Think recent hurricanes were bad? Monster storms could become routine. Knowing when and where they will strike is a matter of life and death.

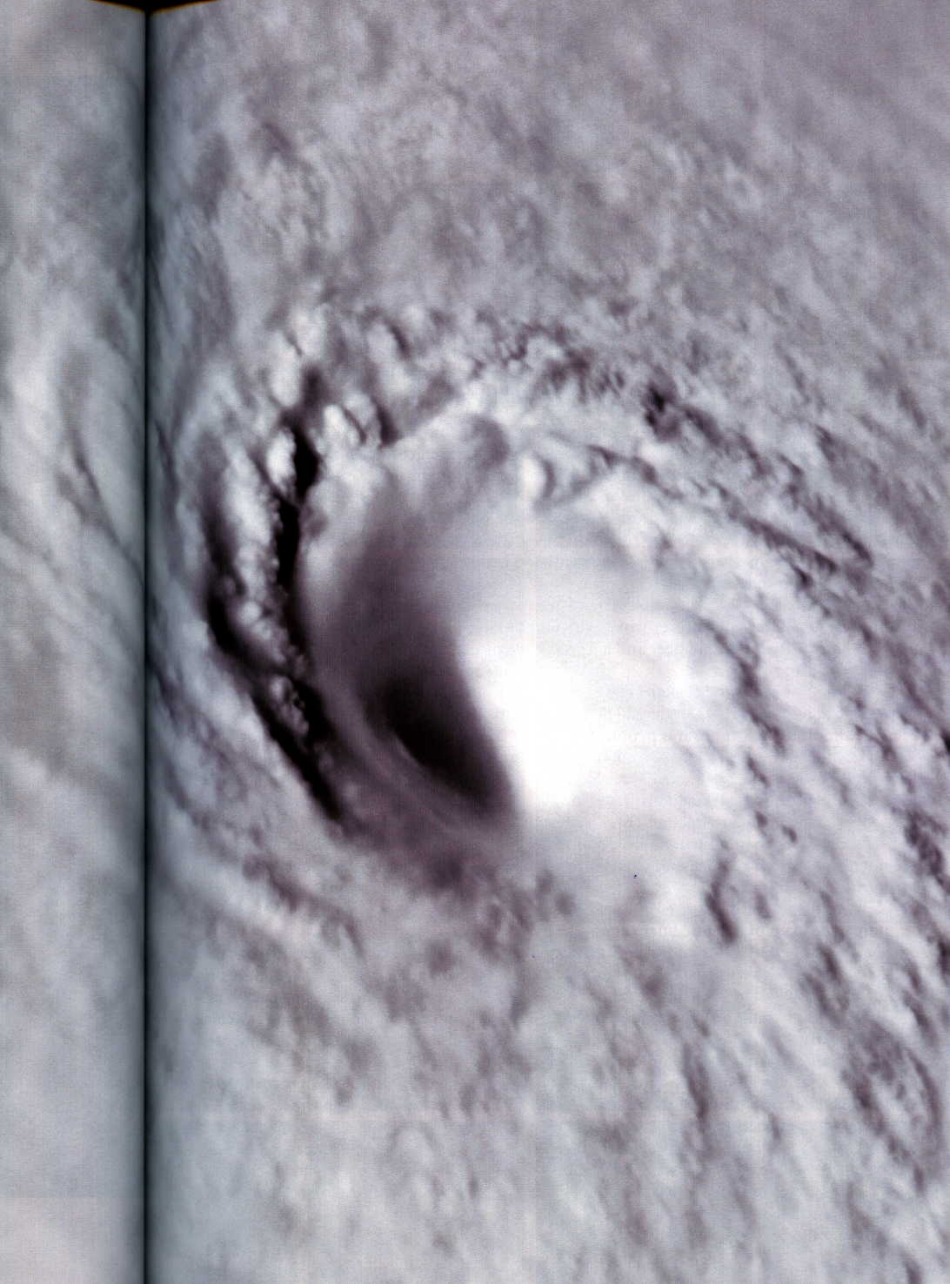
Super Storms

No end in sight

New Low

As Hurricane Wilma spun toward the Yucatán Peninsula on October 19, 2005 (the day this image was shot from the International Space Station), a hurricane hunter plane recorded an atmospheric pressure of 882 millibars in the eye of the storm. This record low drove winds of 185 mph and cemented Wilma's status as the most powerful Atlantic hurricane on record.

NASA



by Thomas Hayden

When the fiercest hurricane ever recorded in the Atlantic is bearing down on you, a salvaged armchair under a wood-and-tin awning might seem a poor choice of shelter. But that's where Don E. ("I'd rather keep my last name out of it") was parked when Wilma hit South Florida at 6:30 a.m. last October 24. For Don and a buddy, it was the start of the workday at Jimbo's Place, a ramshackle beer and bait shop down by the water on Miami's Virginia Key. "Once we got out here, it was kind of too late to do anything but ride it out," Don says with a small laugh.

Jimbo's looks like nothing so much as an abandoned shack. But whether through good luck or unexpectedly sound construction, it survived Wilma's fury. Mercifully, the winds had ebbed from 185 miles per hour at sea to 120 miles per hour by the time the storm hit, but Wilma still left almost all of South Florida without power. For the next two weeks a generator and donated bags of ice kept Jimbo's open—the only establishment on the key where visitors could be assured of a cold beer and a friendly welcome.

Wilma was a record breaker in a season of unsettling records. Katrina, at the end of August, killed more than a thousand people and left much of New Orleans and the neighboring coast in ruins. The damage exceeded a hundred billion dollars—the costliest natural disaster in U.S. history—and the toll in fractured lives is incalculable. Rita, in September, rivaled Wilma in intensity and ravaged the Gulf Coast through western Louisiana and East Texas.

These three monster storms were part of an unmatched run of Atlantic hurricanes—15 in all. With a total of 27 named tropical storms, 2005 was the first year meteorologists exhausted their preseason list of 21 Atlantic cyclone names and had to dip into the Greek alphabet for the latecomers.

Days after Wilma, one visitor to Jimbo's was already worrying about what future hurricane seasons might bring. Sharan Majumdar, 34, is a hurricane researcher at the University of Miami's Rosenstiel School of Marine and Atmospheric Science, just across the highway from Jimbo's. He is one of a cadre of scientists trying to understand nature's most powerful storms and more reliably predict their surges, ebbs, and lurching paths from birth to landfall.

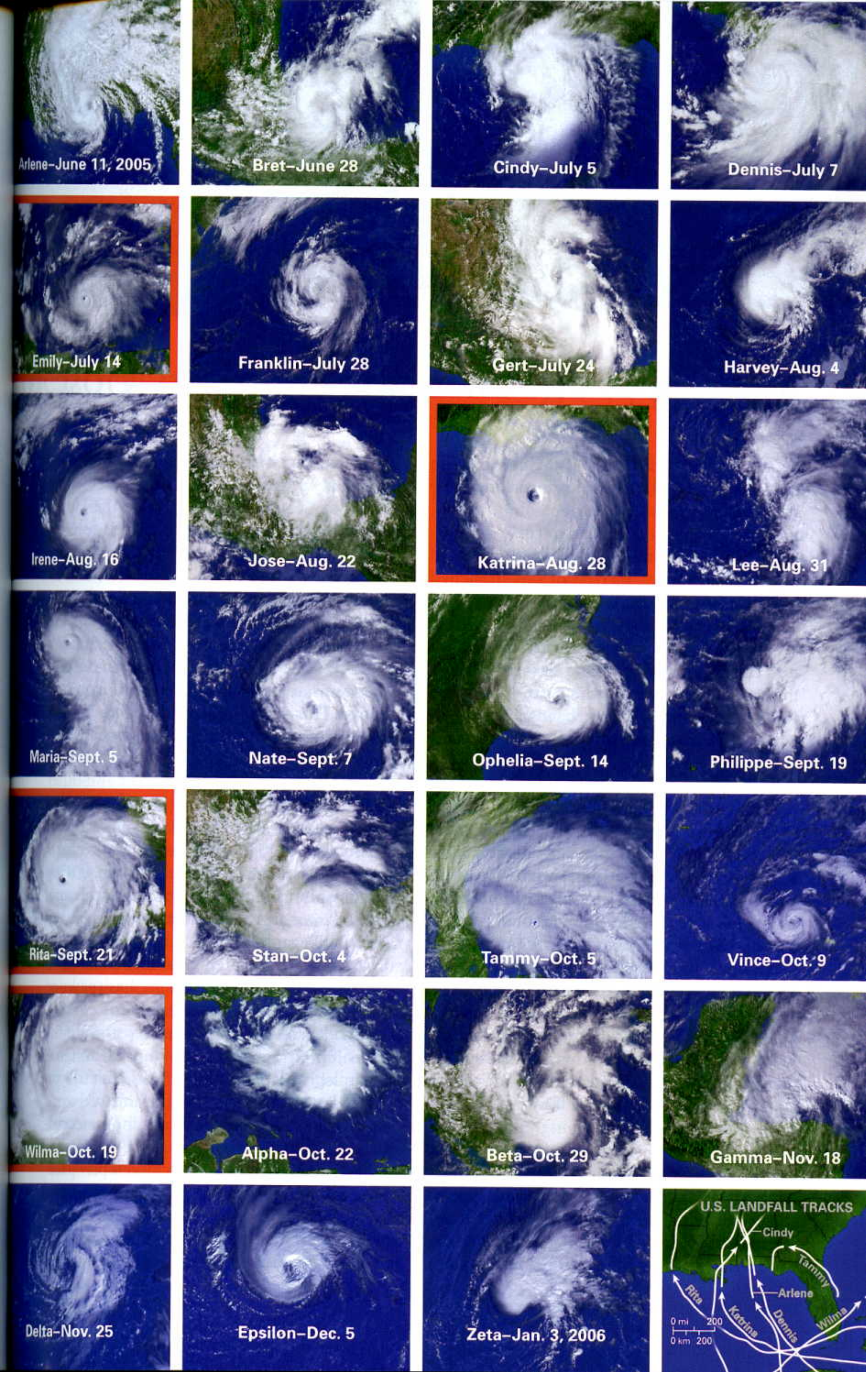
Swatting at sand flies on a warm November night, Majumdar says he can't really blame his fellow patrons at Jimbo's for deciding to stay put during Wilma. Forecasts today can get hurricane tracks wrong by hundreds of miles and wind speeds by tens of miles per hour. As a result, Majumdar says, "people often return after an evacuation to find nothing really happened." The solution, he says, is to improve forecasting through better science. "That's the only way to get people to trust the warnings."

The stakes have never been higher. Population is burgeoning along vulnerable coasts in the U.S., Asia, and the Caribbean. In the southeastern U.S., for example, coastal populations grew more than 50 percent from 1980 to 2003. The North Atlantic hurricane nursery, responding to a natural climate cycle, is experiencing a baby boom that isn't expected to end for a

2005: Year of the Hurricane

It was a season for superlatives. Never before had a hurricane caused as much economic damage as Katrina. Never before had the Atlantic seen 27 named tropical storms—so many that the list of storm names had to be extended with Greek letters. Seven made landfall in the U.S. (lower right). Never had 15 hurricanes been spotted in one season, including four Category 5 storms (colored borders).

AREA IN IMAGES IS 740 MI WIDE. IMAGES: TIM LOOMIS, NOAA ENVIRONMENTAL VISUALIZATION PROGRAM. NGM MAPS


Arlene–June 11, 2005
Bret–June 28
Cindy–July 5
Dennis–July 7
Emily–July 14
Franklin–July 28
Gert–July 24
Harvey–Aug. 4
Irene–Aug. 16
Jose–Aug. 22
Katrina–Aug. 28
Lee–Aug. 31
Maria–Sept. 5
Nate–Sept. 7
Ophelia–Sept. 14
Philippe–Sept. 19
Rita–Sept. 21
Stan–Oct. 4
Tammy–Oct. 5
Vince–Oct. 9
Wilma–Oct. 19
Alpha–Oct. 22
Beta–Oct. 29
Gamma–Nov. 18
Delta–Nov. 25
Epsilon–Dec. 5
Zeta–Jan. 3, 2006
U.S. LANDFALL TRACKS
Cindy
Tammy
Arlene
Rita
Katrina
Dennis
Wilma
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"Mississippi and Alabama are pretty close t i

decade or more. And behind it all lurks the grim possibility that global warming is making these storms stronger.

Like all weather, hurricanes are fueled by heat—the heat of sun-drenched tropical seas, which powers the storms by sending warm, moist air rushing toward the frigid upper atmosphere like smoke up a chimney. As surrounding air is sucked in at the base of the storm, Earth's rotation gives it a twist, creating a whorl of rain bands. These whip-tails of thunderstorm activity are strongest where they converge in a ring of rising, spinning air, the eyewall, which encloses the cloud-free eye.

Hurricanes (called typhoons in the western Pacific and tropical cyclones in the Indian Ocean) can propel themselves to an altitude of 50,000 feet or more, where the rising air finally vents itself in spiraling exhaust jets of cirrus clouds. The largest ever, the 1979 Pacific typhoon Tip, sent gale-force winds across more than 650 miles. Even an average hurricane packs some 1.5 trillion watts of power in its winds—equivalent to about half the world's entire electrical generating capacity.

Starting this great weather engine requires surface waters of 80 degrees or more, moist air, and little wind shear—a difference in wind speed at the surface and aloft that can tear apart a developing hurricane. But those ingredients often produce nothing more than a tropical disturbance—an unremarkable cluster of thunderstorms. "Disturbances look very similar day to day," says David Nolan of the Rosenstiel School, "and then all of a sudden you get a big burst of convection, then within six hours it becomes a depression, then it becomes a hurricane, then it's flooding my apartment." Katrina soaked Nolan's 14th-floor Miami Beach home as the storm crossed Florida on its fateful course to New Orleans and the Gulf Coast. "It would be really nice to say what you need to make a hurricane," he adds. "And we really can't do that yet."

One thing was clear in 2005: Conditions were ideal for making hurricanes. From June through November—the official Atlantic hurricane season—bulletins and warnings streamed from the National Hurricane Center in Miami. But the most telling moment of the season came on November 29, one day before its official end, when NHC director Max Mayfield and other officials gave a summary report. Even as the officials recited a sobering roll call of power and destruction, the NHC duty forecaster was charting tropical storm Epsilon, just then getting ready to spin itself into yet another hurricane.

Yet 2005 was just a continuation of the upward trend that began in 1995. Because of a tropical climate shift that brought warmer waters and reduced wind shear, the Atlantic has spawned unusual numbers of hurricanes for nine of the past eleven seasons. "We're 11 years into the cycle of high activity and landfall," NOAA meteorologist Gerry Bell says, "but I can't tell you if it will last another ten years, or thirty."

Weather satellites make it easy for meteorologists to keep tabs on hurricanes. But ordinary satellite images show only the cloud tops. Spaceborne infrared sensors can reveal more detail, charting the size and shape of the warm eye, and satellite radar and microwave sensors can map the rain. Hurricane hunter aircraft actually fly

to ideal for maximum storm surge."

—RICK LUETTICH, UNIVERSITY OF NORTH CAROLINA AT CHAPEL HILL

right into Atlantic hurricanes. But they only probe conditions at altitudes of several thousand feet, above the worst turbulence, Jack Beven of the NHC says—"not at the surface, where they really matter to people."

Last year, though, scientists flew a robotic aircraft straight into the maelstrom when tropical storm Ophelia was parked off the mid-Atlantic coast. The craft, called Aerosonde, swooped and circled for ten hours, as low as 1,200 feet, monitoring winds and the flow of heat and moisture from the ocean into the storm.

That foray was a test, but forecasters routinely probe the heart of storms with shorter lived devices called dropsondes. Released from high-flying aircraft into hurricanes and the surrounding winds, these instrument-packed tubes descend by parachute. "They take about 15 minutes from 40,000 feet to splash," Majumdar says. Along the way, they measure temperature, pressure, humidity, and wind every half second, transmitting it all to the airplane before they hit the water.

By cranking dropsonde data into computer models that can simulate a storm and how it is likely to evolve, researchers have sharpened their forecasts of storm tracks. Three-day forecasts of Atlantic storm positions were off by an average of 440 miles in the 1970s; by 2005 the average error had dropped to 173 miles. But one-day forecasts were still wide of the mark by an average of 70 miles—more than enough to keep coastal dwellers second-guessing the experts. The data and models still can't capture storms in enough detail to forecast all of their feints and swerves.

Storm intensity is proving even harder to forecast. Three-day wind-speed forecasts, off by an average of 23 miles per hour in the early 1990s, had improved only marginally by 2005. Hurricanes regularly surprise observers with their mood shifts. In a matter of hours, a Category 5 storm (winds over 155 mph) can fade to a Category 3 (111-130 mph), or a mere tropical storm can explode into a killer. "Intensity changes are the things that really hurt people," says NOAA's Bell.

The state of the ocean below a storm explains some intensity shifts. In 1995, tropical storm Opal was inching toward Category 1 status—an entry-level hurricane—as it made its way through the western Gulf of Mexico. Then, in just 14 hours, it surged to Category 4. Satellite readings of the warm sea surface showed nothing unusual. But Nick Shay of the Rosenstiel School and his colleagues discovered that the warm layer wasn't limited to the top few yards of the ocean, as it usually is in the Gulf. Cold water at greater depths acts as a brake on hurricane

A Devastated Shore

Twenty-five feet of water smashed into coastal Mississippi the morning Katrina hit, splintering buildings and killing hundreds of people. In Harrison County (western portion shown above) the water dumped ten-foot piles of debris hundreds of yards inland (red line)—enough, USGS coastal experts estimate, to fill 375,000 city garbage trucks. Scientists warn of the dangers of rebuilding within the debris zone, ground zero for surge in future hurricanes.

MOSAIC AND DEBRIS LINE: MARK HANSEN, USGS; AERIAL IMAGES: NOAA

Looking Inside a Hurricane

To understand how hurricanes work, and improve forecasts, researchers need detailed information from the heart of the storms. During the 2005 hurricane season, the most active on record, scientists investigated hurricanes from top to bottom (this one shown in cross section) with satellites, airplanes, and new kinds of instrumented probes.

A In space

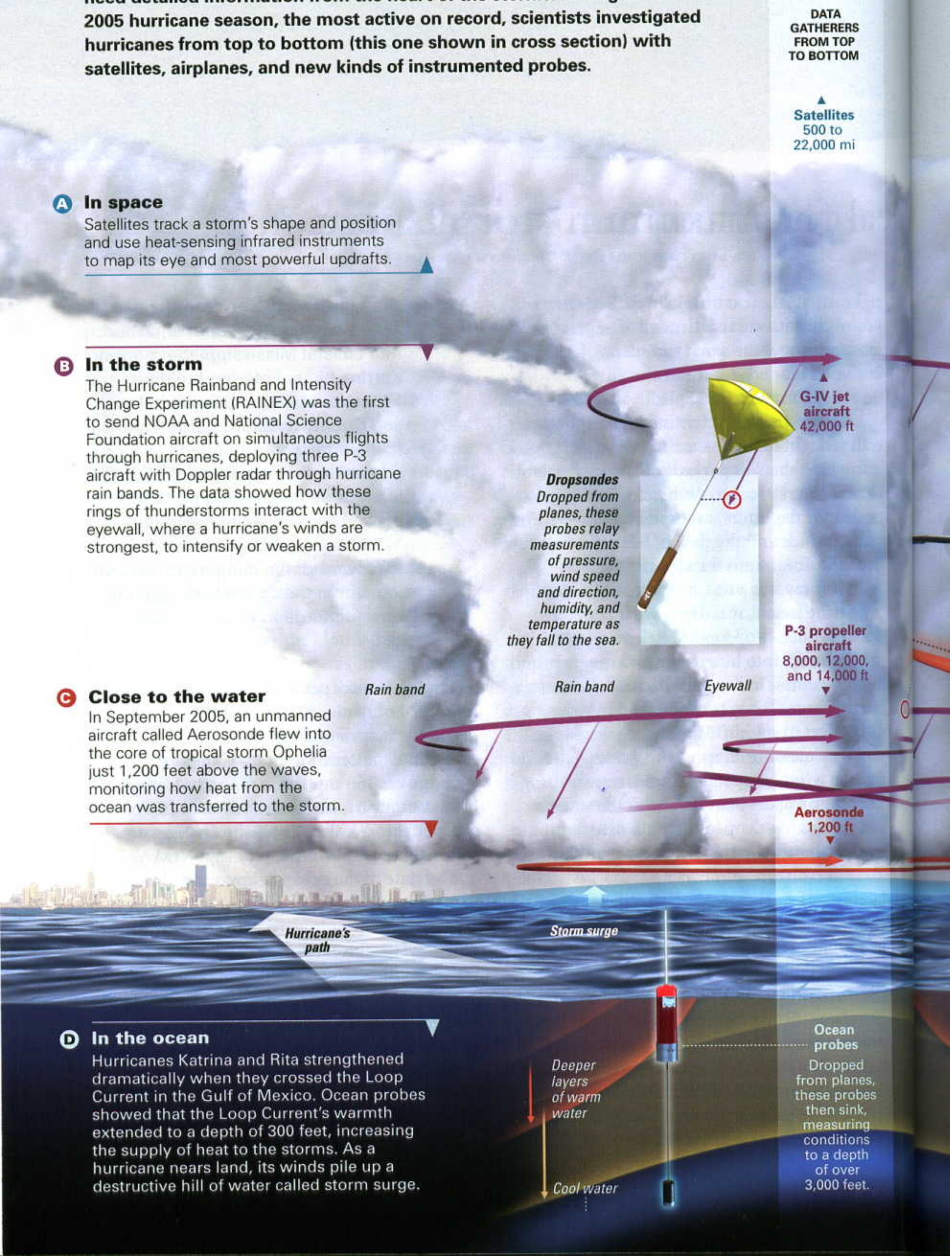
Satellites track a storm's shape and position and use heat-sensing infrared instruments to map its eye and most powerful updrafts.

B In the storm

The Hurricane Rainband and Intensity Change Experiment (RAINEX) was the first to send NOAA and National Science Foundation aircraft on simultaneous flights through hurricanes, deploying three P-3 aircraft with Doppler radar through hurricane rain bands. The data showed how these rings of thunderstorms interact with the eyewall, where a hurricane's winds are strongest, to intensify or weaken a storm.

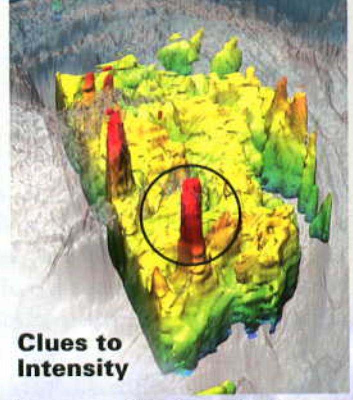
C Close to the water

In September 2005, an unmanned aircraft called Aerosonde flew into the core of tropical storm Ophelia just 1,200 feet above the waves, monitoring how heat from the ocean was transferred to the storm.



D In the ocean

Hurricanes Katrina and Rita strengthened dramatically when they crossed the Loop Current in the Gulf of Mexico. Ocean probes showed that the Loop Current's warmth extended to a depth of 300 feet, increasing the supply of heat to the storms. As a hurricane nears land, its winds pile up a destructive hill of water called storm surge.



Clues to Intensity

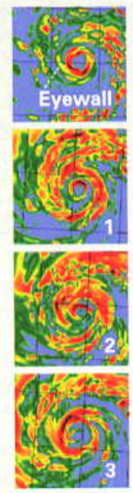
A An image of Hurricane Rita based on infared data from NASA's Tropical Rainfall Measuring Mission (TRMM) satellite reveals a pair of chimney clouds, called hot towers, reaching more than 11 miles high. First observed in 1998, hot towers may indicate that the storm is about to intensify.

G-IV jet
Soon to be equipped with Doppler radar, NOAA's jet flies over and around developing hurricanes.

P-3 hurricane hunters
Two of NOAA's planes were aided by the National Science Foundation's P-3, which carried a Doppler radar with four times more resolution than the standard radar.

Aerosonde
Small enough to be launched from the back of a pickup truck, the 28-pound plane flew in winds that topped 78 mph, relaying data every half second.

B In Hurricane Rita the RAINEX experiment documented a phenomenon called eyewall replacement, in which a second eyewall **(1)** forms around the eye. The inner eyewall collapses **(2)** and temporarily weakens the storm. The outer eyewall then contracts and takes its place **(3)**, strengthening the storm again.



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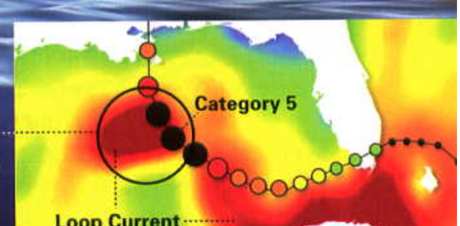


An image of the Loop Current three days before Katrina's landfall shows how the storm intensified as it traveled over warmer waters (red).

SOURCES: PETER BLACK AND JOSEPH CIONE, NOAA ATLANTIC OCEANOGRAPHIC AND METEOROLOGICAL LABORATORY; SHUYI CHEN AND NICK SHAY, ROSENSTIEL SCHOOL OF MARINE AND ATMOSPHERIC SCIENCE

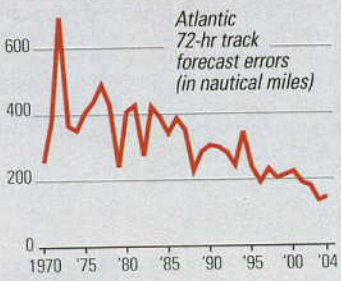
IMAGES: NASA GODDARD SPACE FLIGHT CENTER SCIENTIFIC VISUALIZATION STUDIO (TOP); ROSENSTIEL SCHOOL OF MARINE AND ATMOSPHERIC SCIENCE (MIDDLE AND BOTTOM)

REPORTING BY BRENNA MALONEY; DESIGNED BY JUAN VELASCO; ILLUSTRATIONS BY ROBERT KINKAID AND RAYMOND WONG

Improving Forecasts

Better forecasts of hurricane tracks and intensity could reduce deaths and property damage by enabling officials to issue more timely and accurate warnings and evacuation orders. Total damages in the U.S. for the 2005 Atlantic season alone came to more than one hundred billion dollars, with the loss of at least 1,000 lives.

While track forecasts have improved substantially...



intensity forecasts have not...

in a time when severe hurricanes are more frequent in the Atlantic.

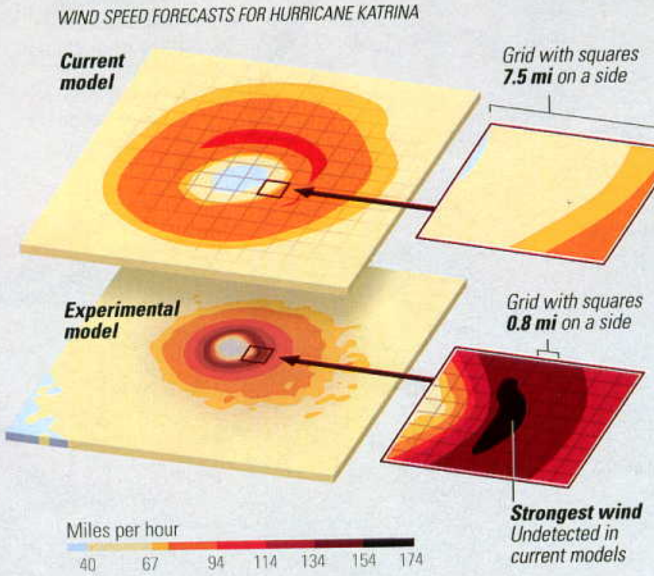
Building Better Models

Computer forecasting models break storms into a grid and use sophisticated methods to calculate the changes in wind speed, humidity, temperature, and clouds. Current NOAA models are too coarse to zero in on the features that determine where the greatest damage might occur. In 2007, the new high-resolution NOAA Hurricane Weather Research and Forecasting (HWRF) model will become operational.

A clearer picture

Below are forecasts of wind speed for Hurricane Katrina for the morning of August 28, 2005, when it intensified to Category 5. The current model runs at a 7.5-mile resolution; HWRF will run at a 5.6-mile resolution. Researchers are experimenting with even higher resolution models (bottom). The finer grid captures critical features that the older models overlook.

WIND SPEED FORECASTS FOR HURRICANE KATRINA



A fuller picture

Accurate forecasts of a storm's track and intensity require the best possible picture of the ocean and atmosphere. Unlike current models, HWRF will rely on real-time wave, ocean, and coastal data to improve forecasts.

SOURCES: GREG HOLLAND, NATIONAL CENTER FOR ATMOSPHERIC RESEARCH; NAOMI SURGI, NOAA ENVIRONMENTAL MODELING CENTER; JAMES FRANKLIN, NOAA TROPICAL PREDICTION CENTER; PETER WEBSTER, GEORGIA INSTITUTE OF TECHNOLOGY; SHUYI CHEN, ROSENSTIEL SCHOOL OF MARINE AND ATMOSPHERIC SCIENCE

Better science is the only way to get people to trust the warnings.

—SHARAN MAJUMDAR, ROSENSTIEL SCHOOL OF MARINE AND ATMOSPHERIC SCIENCE

intensity when the winds churn it to the surface. But Opal had strayed across a pool of warm water extending hundreds of feet down. No matter how hard the wind blew, it stirred up more hurricane fuel, causing the storm to intensify.

The tropical ocean is littered with these deep warm pockets, and their importance was underscored last year by both Katrina and Rita, which shot up to Category 5 when they passed over a deep band of warm Gulf water called the Loop Current. Satellites can detect subsurface warmth by looking for subtle bulges in the sea surface, Shay says. "It's not really rocket science, but here's something that works and improves intensity forecasts by 5 to 15 percent."

Waves, on the other hand, can blunt a storm. Whipped up by a hurricane, they can reach heights of more than a hundred feet, exerting a drag on the winds that created them. "Heat adds fuel, but waves slow the winds down—they're fighting each other," says Shuyi Chen of the Rosenstiel School, who is collaborating on a powerful new computer model, called the Hurricane Weather and Research Forecasting model, that will simulate the fine details of the interplay between atmosphere, waves, and ocean. "You can get a forecast one to two categories wrong if you don't get the waves right."

Forecasters also need to understand a hurricane's internal workings. Katrina, for example, had grown into a certifiable monster by the morning of Sunday, August 28. Sucking energy from the Loop Current, the storm had screamed from the low end of Category 3 to a peak of 175 miles per hour, well into Category 5, in just 12 hours. As Katrina barreled toward land, the NHC issued an apocalyptic warning: "POTENTIALLY CATASTROPHIC HURRICANE KATRINA MENACING THE NORTHERN GULF COAST."

And then, swiftly and remarkably, the storm took a breather. In satellite images late Sunday, hours before landfall, a huge bite appeared in the southern side of the eyewall. Scientists probing the storm with aircraft and radar in a project called RAINEX worked out what had happened. Katrina's ferocious rain bands had converged toward the heart of the storm, cutting off the eyewall's moisture supply. The old eyewall broke up and a new one formed farther out—an inertial brake that slowed the storm just as a skater's arms slow her spin when she thrusts them outward.

If Katrina had been moving just a little faster, it could have hit land as a Category 5 horror. Instead, thanks to the timing of its eyewall replacement, it sideswiped New Orleans as a milder—but still devastating—Category 3.

For a hurricane, landfall is a death sentence. Once its watery fuel supply has been cut off, the storm inevitably weakens. But that is scant solace to those caught up in its death throes.

From a washed-out stretch of Highway 90 along the Mississippi coast, almost four months after Katrina, the view inland took your breath away. The once lush coastline was still a litter of debris and splintered wood, houses swept from their concrete slabs, ancient spreading oaks stripped of Spanish moss and festooned with rags and tattered plastic.

Water was the primary agent of destruction here. Most hurricane casualties come not from wind but from rain, waves, and, as the scene here made harshly evident, surge—the vast mound of seawater that is pushed in front of the storm, rising 28 feet or more in the case of Katrina.

"If you really want to wallop something," says Rick Luettich, a coastal oceanographer at the University of North Carolina at Chapel Hill, "Mississippi and Alabama are pretty close to ideal for maximum storm surge." The coastal waters are shallow, easily plowed up by inrushing winds. Local features matter too, says Luettich, who has worked on a computer program that forecasts surge height. Bays and estuaries can funnel and intensify surge, for example, while barrier islands and wetlands can buffer it.

Coastal development weakens those defenses, as a flight over an adjacent stretch of coast in Louisiana makes clear. Channels crisscross the marshlands, dredged for boat traffic. They let salt water into the back marshes, killing vegetation

“We’re 11 years into the cycle. I can’t tell you if i

that holds them together. Add all the dikes and levees that hem in the Mississippi, cutting off the sediment that once replenished the marshes, and the result is staggering: More than 20 percent of Louisiana’s coastal wetlands reverted to open water from the 1950s through 2000, 27 square miles every year. The pilot holds up his chart of the tattered coast. “This here is the newest edition,” he says. “But it’s already out of date.”

The full impact of a giant hurricane can’t be measured in categories and wind speeds, in damage to homes and ecosystems, or even in lives lost. Those who live through one are never quite the same afterward. Tammy VanderZyl was a manager at Remoulade restaurant in New Orleans. She weathered Katrina in her apartment, then lived on the edge for three weeks with a group of near strangers. “You see things you never thought you would see,” she recalls. “I saw whitecaps in my parking lot.”

In his recent book, *Divine Wind,* Kerry Emanuel, a meteorologist at the Massachusetts Institute of Technology, intersperses the science and lore of hurricanes with paintings, poems, and literary excerpts inspired by the great storms of history. None is more poignant than the haiku VanderZyl composed after confronting Katrina:

Strong wind blows away
Everything that I am
Where do I go now

For VanderZyl and many of her fellow New Orleanians, the answer to the final line is obvious: right back home. The city will be different now. But leave? “No way,” she says. “Things would have to get way worse than this.”

Just over the horizon of scientific certainty lies the disturbing possibility that they might. Kerry Emanuel is by all accounts a cautious scientist. For years he believed there was no good evidence that global warming was making hurricanes any stronger. But last year new calculations stopped him in his tracks. When he looked at the total power of tropical cyclones worldwide, he was faced with the conclusion that during the past three decades, the storms have grown almost twice as destructive.

Emanuel’s results, published weeks before Katrina, were soon joined by another study, led by Peter Webster of the Georgia Institute of Technology. Webster concluded that the strongest storms—Categories 4 and 5—have become nearly twice as common over 35 years. The likely culprit, both scientists say, is global warming, which is adding hurricane-nurturing heat to the oceans.

It would be easier to find a building undamaged by Katrina in New Orleans’ Ninth Ward than to locate a reputable climate scientist who doubts that human activity is warming the Earth. But the claim that hurricanes are growing stronger as a result has set off a tempest of its own. William Gray of Colorado State University, a pioneer hurricane forecaster, has called it “plain wrong.” He and the NHC’s Christopher Landsea say Emanuel and Webster’s statistics are fuzzy and that data on past storms can’t be trusted. Until weather satellites became common in the 1970s, many tropical storms at sea went unrecorded, and since then changes in sensing technology have made it difficult to compare hurricane strengths.

Emanuel agrees that the data aren’t perfect. “But this is an important issue,” he says, “and the only way to get a better answer would be to have a longer record of reliable data,” which would make any trends stand out.

To improve the record, Landsea has been analyzing hurricanes back to the mid-1800s, trying to gauge their intensity from accounts of storm surge and wind damage. Other researchers are looking for signs of past hurricanes at the bottom of coastal lakes, where the strongest

Paradise Lost
The remains of an oceanfront house now stand in the ocean off Dauphin Island, Alabama. More frequent and ferocious storms have made low-lying barrier islands ever more vulnerable. “There are places I wouldn’t pitch a pup tent,” Abby Sallenger of the USGS says.

if it will last another ten years, or thirty."

—GERRY BELL, NOAA METEOROLOGIST

storms deposited layers of windblown beach sand, and in the wood of old trees from coastal forests. Rainwater from hurricanes is minutely lighter than regular rain, so a tree drenched by passing hurricanes preserves a subtle record of each storm in its growth rings.

While the debates go on, hurricanes will continue to strike increasingly populous coasts. That, says Landsea, is reason enough to worry. "The changes in society are as important, if not more important than global warming, or even natural cycles," he says. "When you double some vulnerable populations every 20 to 30 years, that's what's going to cause disasters. We've got a huge problem even if hurricanes don't change at all." □

Hurricane Fury Have you ever lived through a hurricane? How did it affect you? Share your stories in our online forum and post your thoughts on hurricane assistance at **ngm.com/0608**.