Hurricane Prediction

A Century of Advances

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Tropical cyclones, typhoons, and hurricanes are common words used around the world to describe the same natural phenomenon—one of the most deadly, costly, and feared weather systems on Earth. These small, intense tropical weather systems have killed more people than any other natural catastrophe (see Keim, this issue). In the United States during the 20th century, ten times as many deaths and more than three times as much damage occurred from tropical cyclones as compared with earthquakes (Gray, 2003). The continuous rapid rise in coastal populations along the hurricane-prone coast of the southeast United States since the 1950s (Figure 1) has placed more of the public at risk to coastal and inland flooding (see Bowen et al., this issue and Bowen case study, this issue). Nevertheless, advances in technology, communication, and forecasting have reduced risks to public health as is shown by the significant reduction in hurricane-related mortalities between 1900 and 2000 (Figure 1).

However, since 1995, there has been an upswing in Atlantic hurricane activity compared with the 1970s and 1980s (Webster et al., 2005). The strongest hurricanes, categories 4 and 5 on the Saffir-Simpson Scale (Figure 2), increased by 25 percent in the North Atlantic during 1990–2004 compared with 1975–1989, a trend that was documented for all ocean basins (Webster et al., 2005). Although Emanuel (2005a) shows a correlation between increasing water temperatures in the tropical Atlantic and hurricane energy, this relationship does not hold for other oceans (Webster et al., 2005). In 2005, records were broken when three Category 5 hurricanes intensified in the western Atlantic Ocean basin within a two-month period (Figure 3). The increased vigor of hurricanes is a growing concern for public health and safety, and presents serious challenges not only to modelers of hurricane track, intensity, and coastal surge but to emergency managers, traffic engineers, the insurance industry, and government budgets. In this article, we review the major advances in hurricane prediction during the 20th century and the possibilities for continued technological advances that will potentially improve public health and safety in the years to come.

LOOKING BACK IN TIME: GALVESTON 1900

At the turn of the 20th century, the only organized weather information available to hurricane forecasters was collected at land-based weather stations, as radio communications with ocean-going ships had not yet been developed. The "surprise" hurricane that flooded the thriving coastal city of Galveston on September 8, 1900 need not have killed 10,000 people if two ships transiting the Gulf of Mexico had been able to report their weather in-

Left. Storm surge from Hurricane Carol lashes Rhode Island Yacht Club in 1969. Photographer: Providence Journal Co. (Photo available at http://www.photolib.noaa.gov/historic/nws/wea00407.htm.) Below. Damage from the Galveston Hurricane in September 1900—the greatest natural disaster in terms of loss of life in U.S. history. (Photo available at http://www.photolib.noaa.gov/historic/nws/wea00589.htm.)

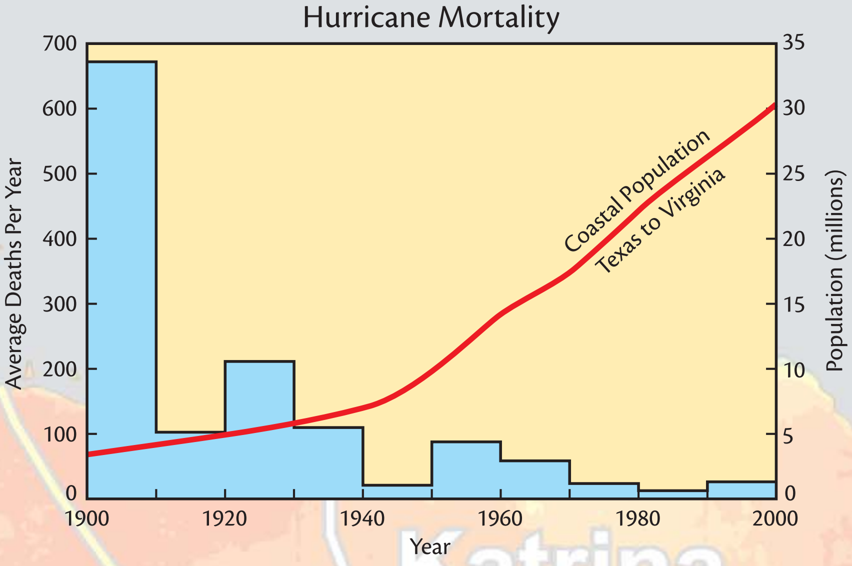
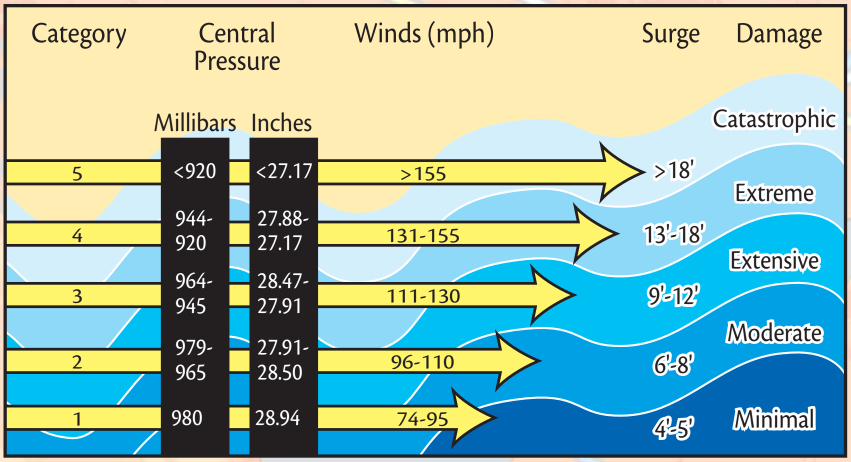


Figure 1. Population growth along the southeast U.S. coastline compared with mortality from hurricanes within the 20th century (modified from Willoughby [2003]).



Category	Central Pressure Millibars	Central Pressure Inches	Winds (mph)	Surge	Damage
5	<920	<27.17	>155	>18'	Catastrophic
4	944- 920	27.88- 27.17	131-155	13'-18'	Extreme
3	964- 945	28.47- 27.91	111-130	9'-12'	Extensive
2	979- 965	27.91- 28.50	96-110	6'-8'	Moderate
1	980	28.94	74-95	4'-5'	Minimal

Figure 2. Hurricane intensity is commonly rated using the Saffir-Simpson scale where categories 1–5 provide information on central pressure, sustained maximum wind speed, storm surge, and damage potential (courtesy of the National Hurricane Center; more information available at http://www.nhc.noaa.gov).

formation to land-based hurricane forecasters (Frank, 2003; Emanuel, 2005b).

As early as September 4, Cuban meteorologists provided an accurate prediction of the path of this hurricane based on their observations as it tracked over Cuba and their experience with former hurricanes. Although the Cuban meteorologists predicted that the hurricane would move northwest across the Gulf of Mexico, U.S. forecasters issued hurricane warnings for the east coast of the United States, believing that the hurricane would continue to turn north and then northeast. Meanwhile, the weak hurricane intensified rapidly over the eastern and central Gulf, where the steamship *Louisiana* recorded a pressure of 973 mb with wind speeds of 100 mph (161 kph)

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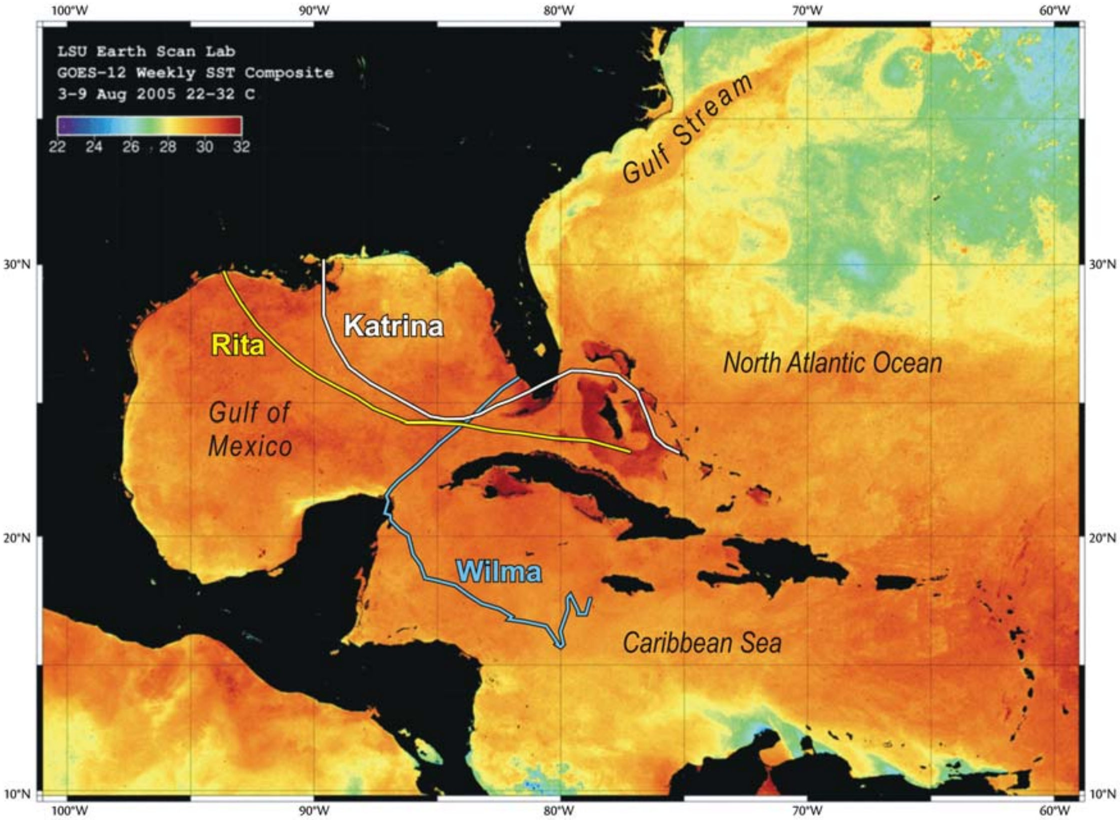

Figure 3. Hurricanes Katrina, Rita, and Wilma developed in the western Atlantic Basin between 15°N and 25°N in a broad region of relatively high (> 30°C) sea surface temperatures (SSTs) as is shown in this *GOES-12* satellite composite image for August 3–9, 2005 (see Walker et al., [2003] for methodology; real-time SST imagery is available at http://www.esl.lsu.edu). These three Category 5 hurricanes, which were spawned all in the 2005 hurricane season, have raised concerns about whether we are entering a period of increased hurricane frequency and intensity.

on September 6. Later, the steamship *Pensacola*, bound for Galveston, was thrashed by the developing hurricane.

These ships had no forewarning of this extreme weather in the Gulf of Mexico. Because they had no means of communicating with land stations, their much-needed information on the intensifying hurricane only reached U.S. meteorologists after they were safely in port (Emanuel, 2005b). Forecasters at the U.S. Weather Bureau Central Office in Washington, D.C. finally issued storm warnings for the Gulf coast region when the hurricane never materialized along the coast of Florida or the Carolinas.

Meanwhile, along the Galveston beaches, heavy breakers had developed, which alerted the chief of the Galveston weather office of a storm in the Gulf, even before he received official notification from the Washington, D.C. office. No official hurricane warning was released, however, and the city of Galveston received a surprise assault on the evening of September 8 when it was quickly inundated by a 20-foot (6.1-meter) storm surge and impacted by enormous waves and winds near 140 mph (225 kph). Eventually, the death toll was estimated at 8,000 to 12,000, and the city of Galveston, built on a barrier island only a few feet above sea level, suffered nearly complete devastation (Larson, 1999; Emanuel, 2005b).

TECHNOLOGICAL ADVANCES DURING THE 20TH CENTURY

Within a decade of the Galveston disaster, ships were instrumented with radio communications that augmented the sparse coverage from telegraphed land stations (Willoughby, 2003). This advance was particularly important because hurricanes form, intensify, and spend most of their lives over the ocean. In 1912, thirty ships steaming regularly from New York to New Orleans began sending weather observations twice daily by wireless telegraph. Besides these observations from ocean-going vessels and sporadic upper-air observations from weather balloons beginning in the 1930s, major advances in hurricane tracking and prediction were not realized until the early 1940s. Military operations during World Wars I and II led to important technological advances that spilled over into the world of weather forecasting. These advances brought forth improvements in the detection, tracking, and warning of hurricanes as well as the first information on the internal structure and development of tropical cyclones (Rappaport and Simpson, 2003).

The two most important gifts to meteorology as fallout from wartime technology were the development of weather RADAR and aircraft reconnaissance. The RADAR (i.e., radio detection and ranging) was developed in Great Britain after World War I, yielding, in 1944, the first view of the internal rain-band structure within a hurricane. In 1943, Colonel Joseph Duckworth and his navigator, Lt. Ralph O'Hair, became the first to deliberately fly an aircraft into the eye of a hurricane, near Galveston. This flight of "curiosity" in a single-engine Air Force AT-6 quickly led to the development of a formal program (the following cyclone season) of daily reconnaissance of Atlantic hurricanes by both the U.S. Air Force and Navy.

In 1943, Grady Norton, the first director of the newly established Miami Hurricane Forecast Office, was greatly concerned about predicting hurricane landfall positions and understanding the steering currents that he believed to control hurricane motion. His hypotheses led to the "piggy-backing" of research missions on hurricane reconnaissance flights. In 1947, two missions were flown into the Great Atlantic Hurricane of September 15th, which eventually hit New Orleans. These missions revealed startling new discoveries on the internal structure of the developing hurricane and energy processes within the eye (Rappaport and Simpson, 2003).

The invention of weather satellites in the early 1960s rapidly solved the problems of hurricane detection and tracking, meaning that "surprise" hurricanes were a problem of the past. The first meteorological satellite sensors orbited the poles, capturing data in the visible and infrared wavelengths every six hours. These data clearly revealed developing storm systems in isolated ocean areas, crude motion over time, and cloud-top temperatures, which could be related to hurricane strength. The next major advance in hurricane detection from space occurred with the design and launch in 1966 of the first geostationary weather satellite, *ATS-1*, carrying Professor Verner Suomi's famous spin-scan cloud imager (Willoughby, 2003). These satellites, positioned over the equator, imaged the same area of Earth every 20 minutes, providing superior repeat coverage, so essential to emergency-response activities.

A major breakthrough in satellite meteorology is attributed to Vern Dvorak, who designed a cloud-recognition technique for estimating the intensity of tropical cyclones from satellite images that has been broadly used by hurricane forecasters around the world (Dvorak, 1975; Gray, 2003). More recently, his techniques have been automated, adding to the suite of satellite-based guidance tools used by National Hurricane Center (NHC) forecasters (Velden et al., 2003).

During the 1980s, image processing and visualization systems proliferated, and analysts and forecasters used them. The NHC Director, Neil Frank, soon introduced color-enhanced animated movie loops of hurricane motion on TV to educate and help warn the public about approaching storms (Velden et al., 2003). Satellite images and image animations have since become a staple on TV weather broadcasts and on the World Wide Web.

Hurricane-related applications for the data from geostationary satellites continued to grow with the launch of *GOES-I*, the first of a new generation of geostationary operational environmental satellites covering the tropical Atlantic and Pacific Oceans (Menzel and Purdom, 1994). Weather processes over the entire globe are now under constant surveillance using geostationary satellites. In rapid-scan mode, satellite measurements of cloud-top temperatures and atmospheric water vapor are available every few minutes and from which wind speed and direction at the upper levels of the atmosphere can now be determined by tracking cloud and water-vapor features over remote ocean areas (Figure 4). These satellite measurements are of particular value over remote ocean areas where atmospheric-profile data are unavailable.

FORECASTING HURRICANE TRACKS AND WIND INTENSITY

Until the late 1950s, forecasting was largely a subjective exercise. This situa-

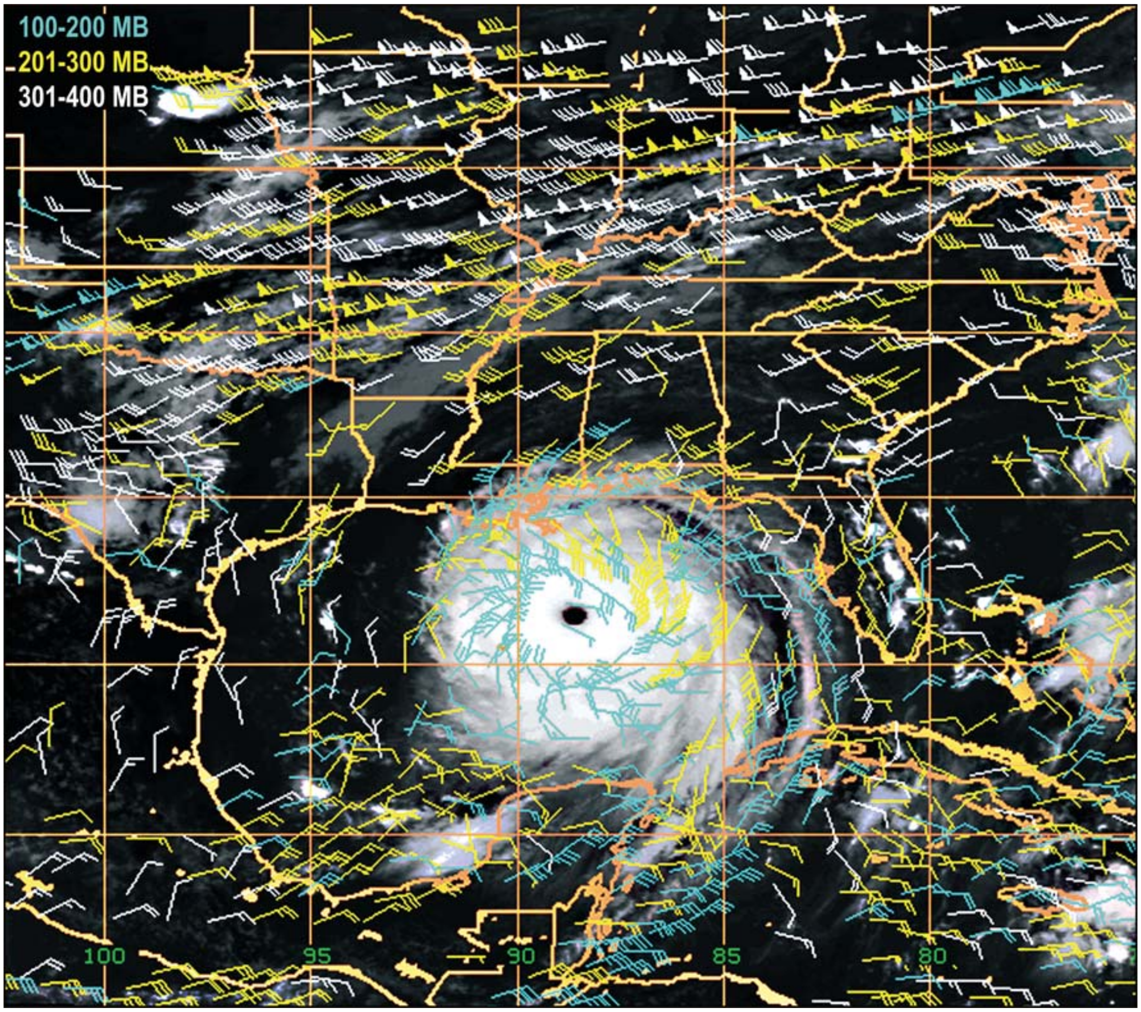

Figure 4. Analysis of successive 30-minute *GOES-12* images provides crucial information on mid- and upper-level winds influencing both hurricane motion and intensity. This analysis shows Hurricane Katrina in the Gulf of Mexico on August 28, 2005 (1800 UTC) with wind barbs determined by tracking upper-level cloud motion and water vapor (University of Wisconsin, Cooperative Institute for Meteorological Satellite Studies; real-time imagery available at http://cimss.ssec.wisc.edu/tropic/tropex).

tion changed when scientists at Princeton started using computers for numerical weather forecasts and, in 1957, Akira Kasahara at the University of Chicago performed the first numerical forecast of hurricane motion. Computer models became a primary tool for weather forecasters by the 1960s. However, it was not until the 1990s that the computer models began to out-perform simple statistical models of hurricane tracks (Emanuel, 2005b).

Tropical cyclones present a challenge to modelers, because a relatively small-scale circular symmetric disturbance is embedded in a large-scale surrounding flow (DeMaria and Gross, 2003). Nevertheless, the prediction of hurricane tracks by the NHC has improved significantly over the past 15 years. Hurricane-track errors for 24-, 48-, and 72-hour forecasts have been reduced by about one-half from 1990 to 2004 (Figure 5). However, during the same time period, little improvement was realized in hurricane-intensity forecasts. They are still based on statistical analyses of past hurricane events rather than numerical modeling (Figure 5) (DeMaria and Kaplan, 1994; Emanuel, 1999; Franklin, 2005).

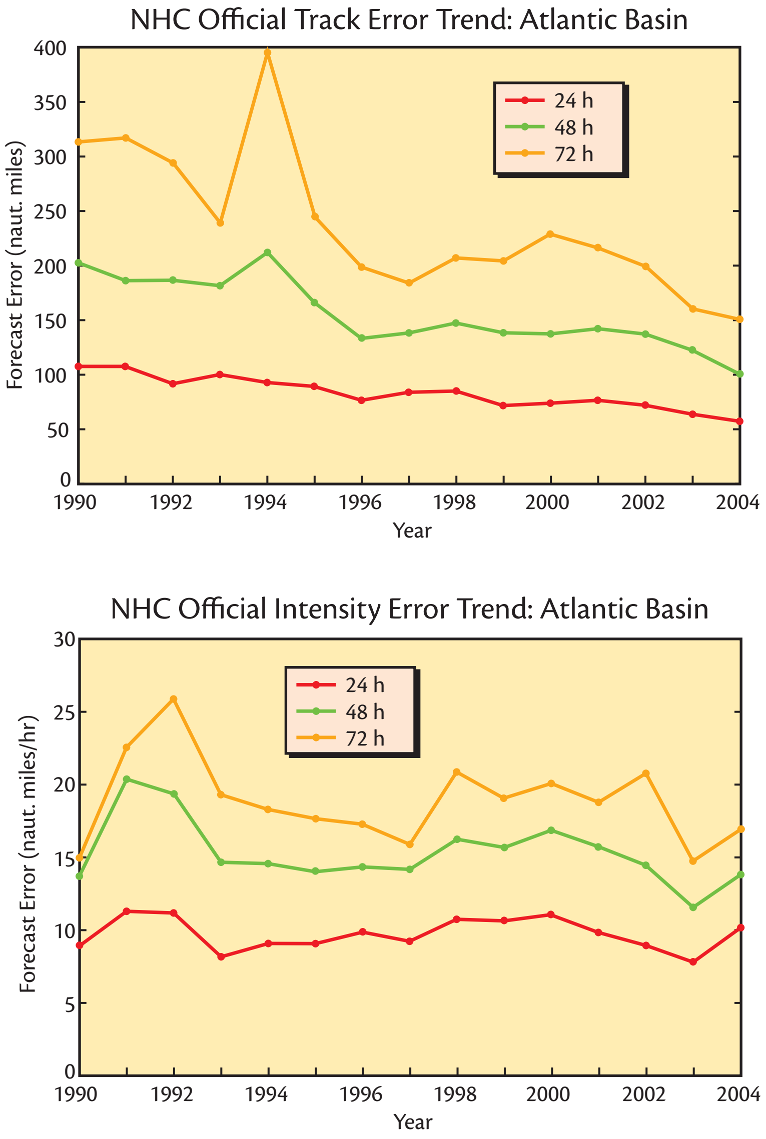

Figure 5. National Hurricane Center predictions of (upper panel) track errors and (lower panel) intensity errors from 1990 to 2004 for 24, 48, and 72 hours (modified from Franklin [2005]; courtesy of Dr. Jack Beven, National Hurricane Center). Track error has improved significantly at all time scales, whereas intensity error has not.

STORM SURGE AND PUBLIC HEALTH: LESSONS FROM HURRICANE KATRINA

Storm surges are the aspect of hurricanes that generate the greatest range and severity of public-health impacts. Historically, nine out of ten deaths from hurricanes have resulted from drowning in the storm surge (Frank, 2003). The accuracy with which storm surge can be predicted depends not only on the model physics, but on the reliability of the hurricane track and intensity predictions fed into the model. In order to determine the physical aspects of any surge flooding event, various numerical models have been developed over the years.

A quarter of a century ago, Chester Jelesnianski (1972) of the U.S. Weather Bureau (as it was then called), developed SPLASH (Special Program to List Amplitudes of Surge from Hurricanes). This model scored an immediate triumph, predicting the devastating surge of 23 feet (7 meters) that hit Bay St. Louis, Mississippi, with the landfall of Hurricane Camille in August 1969 (Sheets and Williams, 2001). Jelesnianski et al. (1992) later developed SLOSH (Sea, Lake, and Overland Surges from Hurricanes), which is still in use by the National Oceanographic and Atmospheric Administration (NOAA) and other agencies. Surge predictions from the SLOSH model are currently not readily available to the public or to local emergency managers, perhaps because it is difficult to accurately calibrate the model for every stretch of the hurricane-prone U.S. coastline.

Westerink et al. (1994) developed an advanced surge model called ADCIRC (ADvanced CIRCulation). It includes important details on river and overland flooding of areas connected to the coastal ocean. Hurricane researchers at the Louisiana State University (LSU) Hurricane Center successfully used ADCIRC to predict coastal surge and the potential topping of levees in the New Orleans area 36 hours before Hurricane Katrina hit the coast (more information available at http://www.hurricane.lsu.edu/floodprediction). Coastal water-level measurements from previous land-falling hur-

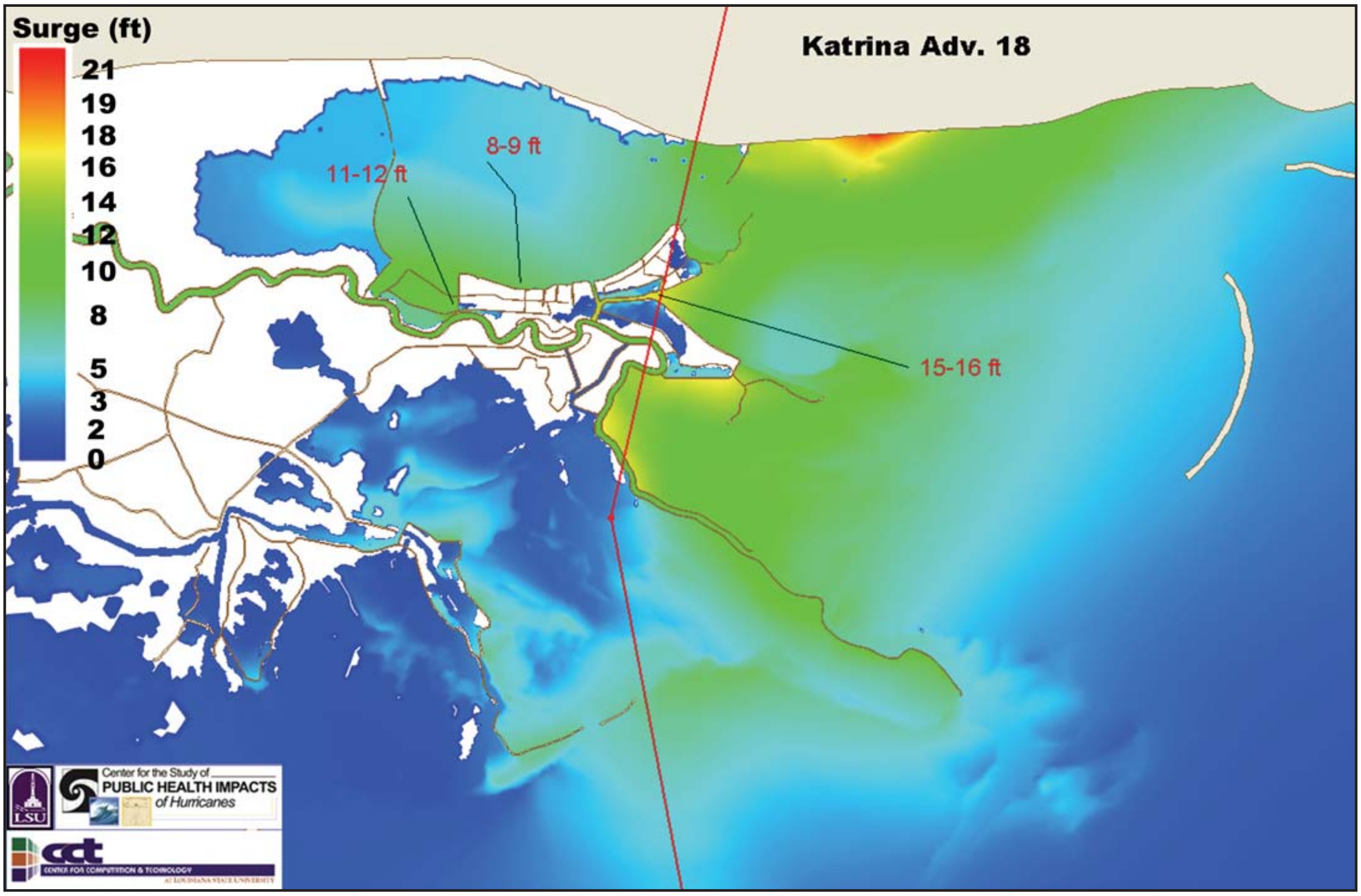

Figure 6. The LSU version of the ADCIRC model predicted a maximum storm surge of 21 feet (6.4 m) along the Mississippi coast and 15-16 feet (4.6-4.9 m) in coastal regions east of New Orleans, based on NHC Advisory 18 issued on August 27, 2005 (2100 UTC) (Center for the Study of Public Health Impacts of Hurricanes; more information available at http://hurricane.lsu.edu/floodprediction/rita18/).

ricanes in the area were used to calibrate the model for local conditions. The New Orleans newspaper, the *Times-Picayune*, took the surge prediction based on NHC advisory #18 and published a modified graphic in their Sunday morning edition (Figure 6). This public access to the ADCIRC output is believed to be responsible for a second wave of evacuees leaving that morning and early afternoon.

State and local officials used both the NWS SLOSH outputs and the LSU ADCIRC predictions to determine when to begin the contra-flow evacuation process. Evacuation from New Orleans before Katrina's landfall was the most successful on record. It is estimated that 80 percent of the greater New Orleans area evacuated the city, and 430,000 cars were counted using the contra-flow evacuation process. The contra-flow technique had been perfected during previous hurricane evacuations.

A major advantage of the ADCIRC products is the improvement in spatial resolution along the coast and inland. This advance enables interpretation in tandem with GIS products, making it of additional value for decision-making by local officials. These capabilities were tested by the New Orleans fire chief, who shared the LSU Hurricane Center's ADCIRC output with his emergency teams. They went into the areas that were predicted to flood due to levee overtopping and moved residents who had not yet evacuated (mostly the elderly) to higher ground, such as the Superdome. Unfortunately, these first responders did

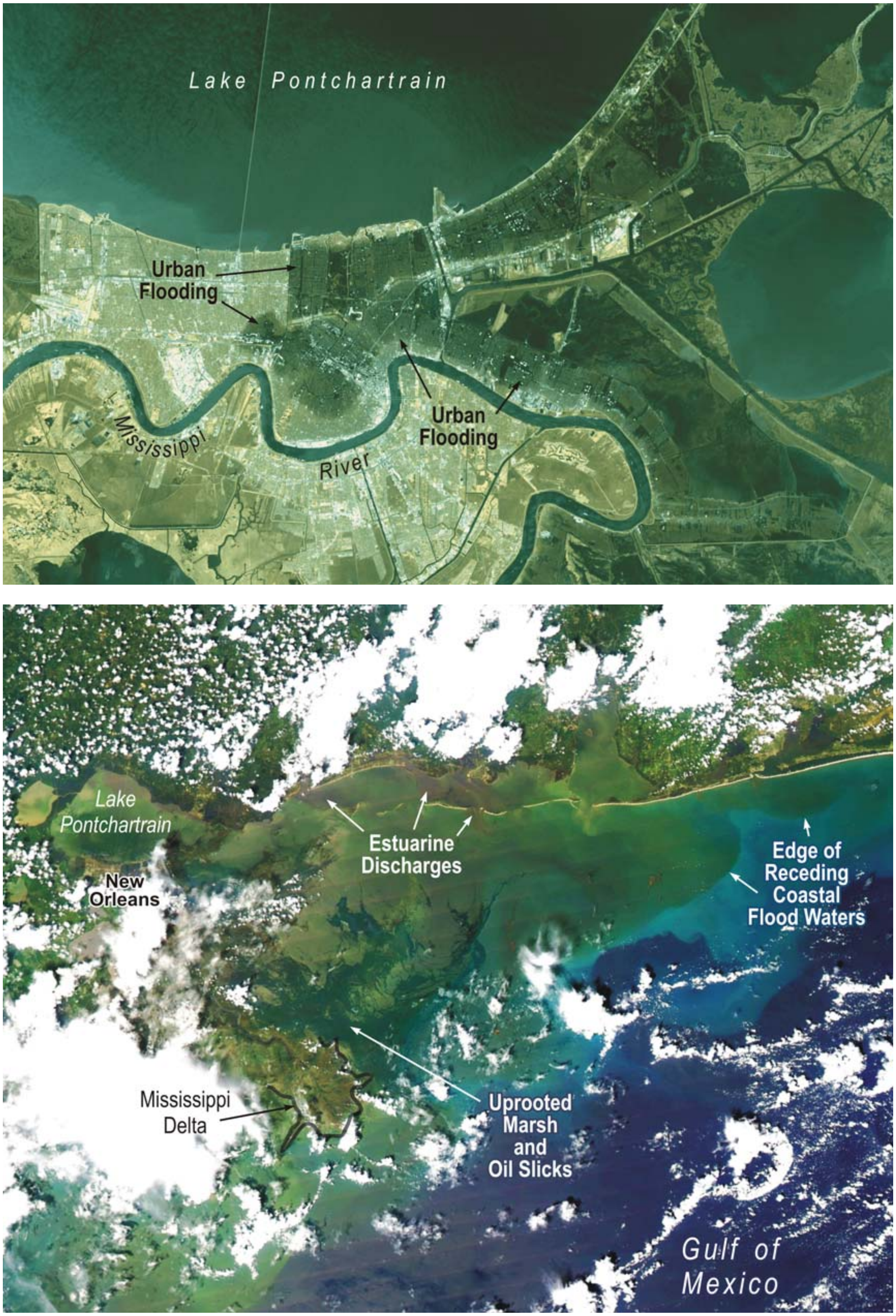

Figure 7. (upper panel) On September 4, 2005, several days after Hurricane Katrina's landfall, clear-sky imagery from the SPOT satellite revealed the extent of flood waters in the New Orleans area. (lower panel) On August 31, 2005, the MODIS sensor detected river and estuarine discharges, uprooted marsh mats and oil slicks, and the seaward extent of the receding flood waters along the Louisiana/Mississippi/Alabama coastline (real-time MODIS imagery available at http://www.esl.lsu.edu). SPOT imagery provided by CSTARS-University of Miami 2005 and © CNES 2005. Distribution by SPOT S.A./SPOT IMAGE CORP.

not realize that the dome surroundings would eventually flood due to the numerous levee breaks that characterized this catastrophe.

Two days after Hurricane Katrina hit, approximately 80 percent of greater New Orleans was under water, which in some areas exceeded 12 feet (3.66 m) in depth. The extent of flood waters in New Orleans was imaged by the SPOT (Satellite Pour l'Observation de la Terre) satellite on several successive days (Figure 7). The receding floodwaters were detectable along the coast within a few days of the catastrophe. Various water masses were revealed by MODIS (Moderate Resolution Imaging Spectroradiometer) true-color imagery, including discharge from flooded rivers and an expansive mass of discolored water extending from Gulf Shores, Alabama to the mouth of the Mississippi River (Figure 7). Reports from aircraft observers indicated that marsh debris and surface oil slicks were in abundance in coastal waters (see Pine, this issue). A few weeks after the flood waters were pumped from New Orleans, Hurricane Rita re-flooded many coastal lakes and bays.

FUTURE FORECASTING AVENUES AND CHALLENGES

The very active hurricane season of 2005 should act as a catalyst to stimulate further advances in hurricane forecasts, especially the predictions of hurricane intensity, which have lagged far behind the hurricane-track predictions. The intensity forecast is of great importance to the prediction of maximum surge along the coast. A focus on understanding and forecasting the development of strong hurricanes (i.e., above Category 2) would be of particular benefit to public health and safety because it is the strongest hurricanes that produce most of the damage, both from wind and coastal flooding. During the 1900 to 1990 period, Category 3, 4 and 5 land-falling hurricanes accounted for 86 percent of the total damage (Gray, 2003).

Emanuel (1999) provides hope that hurricane intensity can be forecast using simple models, given an accurate forecast of the hurricane's track and information on a limited number of controlling factors. These factors include the storm's initial intensity, atmospheric conditions along its path, and heat exchange with the upper layer of the ocean. Many of the essential atmospheric and oceanic measurements are already available from the current suite of Earth-observing satellites. In terms of atmospheric conditions, real-time updates of satellite-derived winds have reduced forecast errors in numerical models of hurricane motion (Goerss et al., 1998; Velden et al., 1998; Soden et al., 2001; Velden et al., 2003). These data, in tandem with advances in satellite observations of the upper ocean, may provide the initial measurements necessary for advancing the development of numerical models for hurricane intensity prediction.

Hurricanes Katrina and Rita provided two vivid examples of how oceanic heat content can fuel rapid hurricane intensification. Both Katrina and Rita were relatively weak hurricanes (Category 2) until they moved over Loop Current waters in the Gulf of Mexico, where they rapidly became Category 5 monsters (Figure 8). The Loop Current is the Gulf of Mexico portion of an enormous moving mass of warm water, which enters the Gulf from the Caribbean Sea and eventually forms the Gulf Stream off the U.S. East Coast. The complete circulation of this important current encompasses much of the North Atlantic Ocean and the Caribbean Sea from the surface ocean to several hundred meters in water depth. Although scientists have used satellite data to routinely and accurately measure sea surface temperatures (SST) since the early 1980s, locating the Loop Current from SST data is not always possible during hurricane season because the surrounding Gulf of Mexico surface waters are equally warm, typically 29°–31°C.

In the summer, scientists rely on satellites that measure sea surface height (SSH) to locate the high-heat-content "hot spots," where hurricanes are likely to intensify (Figure 8). Relatively small changes in satellite-measured SSH (< 100 cm) equate to large differences in potential heat, which can fuel a developing hurricane. Surface-water temperatures exceeding 26°C are essential for development and maintenance of hurricanes. Within the Loop Current and its warm eddies during summer, water temperatures exceed 26°C to a depth of 100 m or more, whereas outside of the current, the layer of warm water is only 50 m or so deep (Goni and Trinanes, 2003). This difference impacts the available heat that can be transferred to the hurricane through evaporation.

Although hurricane strengthening has been previously documented and modeled over the high-heat-content Loop Current waters (Shay et al., 2000; Emanuel, 2005b), other factors such as upper-level winds and large cold water upwelling along the hurricane path also impact hurricane-intensity changes and

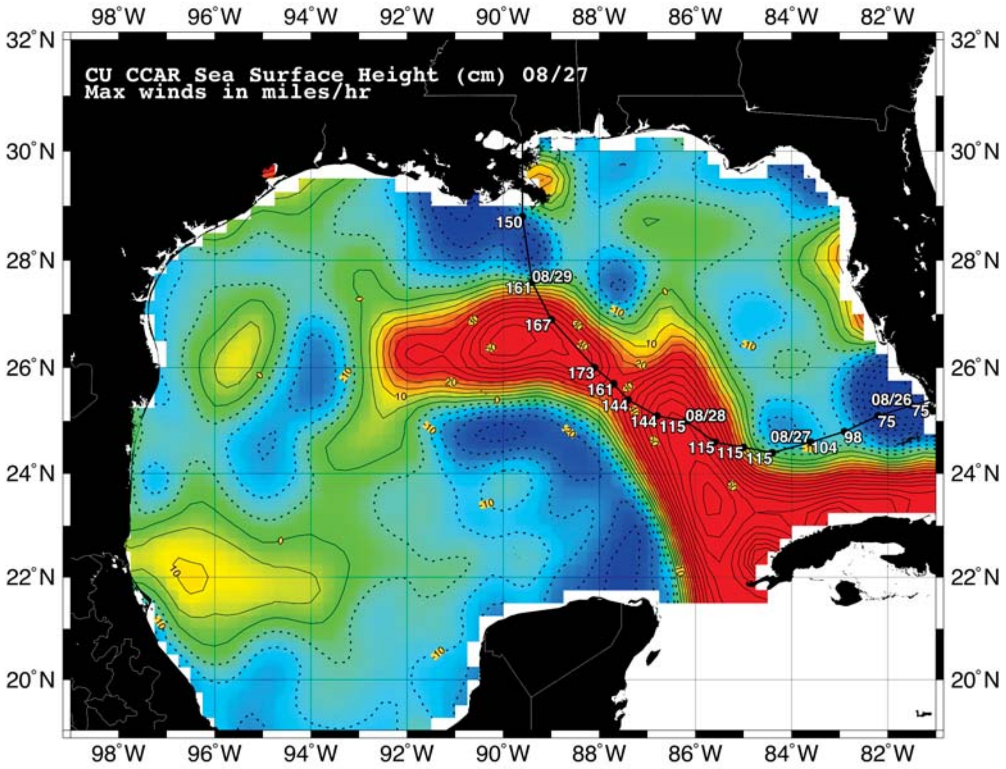

Figure 8. Hurricane Katrina's wind speeds increased from 115 to 173 mph (185 to 278 kph) as it moved over and along the Loop Current and Eddy Vortex, areas of highest heat content in the Gulf of Mexico. Real-time information from satellite altimeters can be used to detect the location of the Loop Current and its eddies, which appear as sea surface highs (red colors). The contours of sea surface height were computed from *Jason-1*, *TOPEX/POSEIDON*, and *Geosat* Follow-on, for Gulf of Mexico waters on August 28, 2005, using methods of Leben et al. (2002). The associated sea surface temperature structure is shown in Figure 3 (real-time data available at http://argo.colorado.edu/~realtime/welcome/).

sometimes counteract the potential impact of ocean heat content (Ritchie et al., 2003; Walker et al., 2005). Hurricane winds create "cool wakes" due to the mixing of cooler waters from below the surface (Monaldo et al., 1997) or upwelling within cold-core cyclones (Walker et al., 2005) (Figure 9). Cool wakes can have an immediate impact on hurricane intensity in addition to impacting subsequent hurricanes passing over them.

Although information on the thermal structure of the upper ocean is available from satellites in real time, this information is not currently being used operationally for forecasting hurricane intensity. Future advances in coupled ocean-atmosphere models in tandem with effective use of satellite and *in situ* measurements should lead to significant improvements in the forecasting of hurricane intensity within the next decade. Technological advances already in motion for weather and ocean-observing satellites to be launched after 2010 will improve the availability and accuracy of atmospheric and oceanic data to be used as model input. Satellite sensors have their limitations, however, and cannot provide all the needed information on the vertical structure of the atmosphere or ocean. A comprehensive data-gathering program is also needed to further the understanding and modeling of the rapid intensity changes within hurricanes.

Improving hurricane prediction models is only part of the solution to solving public health and safety concerns. Addressing the immediate, short-term, and long-term public-health impacts of future large hurricanes will require improvements in infrastructure and contaminant inventories, evacuation planning, and GIS databases where the data can be easily accessed. In addition, new avenues of communication need to be explored and implemented among emergency managers, the media, and the public. Even the best forecast only becomes effective when it has been adequately communicated to the vulnerable communities in the path of the storm (Holland, 2003). The last challenge for emergency managers and others is to actually convince the public of the necessity for evacuation. Timely access to storm-surge predictions may provide the

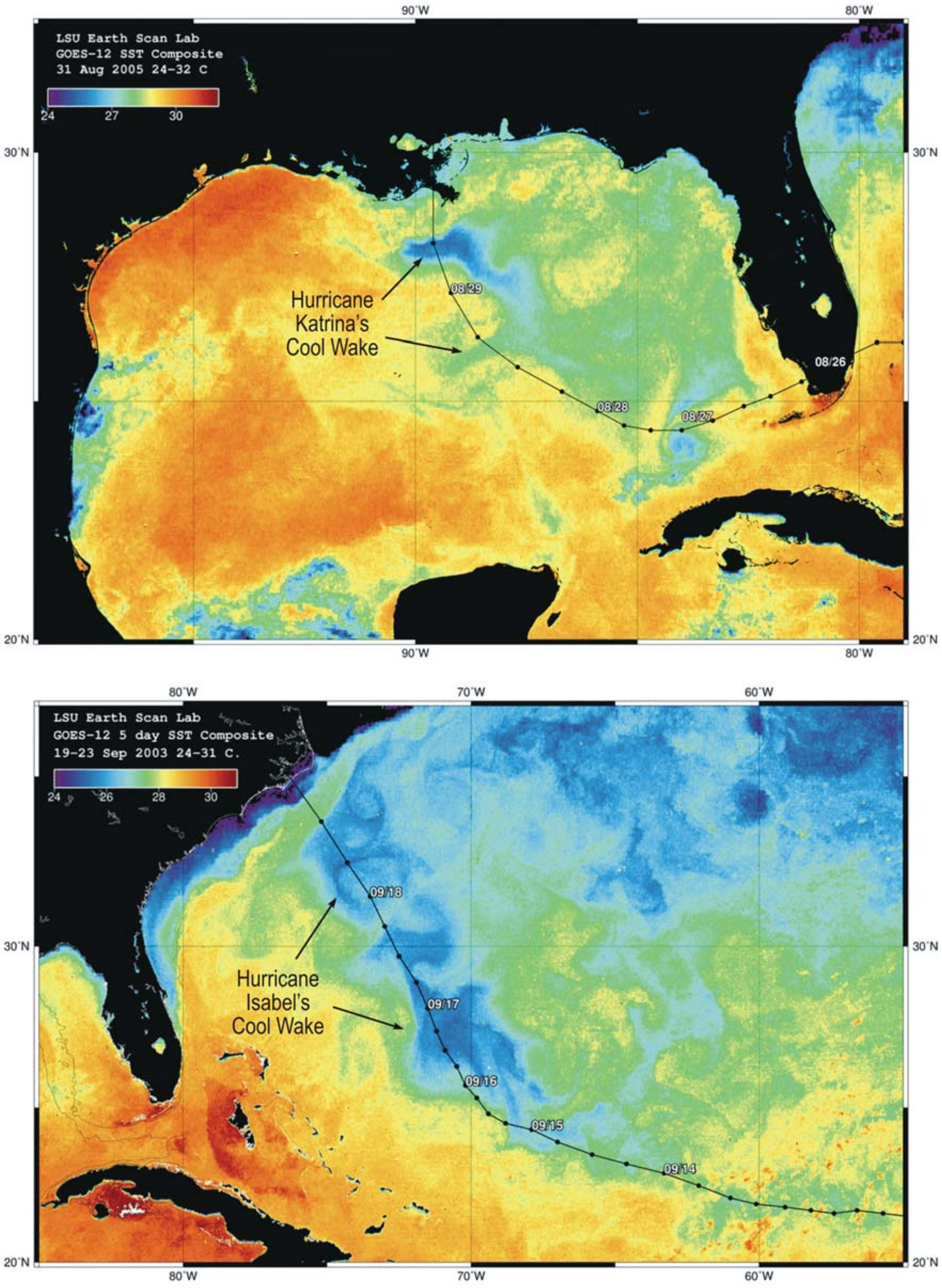

Figure 9. *GOES-12* sea surface temperature composite images reveal (upper panel) the cool wake left by Hurricane Katrina on August 31, 2005 and (lower panel) the cool wake of Hurricane Isabel on September 23, 2003. The National Hurricane Center's official tracks, six-hourly positions, and maximum sustained wind speeds are also shown (from Louisiana State University Earth Scan Laboratory; more information available at http://www.esl.lsu.edu).

most effective means of motivating the public to evacuate, especially given the extreme and long-lived flooding of New Orleans after Hurricane Katrina's landfall in 2005.

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