New Orleans, flooded
U.S. Coast Guard photo

Hurricanes and the Gulf Coast

How Hurricanes Form

A hurricane is the strongest form of a “tropical cyclone,” the term used to describe weather systems that develop over tropical or sub-tropical waters with organized thunderstorms and a well-defined central “eye.”

Most Atlantic hurricanes begin as atmospheric waves that move westward from Africa across the tropical North Atlantic and Caribbean Sea. This stretch of ocean is known as the main development region. Here, warm sea-surface temperatures pass moisture into the atmosphere, increasing humidity levels. Winds moving in from different directions collide with the atmospheric waves and force air upwards. If there is low wind shear the air will continue to rise. The storm’s energy comes from the continuous exchange of heat between the ocean and the atmosphere, which is released through the formation of clouds concentrated in the center of the forming cyclone.

Scouting Katrina from above

U.S. Air Force photo

The appearance of a high-pressure system provides the final ingredient. The high-pressure system floats above the storm and draws the warm ocean air upward, pushing it outward from the top of the gathering storm in a continuous cycle. At this point the Earth’s rotation gives the incoming air a counter-clockwise spin and, propelled by the warm wind currents, the storm moves toward the coast.[1]

Tracking and Predicting Hurricanes

Not all storms in the main development region become hurricanes. Often, preexisting winds will tear apart the storm as it forms. If conditions are favorable, however, scientists will reclassify these “tropical disturbances” into more severe storms as their sustained wind speed rises:

- At 23 miles per hour, the disturbance becomes a “tropical depression.”
- At 39 miles per hour, the depression becomes a “tropical storm” and gets a name.
- At 74 miles per hour, the tropical storm is classified as a hurricane (in the Pacific, a typhoon).[2]

A hurricane needs a constant source of energy. In this case, from June to November, the warm, humid waters of the Atlantic fuel the storm as trade winds from the east and ocean currents direct its path.[3] The storm weakens if it happens to move across cool water or land, losing its thermal energy source.[4]

The National Hurricane Center (NHC) in Miami, Florida, determines the track, intensity, and landfall effects of a storm. The NHC issues 72-hour tropical cyclone track and intensity forecasts four times a day for all storms in the north Atlantic and northeastern Pacific.[5]

A hurricane watch is issued 36 hours before hurricane conditions are expected to affect coastal areas. A warning is issued 24 hours beforehand and may remain in effect even if wind speeds drop below hurricane force to account for the possibility of hurricane-level storm surge.

Storm surge is wind-driven water.[6] As a hurricane churns in the atmosphere, its winds snowball the water below toward the shoreline. Combined with normal tides, this surge can increase the mean water level 15 feet and push up to 100 miles inland.[7] Even if a hurricane has weakened by the time it has reached shore, it has been building up storm surge since a much earlier time, when it was much stronger.

Though hurricanes are measured by their wind speeds, many scientists have come to believe that storm surge is far more deadly than wind, especially considering that the highly populated areas of the Atlantic seaboard and the Gulf Coast lie only 10 feet above mean sea level.[8] Hurricane Andrew (1992), which carried a 17-foot storm surge into Miami's Biscayne Bay, illustrated the danger. Its storm surge shoved the Belzona Barge – a 215-foot, 350-ton barge that had been deliberately sunk 68 feet below the surface, with a thousand tons of concrete resting on deck, off the coast of Florida to establish an artificial reef – 700 feet to the west along the ocean floor.[9] "The greatest potential for loss of life related to a hurricane is from the storm surge," according to an official with the National Oceanic and Atmospheric Administration (NOAA).[10]

Significant progress in hurricane forecasting has prevented major loss of life in areas prone to hurricanes.[11] The National Weather Service (NWS) uses the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) computer program to predict the storm surge of an inbound hurricane and to map the likely impact of hurricanes of different sizes, speeds, strengths, and tracks. The SLOSH program uses a storm's barometric pressure, overall size, forward speed, track, and wind speed, as well as prior hurricane information and other models.[12]

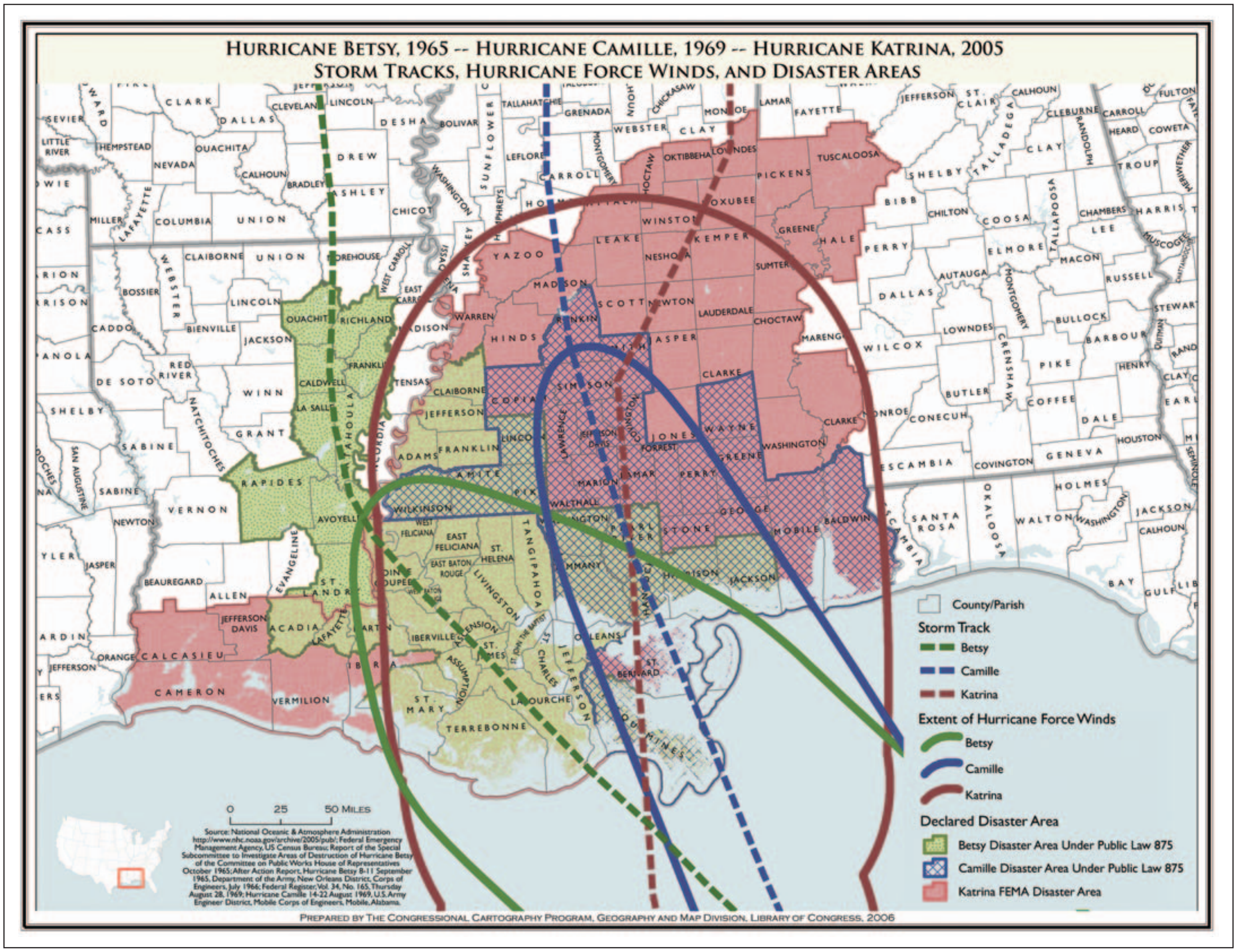
During Hurricane Andrew in 1992, alarmed by scenes in South Florida, approximately 1.2 million people evacuated from the New Orleans metropolitan area. While the evacuation almost certainly saved lives, federal hurricane experts were alarmed that officials in New Orleans expected 60 to 80 hours' warning to complete an evacuation. During testimony before a Congressional committee in 1993, Robert Sheets, Ph.D., then the director of the NHC, warned that "We don't have the skill meteorologically speaking to provide a sufficient warning for those long lead times. There is no way I am going to have 70 hours of lead time for New Orleans to respond to a hurricane."[13]

By 2005, advances in technology, such as refinement of satellite capabilities and improvement of pressure-measuring sensors in reconnaissance planes, had drastically increased the NHC's lead times.[14] By 2 p.m. ET Friday, August 26, 65 hours before Katrina made landfall, NHC Director Max Mayfield, Ph.D., was making calls to emergency officials in the Gulf Coast alerting them that a rapidly strengthening storm was heading directly for New Orleans.[15]

Hurricanes and the Gulf Coast

The same warm waters that give the Gulf Coast its marshy topography and humid climate make it a prime target for hurricanes, while demographic and economic trends have multiplied their potential impact.[16] In earlier periods of our history, the physical impact of major hurricanes in the Gulf was softened by swamps, marshes, and barrier islands, while the societal impact was limited by its relatively small concentrations of buildings and people.

In more recent times, however, the population in the coastal counties from Texas to the Florida Keys has soared. The U.S. Census Bureau reports that 9.46 million people live along



Hurricanes Betsy, Camille, and Katrina

Geography and Map Division, The Library of Congress

the Gulf Coast – 3.5 times the number in 1950 – and their numbers are growing by nearly 7 percent a year.[17] From 1970 to 1994, the Gulf Coast averaged less than one hurricane landfall per season, and the East Coast averaged one hurricane landfall every five years. This is in sharp contrast to the average of three U.S. hurricane landfalls during very active seasons. Unfortunately, decisions about land use, construction standards, etc. were based on an erroneous assumption, growing out of that period, that hurricanes would no longer affect the United States as frequently or as strongly as they had in earlier decades.[18]

Besides economic and population growth – including the swelling numbers of retirees drawn to warm-winter locales – engineering projects intended to prevent or reduce flood damage increased the appeal of the Gulf Coast. Here, as in the Southwest and the West Coast, "We are pushing toward the very areas where nature puts us most at risk from tropical storms, mudslides, and forest fires," Princeton University researcher Edward Tenner wrote in 1996. One of Tenner's examples: "A big storm could leave 20 feet of water in downtown New Orleans and flood evacuation routes."[19]

Ten years before Hurricane Katrina struck New Orleans, NOAA saw signs that the Atlantic Ocean had entered a 10 to 40-year cycle of intense hurricanes that would present an especially serious threat to the Gulf Coast.[20] From 1970 through 1994, the United States enjoyed what meteorologists viewed as "normal" Atlantic hurricane seasons, a period of relatively mild activity that had produced few major hurricanes, That period averaged five hurricanes annually and 1.5 major hurricanes.[21]

Since 1995, however, hurricane seasons have averaged 7.6 hurricanes each year and 3.6 major hurricanes, with reported increases in their destructive power.[22] Historically, the number of major hurricanes and the number of Caribbean hurricanes tended to follow the multi-decade cycle, according to a 2001 analysis by a team of hurricane experts, who said: "The late 1920s to the 1960s were very active, while both the 1900s and the 1970s through the early 1990s were quiescent." [23]

New Orleans was not the only major U.S. population center that was in greater danger of a catastrophic storm. Analysis of historical data showed that two regions of the United States – the East Coast from South Carolina to Maine and the Gulf Coast from Florida to Texas – faced a much greater risk of catastrophic hurricanes and storm surges.

Marking the beginning of a new multi-decade period of hurricanes activity involves extensive analysis of historical trends, conditions in the Atlantic and the atmosphere.[24] Even so, there are no guarantees. Catastrophic hurricanes have occurred in years of normal or even below-normal hurricane activity. In 1972, Hurricane Agnes never got beyond Category 1 strength, but still caused 122 deaths in the United States, with severe flooding in Virginia and the Carolinas.[25] Hurricane Andrew, the most damaging hurricane in U.S. history before Katrina, formed during a season (and cycle, lasting until 1994) of below-normal activity.[26]

Between 1995 and 2000, however, the North Atlantic had the highest level of hurricanes on record, including several that threatened New Orleans.[27] Among them was Hurricane Georges in 1998, a Category 3 storm that caused 602 deaths in the Caribbean, set a track for New Orleans, but turned toward Mississippi before making landfall. [28] By 2000, hurricane experts had concluded that the Atlantic was undergoing "multi-decadal conditions" that favored more major hurricanes. Scientists began calling for improvements in hurricane preparedness.[29] The NWS was issuing annual Atlantic Hurricane Outlooks, long-range forecasts of hurricane activity and severity.[30] Released each May before the June 1 start of the hurricane season, the Outlooks relied on a yardstick known as the Accumulated Cyclone Energy (ACE) Index.[31]

The agency's 2003 Outlook predicted a 55 percent likelihood of above-normal hurricane activity, with an estimated range of two to four major hurricanes. However, the projected ACE value of the season had a staggering range: 110-180 percent of the median, which was much higher than 2002 and the 1971-1994 period.[32] Two months later, the agency increased the probability for an above-normal hurricane season to 60 percent and projected that three to four major hurricanes would threaten the United States.[33] The assessment was correct: By November, the Atlantic had spawned three major hurricanes, including Isabel, a storm that reached Category 5 strength before striking North Carolina as a Category 2.[34]

A year later, the Outlook for 2004 predicted a 50 percent chance of an above-normal hurricane season, with two to four major hurricanes and an ACE index in the range of 100-160 percent. That year, four major storms roared through the Gulf, including Hurricane Ivan. This Category 5 storm produced at least 34 tornadoes and was the most destructive hurricane to strike the Florida Panhandle and Alabama coast in a hundred years.[35]

The NWS's 2005 Outlook, issued in May, predicted yet another above-normal hurricane season with twice the usual number of major hurricanes.[36] This time, the pre-season estimate called for three to five major storms and made it clear that the odds of a catastrophic storm were increasing. "The main uncertainly in this outlook is not whether the season will be above normal, but how much above normal it will be," the report said.[37]

During the next 60 days, the Atlantic spawned seven tropical storms and two major hurricanes, Dennis and Emily.[38] On August 2, the NWS issued an update of its 2005 Outlook that predicted a "95% to 100% chance" of an above-normal hurricane season and increased its estimated range from three to five, to five to seven storms. [39]

Twenty-one days later, on August 23, Tropical Depression 12 developed about 175 nautical miles southeast of Nassau, in the Bahamas. The following day, it was designated Tropical Storm Katrina.[40]

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1 Christopher Landsea et al., "Atlantic Basin Hurricanes: Indices of Climatic Changes," *Climatic Change* 42:1, May 1999, pp. 89-129; Stanley B. Goldenberg et al., "The Recent Increase in Atlantic Hurricane Activity: Causes and Implications," *Science*, July 20, 2001, pp. 475-467 [hereinafter Goldenberg, "The Recent Increase in Atlantic Hurricane Activity"]; and Lloyd J. Shapiro and Stanley B. Goldenberg, "Atlantic Sea Surface Temperatures and Tropical Cyclone Formation," *Journal of Climate* 11, 1997, pp. 578-590; National Aeronautics and Space Administration, Earth Observatory "Hurricanes: The Greatest Storms on Earth." http://earthobservatory.nasa.gov/Library/Hurricanes/index.html. Accessed on Mar. 31, 2006 [hereinafter NASA, "Hurricanes: The Greatest Storms on Earth"] ("Hurricanes form over tropical waters (between 8° and 20° latitude) in areas of high humidity, light winds, and warm sea surface temperatures (typically 26.5°C [80°F] or greater). These conditions usually prevail in the summer and early fall months of the tropical North Atlantic and North Pacific Oceans and for this reason, hurricane 'season' in the northern hemisphere runs from June through November.").

2 NASA, "Hurricanes: The Greatest Storms on Earth."

Hurricanes are sorted into categories on the Saffir-Simpson Scale, named for the engineer and the meteorologist who developed it in the 1970s. Its five categories are now the standard method for classifying hurricanes:

Category	1	2	3	4	5
Wind speed (mi/hr)	74–95	96–110	111–130	131–155	155+
Storm surge (ft)	4–5	6–8	9–12	13–18	18+
Damage	Minimal	Moderate	Extensive	Extreme	Catastrophic

3 National Oceanic and Atmospheric Administration, Hurricane Research Division, "When is Hurricane Season?" http://www.aoml.noaa.gov/hrd/tcfaq/G1.html. Accessed on Jan. 24, 2006 ("The Atlantic hurricane season is officially from 1 June to 30 November. There is nothing magical in these dates, and hurricanes have occurred outside of these six months, but these dates were selected to encompass over 97% of tropical activity. The Atlantic basin shows a very peaked season from August through October, with 78% of the tropical storm days, 87% of the minor (Saffir-Simpson Scale categories 1 and 2 – see Subject D1) hurricane days, and 96% of the major (Saffir-Simpson categories 3, 4 and 5) hurricane days occurring then (*Landsea* 1993). Maximum activity is in early to mid September.").

4 *Technical Data Report: Southeast Louisiana Hurricane Preparedness Study*, prepared by U.S. Army Corps of Engineers, New Orleans District for Federal Emergency Management Agency, Aug. 1994, p. 2–12 [hereinafter *Southeast Louisiana Hurricane Preparedness Study*, Aug. 1994] ("Most hurricanes weaken after landfall because the central pressure increases and the radius of maximum winds tends to increase. The terrain of southern Louisiana is very low, flat, and marshy and the transition to land from water is not abrupt.").

5 *See:* National Weather Service, National Hurricane Center, Tropical Prediction Center. http://www.nhc.noaa.gov.

6 *Southeast Louisiana Hurricane Preparedness Study*, Aug. 1994, p. 2–2 ("A hurricane moving over the continental shelf produces a buildup of water at the coastline which is commonly referred to as storm surge. Storm surge is the increase in height of the surface of the sea due to the forces of an approaching hurricane. Storm surge normally occurs over a coastline for distances of 100 miles or more. The winds associated with a hurricane are the largest single component responsible for the buildup of storm surge within a basin. The wind blowing over the surface of the water exerts a horizontal force which induces a surface current in the general direction of the wind. The surface current, in turn, induces currents in subsurface water. This process of current creation continues to a depth which is determined by the depth of the water and by the intensity and forward motion of the hurricane. For example, a fast moving hurricane of moderate intensity may only induce currents to a depth of a hundred feet, whereas a slow moving hurricane of moderate intensity might induce currents to several hundred feet. These horizontal currents are impeded by a sloping continental shelf as the hurricane approaches the coastline, thereby causing the water level to rise. A wide gently sloping continental shelf is particularly conducive to the formation of large storm surges. The amount of rise increases shoreward to a maximum level at, or some distance inland from the shoreline.").

7 Louisiana Office of Homeland Security and Emergency Preparedness and Louisiana State Hazard Mitigation Planning Committee, *State of Louisiana Hazard Mitigation Plan*, Apr. 15, 2005, p. I–46 [hereinafter *State of Louisiana Hazard Mitigation Plan*, Apr. 15, 2005] ("In Louisiana, storm surges are large waves of Gulf waters that sweep across coastlines where a tropical storm makes landfall. Generally the more intense the storm, the greater the height of the storm surge; the higher the storm surge, the greater the damage to the coastline. Storm surges inundate coastal floodplains, wash out dunes, cause backwater flooding through coastal river mouths, generate large waves that run up and flood coastal beach-

es, and can flood streets and buildings in coastal communities….The coastal bathymetry of southeastern Louisiana, with its low, flat topography and land surface elevations that in many places dip below sea level, can experience storm surges up to 100 miles inland. Category 3 storms can bring depths up to 24 feet as far north as the City of New Orleans. Category 5 storms can produce depths as high as 36 feet. Furthermore, lakes along the coast, namely, Lake Maurepas, Lake Borgne, and Lake Pontchartrain, exacerbate the effects of coastal flooding because of wave effects that can regenerate over inland lakes. It is important to note that the map represents the cumulative storm surges for hundreds of modeled hypothetical hurricane tracks; no single hurricane event would produce the inundation pattern depicted on the map.").

8 National Hurricane Center, Hurricane Preparedness, "Hurricane Preparedness Week." http://www.nhc.noaa.gov/HAW2/english/intro.shtml. Accessed on Jan. 16, 2006.

9 Ed Rappaport, National Hurricane Center, *Preliminary Report: Hurricane Andrew, 16-28 August 1992*, Dec. 10, 1993. http://www.nhc.noaa.gov/1992andrew.html. Accessed on Apr. 26, 2006 [hereinafter Rappaport, *Preliminary Report: Hurricane Andrew*].

10 Brian Jarvinen, National Hurricane Center, Hurricane Preparedness, "Storm Surge." http://www.nhc.noaa.gov/HAW2/english/storm_surge.shtml. Accessed on Apr. 27, 2006.

11 Written Statement of Brig. Gen. David L. Johnson, U.S. Air Force (Ret.), Assistant Administrator for Weather Services, and Director, National Weather Service, National Oceanic and Atmospheric Administration, for the U.S. House of Representatives, Committee on Science, hearing on *NOAA Hurricane Forecasting*, Oct. 7, 2005, p. 3 ("The mission of the National Weather Service (NWS) is to issue weather, water and climate forecasts and warnings for the protection of life and property and the enhancement of the national economy. Nowhere is that more evident than in the hurricane program."). *Source:* Written Statement of Brig. Gen. Johnson, House Committee on Science hearing, Oct. 7, 2005, p.1. In 1943, aircraft reconnaissance of the hurricanes began. In 1959, land-based weather radars were placed at Lake Charles and Slidell, Louisiana and Pensacola, Florida. In the 1960s scientists gained the ability to observe tropical storm behavior through the use of satellite photography. *Source*: *Southeast Louisiana Hurricane Preparedness Study*, Aug. 1994, p. 1-9.

12 Written Statement of Brig. Gen. Johnson, House Committee on Science hearing, Oct. 7, 2005, p. 4 ("Following Hurricane Camille in 1969, NOAA established a group that developed and implemented a storm surge model called SLOSH (Sea, Lake, and Overland Surges from Hurricanes) The SLOSH model calculates storm surge heights resulting either from historical, hypothetical or actual hurricanes. SLOSH incorporates bathymetry and topography, including bay and river configurations, roads, levees, and other physical features that can modify the storm surge flow pattern."). *See also: Southeast Louisiana Hurricane Preparedness Study*, Aug. 1994, p. 2-6 ("In addition to furnishing surge heights for the open coast, the SLOSH model has the added capability to compute the routing of storm surge into bays, estuaries, or coastal river basins as well as calculating surge heights for overland locations. Significant natural and man-made barriers are represented in the model and their effects simulated in the calculations of surge heights within a basin."); *State of Louisiana Hazard Mitigation Plan*, Apr. 15, 2005, p. I–46 ("Storm surge areas can be mapped by the probability of storm surge occurrences using Sea, Lake and Overland Surges from Hurricanes modeling (referred to as SLOSH modeling)… SLOSH models represent the storm surge of hundreds of simulated hurricanes, taking into account storm wind intensities, forward speeds, directions of motion, and radius of maximum winds.").

13 Testimony of Robert Sheets, Ph.D., Director, National Hurricane Center, before the U.S. Senate, Committee on Governmental Affairs, hearing on *Rebuilding FEMA: Preparing for the Next Disaster*, May 18, 1993, p. 45.

14 Written Statement of Max Mayfield, Ph.D., Director, National Hurricane Center, for the U.S. House, Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina, hearing on *Predicting Hurricanes: What We Knew About Katrina and When*, Sept. 22, 2005, p. 5. For instance, the NWS used reconnaissance aircraft equipped with Stepped Frequency Microwave Radiometer (SFMR) that collects data about hurricane structure, surface wind and rain rate. *See also:* Written Statement of Brig. Gen. Johnson, House Committee on Science hearing, Oct. 7, 2005, p. 3 NWS also uses hurricane monitoring buoys deployed in the Caribbean.

15 Committee staff interview of Max Mayfield, Ph.D., Director, National Hurricane Center, conducted on Jan. 27, 2006, transcript pp. 29-40.

16 For a detailed description of topography and economic development of the Louisiana Gulf Coast, *see: Southeast Louisiana Hurricane Preparedness Study*, Aug. 1994, pp. 1–2 through 1–5.

17 U.S Census Bureau, U.S. Census Bureau News, Newsroom "Almost 10 Million Gulf Coast Residents Bracing for Hurricane Dennis," press release, July 8, 2005. http://www.census.gov/PressRelease/www/releases/archives/hurricanes_tropical_storms/005345.html. Accessed on Jan. 27, 2006.

18 National Oceanic and Atmospheric Administration, "NOAA Attributes Recent Increase in Hurricane Activity to Naturally Occurring Multi-Decadal Climate Variability," *NOAA Magazine*, Nov. 29, 2005. http://www.magazine.noaa.gov/stories/mag184.htm. Accessed on Mar. 8, 2006 [hereinafter NOAA, "NOAA Attributes Recent Increase in Hurricane Activity to Naturally Occurring Multi-Decadal Climate Variability"].

19 Edward Tenner, *Why Things Bite Back: Technology and the Revenge of Unintended Consequences*, New York: Knopf, 1996, pp. 93-94.

20 Goldenberg, "The Recent Increase in Atlantic Hurricane Activity" pp. 474-479 ("The years 1995 to 2000 experienced the highest level of North Atlantic hurricane activity in the reliable record. Compared with the generally low activity of the previous 24 years (1971 to 1994), the past 6 years have seen a doubling of overall activity for the whole basin, a 2.5-fold increase in major hurricanes … five-fold increase in hurricanes affecting the Caribbean.").

21 National Weather Service, Climate Prediction Center, "Background Information: The North Atlantic Hurricane

Season." http://www.cpc.ncep.noaa.gov/products/outlooks/background_information.shtm. Accessed on Apr. 6, 2006. ("An average hurricane season features ten tropical storms (maximum sustained winds between 39-73 mph), of which an average of six become hurricanes (maximum sustained winds of at least 74 mph) and two become major hurricanes (maximum sustained winds exceeding 110 mph, categories 3-5 on the Saffir-Simpson scale).").

22 National Oceanic and Atmospheric Administration, National Climatic Data Center, National Environmental Satellite, Data, and Information Service, "Climate of 2005, Atlantic Hurricane Season." http://www.ncdc.noaa.gov/oa/climate/research/2005/hurricanes05.html. Accessed on Apr. 30, 2006. ("Tropical cyclone activity in the Atlantic basin has been above normal since 1995. This has been largely in response to the active phase of the multi-decadal signal. The average number of named storms since 1995 has been 13, compared to 8.6 during the preceding 25 years during which time the multi-decadal signal was in an inactive phase. An average of 7.7 hurricanes and 3.6 major hurricanes since 1995 compares to 5 hurricanes and 1.5 major hurricanes from 1970-1994. Characteristics of an active multi-decadal signal in the Atlantic include: warmer SSTs in the tropical Atlantic region, an amplified sub-tropical ridge at upper levels across the central and eastern North Atlantic, reduced vertical wind shear in the deep tropics over the central North Atlantic, and an African Easterly Jet (AEJ) that is favorable for promoting the development and intensification of tropical disturbances moving westward off the coast of Africa. Recent studies also indicate that in addition to this multi-decadal oscillation the destructive power of hurricanes has generally increased since the mid-1970s, when the period of the most rapid increase in global ocean and land temperatures began.").

23 Goldenberg, "The Recent Increase in Atlantic Hurricane Activity," pp. 476-477 ("The Caribbean Sea has shown dramatic changes in hurricane activity – averaging 1.7 occurrences per year during the warm periods compared with only 0.5 per year during the cold period (34). The current warm period has produced an average of 2.5 occurrences per year with an unprecedented (since 1944) six hurricanes in the region during 1996. … This means that during the next 10 to 40 years or so, most of the Atlantic hurricane seasons are likely to have above average activity, with many hyperactive, some around average, and only a few below average. Furthermore, consistent with experience since the active phase began in 1995, there would be a continuation of significantly increased numbers of hurricanes (and major hurricanes) affecting the Caribbean Sea and basin-wide numbers of major hurricanes.").

24 Goldenberg, "The Recent Increase in Atlantic Hurricane Activity," pp. 474-479 ("The greater activity results from simultaneous increases in North Atlantic sea-surface temperatures and decreases in vertical wind shear."). *See also:* NOAA, "NOAA Attributes Recent Increase in Hurricane Activity to Naturally Occurring Multi-Decadal Climate Variability" ("This era has been unfolding in the Atlantic since 1995, and is expected to continue for the next decade or perhaps longer. NOAA attributes this increased activity to natural occurring cycles in tropical climate patterns near the equator. These cycles, called 'the tropical multi-decadal signal,' typically last several decades (20 to 30 years or even longer). As a result, the North Atlantic experiences alternating decades long (20 to 30 year periods or even longer) of above normal or below normal hurricane seasons.").

25 National Oceanic and Atmospheric Administration, NOAA Coastal Services Center, "Hurricane History." http://www.nhc.noaa.gov/HAW2/english/history.shtml. Accessed on Apr. 16, 2006. Agnes was barely a hurricane at landfall in Florida, and the effects of winds and storm surges were relatively minor. The major impact was over the northeastern United States, where Agnes combined with the non-tropical low to produce widespread rains of 6 to 12 inches with local amounts of 14 to 19 inches. These rains produced widespread severe flooding from Virginia northward to New York, with other flooding occurring over the western portions of the Carolinas. Agnes caused 122 deaths in the United States. Nine of these were in Florida (mainly from severe thunderstorms) while the remainder were associated with the flooding. The storm was responsible for $2.1 billion in damage in the United States, the vast majority of which came from the flooding. Agnes also affected western Cuba, where seven additional deaths occurred.

26 Rappaport, *Preliminary Report: Hurricane Andrew* ("Andrew was a small and ferocious Cape Verde hurricane that wrought unprecedented economic devastation along a path through the northwestern Bahamas, the southern Florida peninsula, and south-central Louisiana. Damage in the United States is estimated to be near 25 billion, making Andrew the most expensive natural disaster in U.S. history.[1] The tropical cyclone struck southern Dade County, Florida, especially hard, with violent winds and storm surges characteristic of a category 4 hurricane (see addendum on upgrade to category 5) on the Saffir/Simpson Hurricane Scale, and with a central pressure (922 mb) that is the third lowest this century for a hurricane at landfall in the United States. In Dade County alone, the forces of Andrew resulted in 15 deaths and up to one-quarter million people left temporarily homeless. An additional 25 lives were lost in Dade County from the indirect effects of Andrew. The direct loss of life seems remarkably low considering the destruction caused by this hurricane.").

27 Goldenberg, "The Recent Increase in Atlantic Hurricane Activity," pp. 474-479.

28 John L. Guiney, National Hurricane Center, Preliminary Report: Hurricane George, 15 September – 01 October 1998, Jan. 5, 1999. http://www.nhc.noaa.gov/1998georges.html. Accessed on Apr. 26, 2006. ("Georges (pronounced Zhorzh) was the second deadliest and second strongest hurricane within the Atlantic basin during the 1998 season. Its 17 day journey resulted in seven landfalls, extending from the northeastern Caribbean to the coast of Mississippi, and 602 fatalities – mainly in the Dominican Republic and Haiti.").

29 Goldenberg, "The Recent Increase in Atlantic Hurricane Activity" p. 474 ("The years 1995 to 2000 experienced the highest level of North Atlantic hurricane activity in the reliable record. Compared with the generally low activity of the previous 24 years (1971 to 1994), the past 6 years have seen a doubling of overall activity for the whole basin, a 2.5-fold increase in major hurricanes (≥50 meters per second), and a twofold increase in hurricanes affecting the Caribbean. The greater activity results from simultaneous increases in North Atlantic sea-surface temperatures and decreases in vertical wind shear. Because these changes exhibit a multidecadal time scale, the present high level of hurricane activity is likely to persist for an additional ~ 10 to 40 years. The shift in climate calls for a reevaluation of preparedness and mitigation strategies.").

30 *See:* National Weather Service, Climate Prediction Center, "August 2004 Update to Atlantic Hurricane Season Outlook," Aug. 10, 2004. http://www.cpc.noaa.gov/products/outlooks/hurricane2004/August/hurricane.html.

31 National Oceanic and Atmospheric Administration, National Climatic Data Center, "Hurricane Katrina A Climatological Perspective," Oct. 2005, p. 23 ("The Accumulated Cyclone Energy Index is one method to describe trends in tropical cyclone activity. This index is a combination of the tropical cyclone's duration in a particular ocean basin, along with the strength of each storm.").

32 National Weather Service, Climate Prediction Center, "NOAA: 2003 Atlantic Hurricane Outlook," May 19, 2003. http://www.cpc.noaa.gov/products/outlooks/hurricane2003/May/hurricane.html. Accessed on April 5, 2006 ("This expected activity is considerably more than the four hurricanes and ACE value of 74% of the median observed during 2002. It is also much larger than the seasonal average of five hurricanes and ACE value of 75% of the median observed during the relatively quiet period 1970-1994.").

33 National Weather Service, Climate Prediction Center, "NOAA: 2003 Atlantic Hurricane Outlook Update," Aug, 7, 2003. http://www.cpc.noaa.gov/products/outlooks/hurricane2003/August/hurricane.html. Accessed on Apr. 4, 2006.

34 Isabel is considered to be one of the most significant tropical cyclones to affect portions of northeastern North Carolina and east-central Virginia since Hurricane Hazel in 1954 and the Chesapeake-Potomac Hurricane of 1933. Jack Bevin and Hugh Cobb, National Oceanic and Atmospheric Administration, "Tropical Cyclone Report for Hurricane Isabel 6 – 19 September 2003." Jan. 16, 2004. http://www.nhc.noaa.gov/2003isabel.shtml. Accessed on Apr. 14, 2006.

35 Gerald Bell, et al., "The 2004 North Atlantic Hurricane Season: A Climate Perspective," pp. 1-4. http://www.cpc.ncep.noaa.gov/products/expert_assessment/hurrsummary_2004.pdf#search='The%202004%20North%20Atlantic%20Hurricane%20Season%3A%20A%20Climate%20Perspective'. Accessed on Apr. 26, 2006 ("The 2004 Atlantic hurricane season had well above-normal activity, with 15 named storms, 9 hurricanes (H), and 6 major hurricanes [MH, defined as categories 3-5 on the Saffir-Simpson scale, Simpson (1974)]. Nine of these systems struck the continental United States, three as tropical storms (Bonnie, Hermine, and Matthew) and six as hurricanes (Alex, Charley, Frances, Gaston, Ivan, and Jeanne). Three of the hurricanes (Charley, Ivan, and Jeanne) hit as major hurricanes… MH Ivan, the strongest of the 2004 hurricanes, eventually made landfall in Alabama and produced the largest storm total ACE value (70.4 x 104 kt2) in the reliable record.").

36 National Weather Service, Climate Prediction Center, "NOAA: 2005 Atlantic Hurricane Outlook," May 16, 2005. http://www.cpc.noaa.gov/products/outlooks/hurricane2005/May/hurricane.html. Accessed on Apr. 4, 2006; Written Statement of Max Mayfield, Ph.D., Director, National Hurricane Center, for the U.S. Senate, Committee on Commerce, Science, and Transportation, hearing on *The Life Saving Role of Accurate Hurricane Prediction*, Sept. 20, 2005, p. 6 ("The natural cycles are quite large with on average 3-4 major hurricanes a year in active periods and only about 1-2 major hurricanes annually during quiet periods, with each period lasting 25-40 years.").

37 National Weather Service, Climate Prediction Center, "NOAA: 2005 Atlantic Hurricane Outlook," May 16, 2005. http://www.cpc.noaa.gov/products/outlooks/hurricane2005/May/hurricane.html. Accessed on Apr. 4, 2006.

38 National Weather Service, Climate Prediction Center, "NOAA: August 2005 Update to Atlantic Hurricane Season Outlook," Aug. 2, 2005. http://www.cpc.noaa.gov/products/outlooks/hurricane2005/August/hurricane.html. Accessed on Apr. 4, 2006 ("The predicted seasonal totals include the considerable activity that has already occurred prior to this update (7 tropical storms and 2 major hurricanes)...Of particular relevance to this outlook is that two July tropical systems, Major Hurricanes Dennis and Emily, formed over the eastern Caribbean Sea and over the central tropical Atlantic (near 10°N), respectively. It is rare for hurricanes to develop in these regions during July because the wind patterns are normally so unfavorable.").

39 National Oceanic and Atmospheric Administration, "August 2005 Update to Atlantic Hurricane Season Outlook," Aug. 2, 2005. http://www.cpc.noaa.gov/products/outlooks/hurricane2005/August/hurricane.html. Accessed on Apr. 4, 2006 ("The updated outlook calls for an extremely active season, with an expected seasonal total of 18-21 tropical storms (mean is 10), with 9-11 becoming hurricanes (mean is 6), and 5-7 of these becoming major hurricanes (mean is 2-3). The likely range of the ACE index for the season as a whole is 180%-270% of the median. The predicted seasonal totals include the considerable activity that has already occurred prior to this update (7 tropical storms and 2 major hurricanes). Therefore, for the remainder of the season, we expect an additional 11-14 tropical storms, with 7-9 becoming hurricanes, and 3-5 of these becoming major hurricanes. The expected ACE range during August-November is 110%-200% of the median. These very high levels of activity are comparable to those seen during August-November 2003 and 2004.").

40 Richard D. Knabb, Jamie R. Rhome, and Daniel P. Brown, National Hurricane Center, "Tropical Cyclone Report Hurricane Katrina 23-30 August 2005," Dec. 20, 2005, p. 1. http://www.nhc.noaa.gov/pdf/TCR-AL122005_Katrina.pdf#search='Tropical%20Cyclone%20Report%20Hurricane%20Katrina'. Accessed on Apr. 26, 2006.