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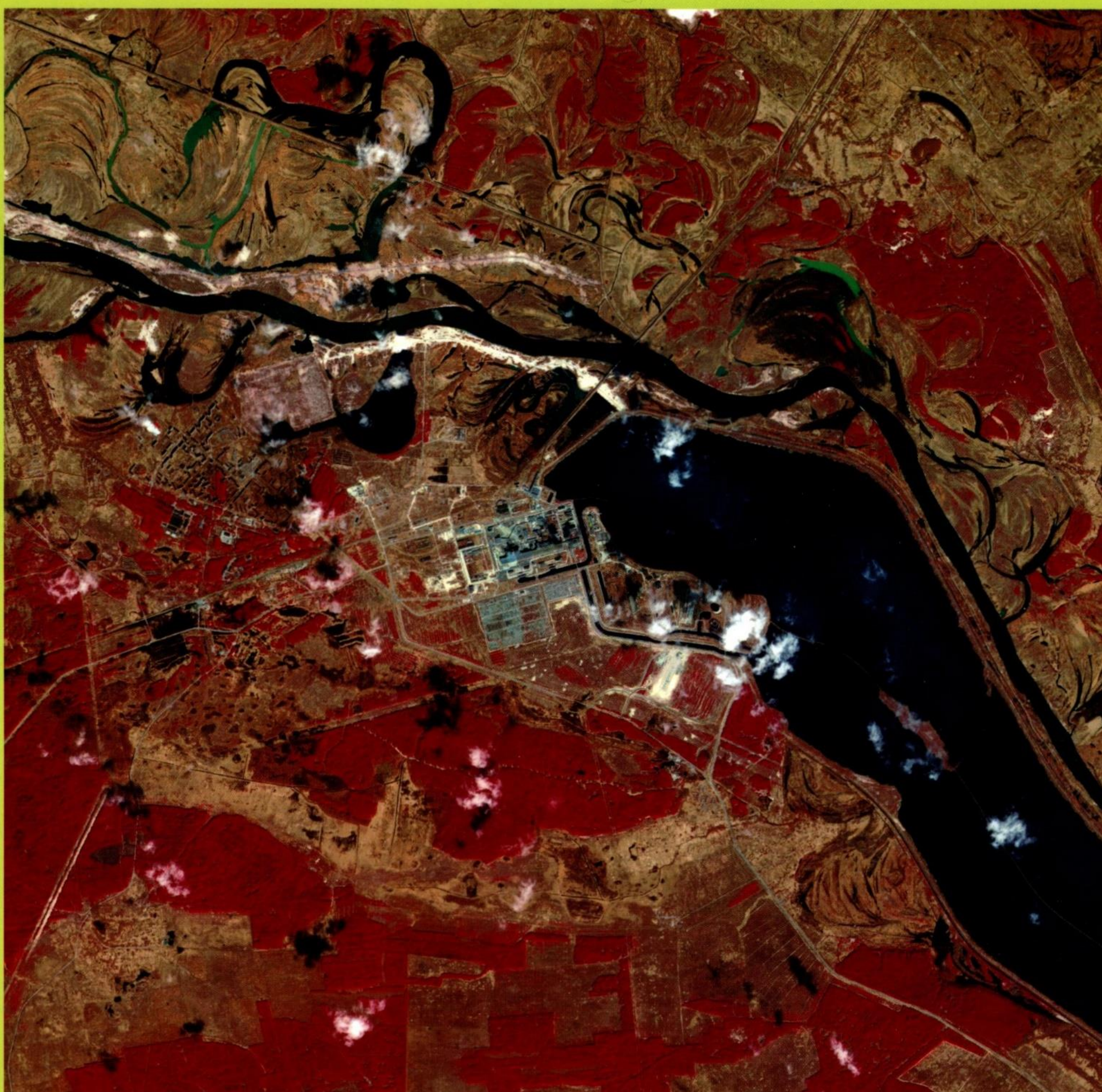

SPOT-5 Satellite Image of Chernobyl, 2006

This 2.5-m resolution image was acquired by SPOT-5 satellite on April 11, 2006

The Earth From Afar: Image Review

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Katrina: The "Big One" Arrived

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Katrina, an extremely powerful and catastrophic hurricane, caused a staggering amount of economic and environmental damage and killed an unknown number of people as it marched throughout the southeastern United States. This storm was the costliest and one of the deadliest reported hurricanes to batter North America.[1] For the people of southern Louisiana the long anticipated "Big One" had finally arrived (Baumann 2005). Through the use of a variety of remotely sensed imagery this report first tracks Katrina's movement and growth between August 23 and August 29, 2005 and then examines the storm's impact on New Orleans.

Katrina: Its Evolution

On August 23, 2005 a tropical depression formed from a wide low pressure system centered about 95 miles southeast of Nassau. The next day, the depression started moving slowly (near 7 mph) northwest through the central Bahamas developing into a minimal tropical storm. This depression became the eleventh named storm of the 2005 Atlantic Hurricane season and was given the name Katrina. By 11:50 a.m., Eastern Daylight Savings Time (EDT) the MODIS sensor on the Terra satellite captured its first image (Figure 1A) of the storm. Winds of 40 miles per hour (64 km/hr) were being measured and the recognizable swirling shape of a hurricane emerged. By all indicators, the storm was getting stronger as it neared the south Florida coast and most likely would become a Category 1 hurricane before reaching land (Knabb 2005).

Although the storm had the potential to become a

[1] The American Insurance Service Group reports the insured losses in the United States at $38.1 billion. The National Hurricane Center estimates the storm's total damages to be $75 billion, or about twice the insured losses. After adjusting for inflation, Katrina's total damage cost doubles that of Hurricane Andrew, making it the costliest hurricane to strike the United States (Knabb 2005 and Masters 2005). Known fatalities amount to over 1300 and thousands of Gulf Coast residents are still missing. Known loss of life makes Katrina one of the 5 most deadly hurricanes to ever strike the United States (Knabb 2005).

hurricane, concern centered more on the amount of rain it might generate rather than its winds. Katrina was a slow moving storm, just 8 mph (13 km/hr) and its forward speed was expected to slow down as it crossed land. These conditions were ideal for heavy rains, and in a low, flat state like Florida, major flooding was likely to occur. Expectations were 6-10 inches (15-25 cm) over south Florida with predictions for some areas amounting to as much as 15 inches (38 cm). In reality over 18 inches (46 cm) of rain fell in some areas of Florida, creating major flood conditions.

On August 25, Katrina came ashore between Hallandale Beach and North Miami Beach, Florida as a Category One hurricane and its impact was evident At 12:30 p.m. (EDT) MODIS recorded its second image (Figure 1B) of Katrina. The storm was over south Florida with winds still being clocked at 75 miles per hour (120 km/hr). At 7 p.m., nine deaths were attributed to the storm and 1.2 million people were without electricity. Along the southeast coast of Florida, Broward County recorded wind gusts as high as 92 mph (148 km/hr), and Miami-Dade County had more than a foot of rain. After its winds diminished briefly Katrina moved into the Gulf of Mexico and regained its hurricane strength. At this point the storm entered the first of two periods of rapid intensification - defined as a 34.5 mph (63 km/hr) or greater intensity increase within a 24-hour period. On August 26th the first period began when within one day the maximum sustained winds strengthened from 75 mph (120 km/hr) to 109 mph (176 km/hr) and Katrina was upgraded to a Category 2 hurricane (Figure 1C) (NASA 2005 and Knabb 2005).

At 4 p.m. August 26 the National Hurricane Center put out a warning that Katrina was expected to intensify to a dangerous Category 4 level and was moving toward the states of Mississippi and Louisiana. Hours later, the governors of those two states declared states of emergency. On the Saffir-Simpson scale a Category 4 storm has sustained winds between 131 and 155 mph (211-249 km/hr) and can create a storm surge of 13 to 18 feet (4 to 5 meters). It can do severe damage to permanent buildings, demolish mobile homes, and flood low coastal areas as far as 6 miles (9.6 kilometers) inland. The last time Mississippi or Louisiana experienced a Category 4 or stronger storm was in August 1969, when Hurricane Camille struck the Mississippi coast with winds in excess of 155 mph (249 km/hr).

By the morning of August 27, infrared satellite imagery clearly showed the development of an eye and Katrina was a Category 3 hurricane with 115 mph (185 km/hr) winds. Throughout the day the storm's inner eyewall weakened and a new, outer eyewall formed. As Katrina intensified and its inner eyewall deteriorated, the wind field significantly expanded resulting in the storm doubling in size on August 27. Storm-force winds extended 161 miles (259 km) from the center. Meteorologists were surprised at how fast the storm intensified over the warm water. Air pressure at the storm's center reached 902 millibars, one of the lowest pressures ever recorded.[2] At 8 a.m. Saturday, the eye of the hurricane was located about 430 miles southeast of the mouth of the Mississippi River and was moving northwest at nearly 7 mph (11.25 km/hr). The storm was also huge in area, covering nearly 90 percent of the Gulf with cloud cover (NASA, 2005)

The Louisiana State University's Earth Scan Laboratory created the image shown in Figure 2. The image was acquired from the GOES-12 satellite and shows water temperatures in both °F and °C. Darker shades of red represent increasingly higher measured temperatures. The very dark red along the Louisiana coastline represents temperatures in excess of 87°F (30°C). Hurricanes gain in strength as the water temperature increases. Superimposed on this image is the path of Katrina as it traveled across the Gulf of Mexico and at selected points along the path wind speeds in miles per hour are recorded. Figure 2 shows how on August 27, Katrina's winds increased from 104 to 115 mph (167-185 km/hr), making it a Category 3 hurricane.

By the morning of August 28, Katrina had become a powerful Category Five hurricane with sustained winds of 160 mph (257 km/hr). A new eyewall became a sharply defined ring and the second, more rapid intensification of winds occurred. Within twelve hours Katrina increased from a Category 3 to a Category 5 hurricane. Figure 2 shows that sustained winds had reached 173 mph (278 km/hr). It had acquired a tremendous amount of energy from the warm waters of the Gulf of Mexico. The August 27 MODIS image (Figure 1-D) shows Katrina heading westward from south Florida toward the Yucatan section of Mexico; however, computer models indicated that the storm would change course and move north. By the time the August 28 image (Figure 1-E) had been recorded, Katrina had turned northward. With its strongly developed eye and Category Five winds, Katrina was now on the doorstep of the mouth of the Mississippi River (Knabb 2005 and NASA 2005).

People residing in Louisiana's low-lying areas were ordered to evacuate. U.S. President Bush declared a state of emergency in Louisiana, even before Katrina arrived. People were leaving New Orleans, heading inland to higher locations. Cars were bumper-to-bumper and Interstates 10, 12, 55, and 59 were converted into one-way routes away from the city. The National Hurricane Center issued a warning that Katrina was on its way and landfall would occur within the next 24 hours, somewhere between Morgan City, Louisiana and the Alabama-Florida border.

At 10 a.m. (EDT) as Katrina's winds reached 175 mph (281 km/hr), the mayor of New Orleans ordered the first mandatory evacuations in the history of the city. The National Hurricane Center predicted that Katrina would come ashore

[2] This pressure level was the fourth lowest on record in the Atlantic Basin. Only Gilbert (1988) at 888mb, the Labor Day Hurricane (1935) at 892mb, and Allen (1980) at 899mb were lower. However, Katrina's record was soon surpassed by Rita (September 2005) at 897mb and Wilma (October 2005) at 882mb, making it the sixth lowest recorded pressure (Knabb 2005).

early the next day, August 29, with top sustained winds of 160 mph (257.5 km/hr) and storm surges of up to 25 feet (7.62 m). An estimated 1 million people had fled the city and its neighboring communities by the night of August 28. However, many people did not have the transportation or the funds to leave the city. These people had no choice but to stay in their homes or go to the only available shelter, the Louisiana Superdome (Knabb 2005).

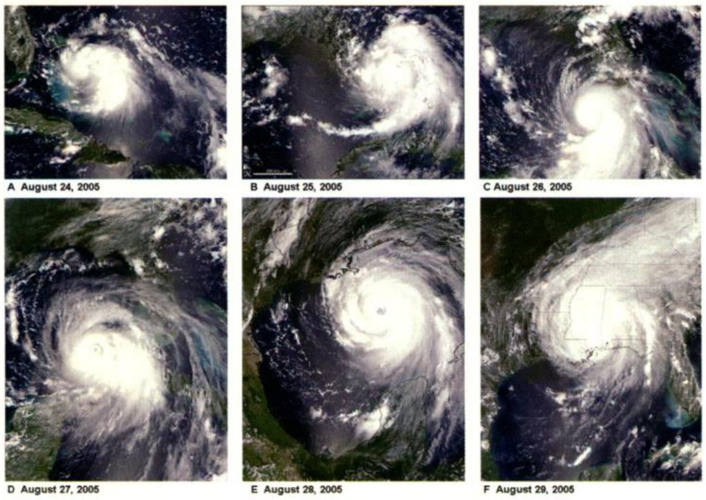

Figure 1A-F MODIS (Moderate Resolution Imaging Spectroradiometer) images of Katrina from August 24 to August 29, 2005. NASA images courtesy Jeff Schmaltz, MODIS Land Rapid Response Team at NASA GSFC.

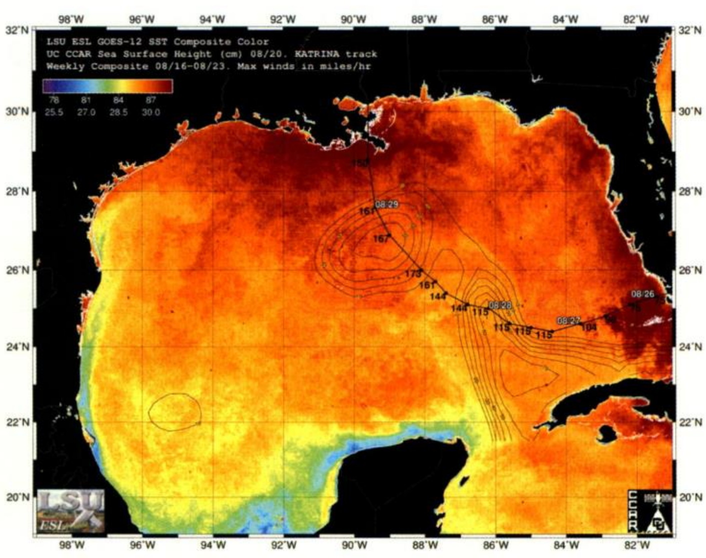

Figure 2 GOES-12 image showing the path and wind speeds across the Gulf of Mexico. Water temperatures provided in both °F and °C. Image developed at the Earth Scan Laboratory, Coastal Studies Institute, Louisiana State University.

A hurricane of this magnitude would generate storm surges greater than 18 ft (5.5 m), demolish many residential structures and large buildings, and flatten all trees, shrubs, and signs. Between 3-5 hours before the heart of the hurricane arrives, low-lying roads would be under water, eliminating them as escape routes. Severe damage would occur to all structures located below 15 ft (4.5 m) in elevation and within 500 yards (457 m) of the coast. These predictions were particularly alarming to New Orleans because most of the city is below sea level. Up to this point, only three known Category Five hurricanes had hit the United States.[3] It appeared that the Big One was on its way.

After three days from first entering the Gulf, Katrina arrived on land between Grand Isle, Louisiana and the mouth of the Mississippi River. Landfall was shortly after 7:00 a.m. (EDT) on August 29. Soon thereafter hurricane force winds reached New Orleans. Just before landfall Katrina weakened slightly to a Category 4 hurricane - a very typical condition for a storm as it encounters dry land air, slightly cooler sea surface temperatures near the coast, and the friction associated with crossing land (Masters 2005). Also, as the storm made landfall, its path shifted slightly to the east avoiding a direct hit on New Orleans. This shift placed the city on the storm's west side, which is frequently the weakest side of a hurricane. Initially it appeared that New Orleans once again dodged the Big One but the full consequences of the storm were yet to be felt.

By 10 p.m., more than 12 hours after making landfall, Katrina was downgraded to a regular tropical storm. It headed north toward Tennessee and the Ohio River Valley (Figure 1F), generating heavy rains, high winds, and tornadoes. One of the most powerful and devastating hurricanes to hit North America within the last century was in its final stages (NASA 2005).

Over New Orleans

Katrina's eye came within 20 miles east of downtown New Orleans. The sustained winds over the city and Lake Pontchartrain had likely weakened to a Category 3 storm. The actual wind intensity is not known since power failures shut down the Automated Surface Observing Stations (ASOS) prior to the peak winds. However, Katrina's winds created chaos over the city by damaging the roofs of approximately 105,000 buildings (U.S. Congress 2005) including ripping off large sections of the

[3] The three Category Five hurricanes were the Labor Day "Storm of the Century" hurricane in 1935 which was the strongest recorded storm to strike the U.S., Hurricane Camille in 1969 which came ashore in Mississippi and killed 256 people, and Hurricane Andrew in 1992 which until Katrina was the costliest U.S. hurricane on record, with $26.5 billion in losses (CNN 2005).

Superdome's roof, blowing out windows on high rise buildings, stripping off siding and doing severe structural damage to many homes, and downing thousands of trees, power lines, and signs. This damage is frequently overlooked by the flooding that occurred during and immediately after the storm.

Much of New Orleans rests below sea level with no natural means for being drained. Normal precipitation levels often cause local flooding within these areas of the city. A network of pumping stations and canals has been built to handle such flooding, which is designed to drain the water mainly into Lake Pontchartrain. Flooding from Katrina's rainfall was expected but the amount was not known. Also, flooding from water overtopping the levees and floodwalls was expected. The levees and floodwalls were designed to handle storms up to a fast-moving Category 3 hurricane (Carter 2005). Katrina was not a fast-moving Category 3 storm, and at times, was a Category 4 hurricane as it crossed southern Louisiana and coastal Mississippi.

Within a period of 51/2 to 6 hours Katrina dropped over 10 inches (25.4 cm) of rain on the city, causing flooding. Some pumping stations were overwhelmed. These stations are designed to handle 1 inch (2.54 cm) of rain within the first hour of a storm and 0.5 inches (1.27 cm) in the hours thereafter. Under these conditions a 10-inch (25.4-cm) rainfall would require 19 hours of pumping to get the water out of the city. Thus, more rain was falling than the stations could handle, leading to flooding. During this period hurricane winds were ripping through the city and storm surges were stretching the limits of the levees and floodwalls. In addition, debris was clogging the pumping stations' grates (drains the size of 2 to 3 average size houses). The grates must be clear of debris in order to allow the proper amount of water to enter the in-flow pipes, and thereby, permit the proper amount of water pressure for the pumps. Because this debris could not be removed during the storm, and for some time thereafter, certain pumping stations stopped operation to protect the pumps from being damaged. This situation led to additional flooding from heavy rainfall.

Figure 3 illustrates the heavy rain being carried by Katrina as it moved inland. This image was recorded on Sunday, August 28, 2005 at 10:25 PM EDT by the Tropical Rainfall Measuring Mission (TRMM) satellite. TRMM is a joint endeavor between NASA and the Japan Aerospace Exploration Agency (JAXA) designed to monitor and study tropical rainfall. This satellite is capable of observing below clouds to measure precipitation conditions. The various colors represent the amount of rainfall per hour, with blue being at least 0.25 inch (.64 cm), green 0.5 inch (1.27 cm), yellow 1.0 inch (2.54 cm), and red 2.0 inches (5.08 cm).

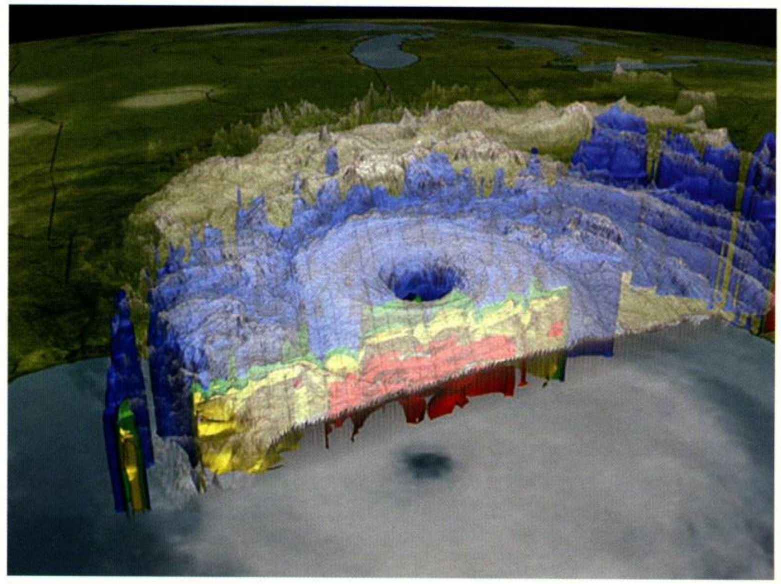

Figure 3 Three-D image of precipitation conditions in Katrina at 5:30 PM EDT (21:33 UTC) on Sunday, August 28, 2005. Taken by the Tropical Rainfall Measuring Mission (TRMM) satellite's PR (Precipitation Radar), VIRS (Visible Infrared Scanner), TMI (Tropical Microwave Imager) and the GOES spacecraft. Credit NASA and the Japan Aerospace Exploration Agency (JAXA)

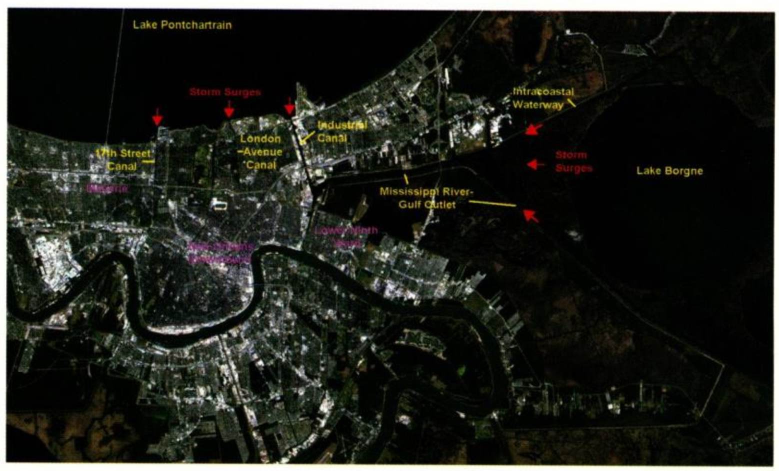

Figure 4 Landsat 7 true color composite image taken on November 18, 1999.

During the storm three major breaks in the levees-floodwalls protecting the city occurred. These breaks unleashed waves of water into the city shifting buildings off their foundations and inundating 100,000 homes or about 80 percent of the city to varying depths up to about 13 ft. (3.9 m). The breaks took place along three canals in different sections of the city. Although the specific times of these breaks are not known, they did occur on August 29. The 17th Street Canal break was 450 ft. (137 m) in length

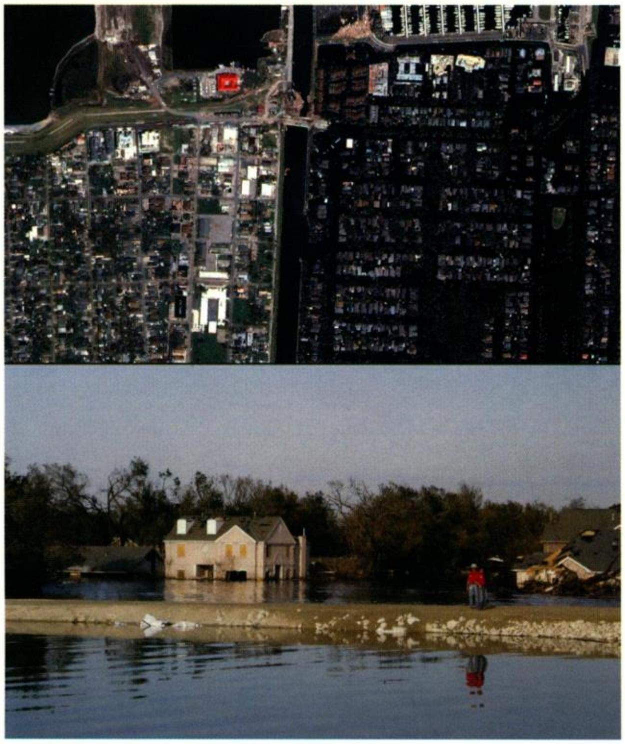

Figure 5 (Top) 17th Street Canal break near Hammond Highway Bridge. Water flows from canal into the Lakeview residential area. Natural color satellite image taken on September 3, 2005 - north up. Image provided by DigitalGlobe. (Bottom) 17th Street Canal levee with flooded homes in background. Ground level picture taken on September 7, 2005 by Liz Roll/FEMA.

and represented a breach in the levee-floodwall combination. This breach happened in the early morning hours, possibly before the center of the storm came ashore in Louisiana. Two sizeable breaks occurred in the Industrial Canal floodwall, one a 100-foot (30.5-m) breach and the other a 500-foot (152.4-m) breach. These breaks also occurred in the early morning hours. The London Avenue Canal floodwall had a 300-foot (91.4-m) breach that happened later in the day (Carter 2005). (See Figure 4.) In addition to these three major breaks, a number of smaller breaks also occurred.

The 17th Street Canal and the London Avenue Canal represent parts of the system that drains floodwater out of the city. Normally, water is pumped into these canals that drain into Lake Pontchartrain. However, as the water level in the lake increased due to the heavy rains followed by storm surges, water was pushed into the canals weakening the levees and floodwalls. At the same time the canals were trying to drain water into the lake. Residential conditions exist mainly along these canals where floodwater levels ranged between 10 and 13 ft. (3 m to 3.9 m). Most of the flood damage in these sections of the city impacted homeowners. Figure 5 is a satellite view (top) recorded on September 3, 2005 of the 17th Street canal and its breach and a ground level picture (bottom) taken on September 7, 2005 showing the water level around homes adjacent to the canal.

Figure 6 (Top) Industrial Canal break at N. Claiborne Avenue. Water flows from canal into the Lower Ninth Ward with barge near image center. Natural color satellite image taken on August 31, 2005 - north up. Image provided by DigitalGlobe. (Bottom) Low-oblique aerial photo taken on August 30, 2005 by Jocelyn Augustino/FEMA

A dramatic contrast occurred along the 17th Street Canal where floodwater poured into the Orleans Parish side of the canal while the Jefferson Parish side remained relatively dry. Also, the canal forms the political boundary between the cities of Metairie and New Orleans.

The Industrial Canal, officially called the Inner Harbor Navigation Canal, is an important link in the nation's inland waterway system. This canal connects together the Mississippi River, the Gulf Intracoastal Waterway (GIWW), the Mississippi River-Gulf Outlet (MRGO), and Lake Pontchartrain. Reports indicate that major storm surges came up the MRGO waterway, which links into the Industrial Canal at a southward angle, like a river tributary. The MRGO waterway was designed as a shortcut for ships to the Gulf of Mexico but its shallow depth today makes it little used as an outlet for large ships. The waterway forms a relatively straight path to the gulf, making it easy for storms to find their way to the city. (Warrick 2005) In contrast, the meandering nature of the Mississippi River makes it harder for the storm to reach the city. Joining the storm surges moving up the MRGO were surges pushing their way up the Intracoastal Waterway. Situated between the Intracoastal Water and the MRGO is Lake Borgne. Water blown from this lake enhanced the storm surges heading toward the Industrial Canal (Figure 4).

Although not fully confirmed the storm surges coming up the MRGO waterway may have pushed a poorly secured barge from the outlet into the Industrial Canal and this uncontrolled, free-moving barge may have collided with the floodwall, weakening it enough to form a large breach that eventually flooded the section of the city known as the Lower Ninth Ward (Filosa 2006). However, according to a study sponsored by the National Science Foundation a storm surge estimated at 18 to 25 feet (5.48 to 7.62 meters) breached the levee and the barge floated through the breach, destroying property in its path (Seed 2005).[4] Unlike the other canals, the Industrial Canal is lined with mainly dock facilities, warehouses, and factories. The one major exception is the Lower Ninth Ward, which is a residential area. Figure 6 provides a satellite view (top) of the Industrial Canal recorded on August 31, 2005 and a low-oblique aerial photograph (bottom) of the breach taken on August 30, 2005. The barge can be seen in both images where it went across the floodwall and slammed into homes in the flooded Lower Ninth Ward.

Summary and conclusions:

This paper summarizes the formation and impact of Hurricane Katrina on the southeastern United States with a particular focus on New Orleans. Satellite imagery and aerial photography provided crucial data in tracking this tragic natural event, as well as analyzing the extent and impact of the floodwaters and wind on this densely populated area. MODIS, GOES-12, Digital Globe, TRMM, Landsat imagery and low oblique aerial photography provided an array of illustrative perspectives on the hurricane's path, wind speeds, water temperatures, precipitation conditions, and pre and post hurricane impact.

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[4] The barge is evidence in several legal actions. Ingram Barge owns the barge but it was chartered by Lafarge North America to deliver cement. When Katrina hit, the cement had already been delivered; thus, who had legal control of the barge at the time of the storm needs to be determined. (Filosa 2006) Lafarge's insurance carriers had previously paid the company nearly $90 million for the loss of a cement plant in Aceh, Sumatra due to the 2004 tsunami (Baumann 2005) and do not want to endure additional losses due to Katrina.