concluded that the damage could only have been done by a rotating wind, as did William Redfield in 1831. Or perhaps they witnessed tornadoes or waterspouts, which are much smaller phenomena whose rotation is readily apparent, and came to believe that all destructive winds are rotary.

Whatever its source, the image of Huracán remains an enigmatic premonition of what would be seen in radar and satellite imagery many hundreds of years later, and what would form the basis of the internationally recognized symbol of a tropical cyclone, shown in Figure 3.2.

The word *huracán* evolved through several variations (Shakespeare's King Lear cries, "Blow, winds, and crack your cheeks! rage! blow! You cataracts and hurricanoes, spout Till you have drench'd our steeples, drown'd the cocks!"). Today *hurricane* has a very specific meaning. It is one of many regional names given to an intense form of a general phenomenon known as a *tropical cyclone,* a low-pressure area that forms over tropical oceans and is associated with cyclonically rotating winds through most of the atmosphere. (Cyclonic rotation is counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere.) The table on page 21 shows a more precise definition of the term, together with subclassifications and regional names.

For a tropical cyclone to technically qualify as a hurricane, it must have winds of at least 33 m/s (74 mph) and occur over the Atlantic, eastern North Pacific, or eastern South Pacific ocean. But in this book, I shall sacrifice technical accuracy for the sake of brevity by using the popular term *hurricane* rather than *tropical cyclone* to denote the generic phenomenon, though where the distinction is crucial, I shall resort to the latter.

The word *cyclone* itself was coined in 1848 by the Englishman Henry Piddington, then curator of the Calcutta Museum in India and later president of the Marine Courts of Inquiry. Piddington, who was keenly interested in storms affecting India, derived the term from a Greek word meaning "coil of a snake."

The precise origin of the word *typhoon* is, however, controversial. It very likely originated from the Chinese *jufeng*. *Ju* can mean either "a wind coming from four directions" or "scary"; *feng* is the generic word for wind. Arguably the first scientific description of a tropical cyclone and the first appearance of the word *jufeng* in the literature is contained in a Chinese book entitled *Nan Yue Zhi* (Book of the Southern Yue Region), written around A.D. 470. In that book, it is stated that "Many