Forensic Hurricane and Storm Surge Consulting

Brian R. Jarvinen
17120 SW 78th Avenue
Miami, Florida 33157-4811

REPORT

Meteorological and Storm Tide Analysis of Hurricane Katrina in Southeast Louisiana

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Executive Summary

The size and scope of Hurricane Katrina makes it one of the most catastrophic hurricane events in recorded U.S. weather history. The Gulf Coasts of Louisiana and Mississippi suffered the brunt of the hurricane, with record-breaking storm tide heights causing extreme to catastrophic damage to most established structures in its path.

The right-angle nature of the geographical and man-made features of the southeastern Louisiana and Mississippi coastlines contributed greatly to the extremely large storm tide values associated with Hurricane Katrina. In the past several decades, human construction of protective levee systems and altered waterways have been undertaken to provide a means of preventing complete inundation of inhabited areas in the parishes of southeast Louisiana, specifically around the Mississippi River and the city of New Orleans.

Hurricane Katrina made landfall at Buras, Louisiana, and then again at the mouth of the Pearl River, moving north at 18 mph, and possessing 120 to 125 mph sustained wind speeds. As the storm approached from the Gulf of Mexico, it weakened in terms of its maximum sustained wind speed, but expanded its wind field to extend hurricane force winds almost 100 miles from its center. The kinetic energy associated with this expansion was calculated to be an unprecedented 122 TJ (terajoule, or one trillion joules), allowing the storm to transfer a huge amount of energy to the ocean, providing another contributing factor to the higher storm tides.

Besides the geographical makeup of the impacted area and the size of the storm's wind field, there were four other major contributions that resulted in Hurricane Katrina's massive storm tide. First, the sustained wind speeds of 120 to125 mph during landfall allowed for the transfer of energy into the water for wave and current production. Next, Katrina's near-perpendicular track as it approached the coastline focused its wind field

over a large area during landfall. The third factor, the storm's speed of approach, resulted in additional wind energy being transferred to the water. Finally, the wide and shallow continental shelf bathymetry of the coastline areas in Katrina's path did not allow any room for the storm tide to move or dissipate, pushing it inland while piling it upward at the same time.

The storm tide generated by Hurricane Katrina caused extensive flooding throughout all of the areas affected by the storm. The combination of the storm tide and the superimposed wave field on top of it resulted in an unprecedented amount of water being pushed inland during the storm, causing many areas to remain flooded for several days after the storm's passing. In Mississippi, storm tides ranging from at least 18 to 28 feet occurred over 55 miles of coastline, establishing new record maximum storm tide heights at most of these locations. Similarly, in Louisiana, locations along several east-facing parish levee systems also established new record maximum storm tide heights. Nearly all of the protective levee systems were overtopped and damaged by the combination of storm tide and wind driven wave fields.

Hurricane Katrina's storm tide elevations exceeded both the SPH and PMH storm tide elevations for locations along the east facing levees of St. Bernard and Orleans Parishes.

CV Executive Summary

Brian Jarvinen is currently consulting on issues relating to hurricanes and hurricane storm surge. During his thirty-seven year career, he was head of the Storm Surge Unit at the National Hurricane Center and an operational hurricane forecaster. He is nationally recognized as an expert in hurricane storm surge and application of storm surge model results to hurricane evacuation studies for the United States coastal floodplain from Texas to Maine. He was the recipient of the Neil Frank Award in 1990 for his "pioneering leadership in storm surge research and in hurricane evacuation planning in coastal areas of the United States."

His educational background includes a B.S. in Meteorology from Florida State University (FSU) an M.S. degree in Tropical Meteorology from FSU, and some graduate studies towards a Ph. D at FSU. He has authored many articles, both individually and jointly, during his career.

He has been recognized as a hurricane and storm surge expert in numerous depositions, a number of trials, both criminal and civil, as well as a State of Florida Administration Hearing since his retirement from the National Hurricane Center in 2005.

My hourly rate for work on this project is $350.00 per hour.

Introduction

The purpose of this report is to describe the meteorological and storm tide impact of Hurricane Katrina on the southeast Louisiana and Mississippi coastal region. The report begins with a geographical description of the region, including the components that make up the hurricane flood protection system in southeast Louisiana. Next is an overview of Hurricane Katrina's meteorology including kinetic energy, followed by a discussion of hurricane storm tide. Finally is a description of the storm tide in the region including Katrina's storm tide in a historical perspective and its comparison to the Standard Project Hurricane and Probable Maximum Hurricane for the New Orleans area and the Saffir – Simpson Hurricane scale. The summary of my opinions is also stated and the documents that were used to formulate my opinions are listed under the References section of this report.

Graphical Figures 1-11 are part of this report and are attached as a separate file.

I. Description of Region

This section describes the geography of southeast Louisiana. Figure 1 shows a map of the area. The area consists of marsh and wooded swamps with the Mississippi River meandering through and then flowing into the Gulf of Mexico. The elevated Mississippi River banks divide the region into two sections, an east and west bank. There is one large lake, Lake Pontchartrain, located on the east side of the river. A smaller lake, Lake Borgne, is located to the southeast of Lake Pontchartrain and is connected to it by two deep channels called the Pass Chef Manteur and the Pass Rigolets. Lake Borgne, in turn, is connected to Mississippi Sound directly on its east side and to both the Breton and Chandeleur Sounds through marsh areas. The depths in these water bodies are very shallow with Lake Pontchartrain ranging from 1 to 15 feet, Lake Borgne and Mississippi Sound ranging from 1 to 12 feet, and Breton and Chandeleur Sounds ranging from 1 to 20 feet. In addition, there are many bayous, small lakes and bays throughout the region. New Orleans is the largest city in the region and is surrounded by numerous smaller incorporated areas and cities. The Parish boundaries are also highlighted in the figure.

The area also includes many man-made dredged canals and waterways. Due to periodic Mississippi River flooding and hurricane storm tide flooding, levees and floodwalls have been built to protect most of the inhabited areas. The current flood control system for the region is shown in Figures 2 and 3. The levees protecting the various towns and communities in Plaquemines Parish are termed ring levees.

The natural geography of the area plus the addition of man-made barriers has created a unique situation. The Mississippi coastline, the CSX railroad embankment and the levee system on the south side of East Orleans Parish form a barrier that parallels the coast from Biloxi, Mississippi, to New Orleans (Figure 4). Limited openings for water to pass

through are the entrances to St. Louis Bay, the Pearl River and the Pass Chef Manteur and Pass Rigolets channels mentioned above. The lowest elevation along this barrier is the CSX railroad embankment at about 11 to 12 feet above sea level. From New Orleans the levees along the Mississippi River form another barrier extending to Venice, Louisiana, near the southernmost section of Plaquemines Parish. At New Orleans the river levees are 25 feet above sea level and gradually decrease to about 15 feet at Venice. These two barriers form an approximate right angle or "corner" along the coastline that can trap water during tropical cyclone events (Figure 5).

II. Hurricane Katrina's Meteorology

A comprehensive account of Hurricane Katrina is contained in the NHC report. The report includes the 'best track' of Hurricane Katrina -- that is, the NHC's official estimate of three characteristics of the storm: location of center, maximum one-minute surface wind speed, and minimum central sea-level pressure. The best track estimates are based on all available information, including surface observations, satellite, radar and aircraft reconnaissance data. Katrina's track, superimposed on a satellite photograph of the hurricane taken at its maximum intensity, is shown in Figure 6.

Hurricane Katrina originated from the interaction of a tropical wave and the remnants of a tropical depression. The resulting weather system developed into a tropical depression on August 23, 2005, over the southeastern Bahamas. The depression gradually strengthened while moving northwestward over the Bahamas, reaching tropical storm status on 24 August and then category-one hurricane status on the Saffir-Simpson Hurricane Scale (SSHS) with maximum sustained winds of 80 mph late on 25 August. Turning west-southwestward, Katrina's center made landfall on the southeastern Florida coast shortly thereafter.

Katrina weakened to a tropical storm over south Florida, but quickly regained hurricane strength over the waters of the southeastern Gulf of Mexico on 26 August. During the next two days under highly favorable environmental conditions, Katrina strengthened from a minimal category-one hurricane to a category-five hurricane. It reached its peak intensity with maximum sustained (one-minute) surface wind speeds of 175 mph on the afternoon of 28 August while centered over the north-central Gulf of Mexico (Figure 6). During this same period, Katrina's wind field greatly expanded and by late on 28 August, tropical storm-force winds extended out about 225 miles from the center and hurricane force winds extended out about 100 miles. The hurricane turned northward and began a weakening phase during the last 17 hours before landfall.

The center, or eye, of Katrina made its first landfall in the northern Gulf of Mexico when it moved over the Mississippi River delta near Buras, Louisiana, on the morning of 29 August as a category-three hurricane with 125 mph sustained winds located to the east of the center. A few hours later, the center made a final landfall near the mouth of the Pearl River at the Louisiana/Mississippi border with sustained wind speeds estimated near 120 mph (also category-three) by the National Hurricane Center (Figure 7). The hurricane continued moving inland on a northward course at 18 mph, and weakened to a tropical

storm late on 29 August over central Mississippi. By late on 30 August, Katrina had weakened to a depression over the Tennessee Valley and was later absorbed by a frontal system.

1. Kinetic Energy

Another estimate of a hurricane's strength is to calculate the total kinetic energy that is present in the wind field that encircles the hurricane. Kinetic energy is defined as the energy of a body because of its velocity and mass. The kinetic energy (KE) of a body is given by:

$$KE = \frac{1}{2} mv^2$$

where m is its mass and v is its velocity. In a hurricane the mass of air at a particular level will remain approximately constant, so that the KE of the air is directly proportional to the square of the wind velocity. For example, assume that you are at a location some distance from the center of a hurricane and the wind speed is blowing at 40 mph (minimal tropical storm strength). The KE would be ½m(1600) or 800m. Now assume that the hurricane's wind field expanded resulting in the wind speed at the same location doubling to 80 mph (minimal hurricane strength). The KE would be ½m(6400) or 3200m. At our location, doubling the wind speed did not double the KE but increased it by a factor of four. This is important because storm surge generation is created by winds blowing on the surface of the water and transferring energy into the water. This means of transferring energy is called wind stress. Wind stress like the KE is a function of the square of the wind speed. Thus, as the wind speed doubles at a location the wind stress would increase by a factor of four and the storm surge would increase.

The expansion of the wind field in Katrina in the northern Gulf of Mexico resulted in an increase in the kinetic energy of the hurricane. A study by Maclay (6) looked at the kinetic energy for all U. S. landfalling hurricanes from 1995 to 2005 including hurricane Katrina. Figure 8 is from this study and shows a plot of kinetic energy versus maximum sustained wind speed for each hurricane. Some hurricanes, including Katrina, have 2 values because they made two landfalls. The first value labeled Katrina (1) was calculated for the landfall in southeast Florida where the hurricane was a category 1. The second value labeled Katrina (2) was calculated for the northern Gulf of Mexico landfall where Katrina was a category 3. Of special note is that Katrina has the highest kinetic energy value when compared to all other hurricanes including hurricane Charley (1) which was a category 4 hurricane when it made landfall on the southwest Florida coastline. Even though Charley had a higher maximum sustained wind speed than Katrina, it was a very small hurricane with hurricane force winds extending only about 25 miles from the center compared to Katrina's 100 miles. Other notable hurricanes of similar maximum sustained wind speeds but smaller kinetic energy values are Ivan '04, Rita '05 and Wilma '05. All three of these hurricanes were large at landfall, although not as large as Katrina. Since the wind field transfers kinetic energy to the sea surface, hurricane Katrina transferred high values of kinetic energy to the sea surface during its landfall along the northern Gulf of Mexico coastline and is one of the main reasons for

the record storm surge elevations that occurred. In another study, Powell and Reinhold (7), compared the integrated kinetic energy of hurricanes Katrina and Camille (1969) at landfall. Hurricane Camille was a category 5 on the SSHS that made landfall near the mouth of St Louis Bay. The study showed that Camille had 63 TJ[1] units of integrated kinetic energy compared to 122 TJ units for Katrina, almost twice as much. Similar to hurricane Charley, Camille had a much smaller hurricane force wind field then Katrina. Figure 9 is from a NOAA National Climatic Data Center report (5) on hurricane Katrina and is a satellite comparison between hurricanes Camille and Katrina. The larger aerial extent of Katrina is evident as well as the much larger eye.

2. Wind Speed

Katrina was likely a category-four hurricane with maximum sustained winds of about 135 mph a couple of hours before the center made landfall near Buras, Louisiana, but weakened to category-three at the time of landfall. The best track maximum one-minute wind speeds at the time of the landfalls at Buras and the mouth of the Pearl River were 125 mph and 120 mph, respectively. Based upon NOAA Hurricane Research Division (HRD) Hurricane Wind (H*Wind) analyses of the 1-minute 33-foot wind speeds of Katrina, it is estimated that the sustained winds were 110 to 125 mph in the lower part of Plaquemines Parish, 100 to 115 mph in upper Plaquemines and 90 to 100 mph over St. Bernard and East Orleans Parishes. Estimated maximum sustained winds over New Orleans and Lake Pontchartrain were 75 to 90 mph. A H*Wind analysis for hurricane Katrina at 0700 CDT on 29 August, 2005, is shown in Figure 10. The eye of the hurricane is centered in the figure and is located over Plaquemines Parish. The contours are wind speed in knots and are analyzed at 5 knot intervals. The analysis shows that the strongest winds are located to the east of the center and are about 105 knots or approximately 120 mph. The white arrows represent wind direction, which is blowing counter-clockwise. The figure shows the expansive hurricane wind field blowing from the south and southeast into the “corner”, as mentioned previously in this report, and had the effect of piling water into that “corner”.

3. Central Pressure

Central pressure, measured in the eye, is another gauge of a hurricane’s intensity (generally, the lower the central pressure - the stronger the hurricane.) Although Saffir-Simpson categories are based on maximum sustained winds, hurricanes of a given category typically are associated with certain ranges of central pressure. For example, central pressures lower than 920 mb would usually be associated with a category-five hurricane. Katrina’s central pressure dropped rapidly to 902 mb on the afternoon of 28 August, when the center of the hurricane was about 225 miles south of southeastern Louisiana, 17 hours from landfall. The central pressure had risen to 920 mb at landfall near Buras, Louisiana. The central pressure continued to rise and was 928 mb at the Pearl River landfall. This value would normally be associated with a category-four hurricane but the maximum winds indicated that Katrina was a category-three hurricane

[1] TJ is an abbreviation for terajoule, which is a metric unit of energy equal to one trillion joules. One TJ equals approximately 948 million Btu (British Thermal Unit).

at this point. The reason is that the maximum pressure gradient (the rate of change of pressure with distance from the eye), which is correlated with the wind speed, had begun to weaken and spread outward as Katrina approached land. This resulted in a decrease of the maximum wind speed, but caused an expansion of the area affected by hurricane force winds.

Katrina's 902 mb pressure on 28 August is the sixth lowest on record in the Atlantic basin, surpassed only by Wilma (882 mb in 2005), Gilbert (888 mb in 1988), the Labor Day Hurricane of 1935 (892 mb), Rita (897 mb in 2005), and Allen (899 mb in 1980). Even though the hurricane had weakened from category-five to three at landfall near Buras, Louisiana, the central pressure of 920 mb is still the third lowest on record for a U.S. landfall, behind Camille (909 mb in 1969) and the Labor Day Hurricane (892 mb in 1935).

4. Rainfall

Rainfall totals were as high as 12 inches over parts of southeastern Louisiana and up to 10 inches over southwestern Mississippi.

III. Hurricane Storm Surge-Storm Tide Discussion

Hurricane storm surge is the abnormal rise of water caused by the wind and pressure forces in a hurricane. The dominant of these two forces is the wind. Some of the wind's kinetic energy is transferred to the water to form waves. The waves, in turn, transfer some of their energy downward to form currents. In the deep ocean these currents rotate about the hurricane with little effect on water elevation. However, as the hurricane tracks toward a coastline and encounters the continental shelf, the currents, especially on the right side of the hurricane, begin to be slowed and compressed resulting in a rise of water on the continental shelf, which is the storm surge. The rise of water on the continental shelf includes the rise of water along the shoreline. As the hurricane moves across the continental shelf toward landfall the process continues and the height of the storm surge increases. Generally, the peak of the storm surge occurs within plus or minus one hour of landfall or the time of closest approach of the center to a location. In addition, the funneling or squeezing effect of bays and estuaries enhances the storm surge and in many cases the maximum heights are found at the heads of these bays and estuaries. Because a hurricane's wind field encompasses a large area, the storm surge also covers a large area. The highest storm surge elevation along a coastal region generally occurs where the strongest winds are blowing onshore. This is typically in the eyewall region.

The height of the storm surge at any coastal location is a function of six factors; intensity, size, angle of approach, speed of approach, bathymetry and coastal shape.

1. Intensity

Two measures of intensity of a hurricane are the maximum sustained 1-minute winds at the surface and the sea-level pressure in the center or eye. Generally, as the sea-level

pressure decreases the maximum sustained winds increase. Although the Saffir-Simpson Hurricane Scale (SSHS) identifies sustained wind speed and pressure ranges for the various categories, only the sustained wind speed is used to determine the scale number for that particular hurricane. **Since the wind is the dominant force in generating storm surge, an increase in the sustained wind speed will result in an increase in the storm surge.**

2. Size

There are several parameters that are used to determine the size of a hurricane; radius of maximum winds (RMW), radius of the hurricane force winds, radius of the tropical storm force winds and the radius of the 1000 millibar contour. The zero point of the various radii is the center of the hurricane. The radial distances are used because the hurricane is similar to a counter-clockwise turning cylinder. The RMW is the distance from the center of the hurricane to the strongest or maximum winds. These winds are generally found in the eye-wall region of the hurricane. If the central sea-level pressure remains constant, a hurricane with a large RMW will generate a storm surge over a much greater coastal area and a greater maximum value then a small RMW. This result is somewhat of a paradox because the hurricane with the smaller RMW will have a greater maximum sustained wind speed than the hurricane with the large RMW. The amount of kinetic energy that the wind imparts to the water to generate storm surge is a function of the square of the wind speed. **In a hurricane with a large RMW the total amount of kinetic energy that is imparted to the sea-surface is much greater than the total kinetic energy imparted with the small RMW.**

3. Angle and Speed of Approach

A hurricane making landfall normal, or perpendicular, to a coastline (i.e. 90 degrees) will generate a higher storm surge than a hurricane making landfall at other angles (for example 45 degrees to the coastline). As the speed of approach of the hurricane increases the storm surge will increase on the outer coastal areas. This results because the speed of the approach of the hurricane adds to the sustained winds on the right-hand side of the hurricane imparting greater kinetic energy into the water. The faster forward speeds produce higher storm surges but the surges have a shorter duration. Slower moving hurricanes produce lesser storm surge heights on the outer coast but can produce higher surges in lakes, bays and estuaries because the surge has time to flow into these water bodies.

4. Bathymetry

The width and slope of the continental shelf are also important factors in determining the height of the storm surge. **A wide and shallow continental shelf will produce higher storm surge elevations than a short and steep shelf.** The reason is that the short and steep shelf is somewhat similar to the deep ocean where wind generated surge is small. A wide and shallow continental shelf traps the storm surge forcing the water to rise up to higher elevations.

5. Coastal Shape

Outer coastal shorelines that have a concave curvature tend to produce higher storm surge values than straight-line coastal shorelines. Also, coastal configurations that form a right angle can produce very high storm surge values compared to straight-line coasts. There are three of these areas along the U. S. Atlantic and Gulf of Mexico coastlines. They are the right angle formed by New Jersey and Long Island, the right angle formed by the big bend on the Florida Gulf of Mexico coastline **and the right angle formed by the Mississippi River Delta in Louisiana and the Gulf of Mexico coastline of the State of Mississippi.**

6. Storm Tide, Waves and Vertical Datum

Storm tide is defined as the combination of the astronomical tide and the storm surge. Superimposed on the storm tide are wind generated waves which produce forces on structures as well as scouring effects. Of particular concern, are their effect on man-made levees and floodwalls in southeast Louisiana. NAVD88 is a vertical datum established by the National Geodetic Survey so that the heights of land, structures, and water surfaces all have a common reference.

IV. Hurricane Katrina's Storm Tide

Katrina's massive and extensive storm tide in Southeast Louisiana and Mississippi can be explained by the six factors just discussed. One, the intensity was a category 4 hurricane weakening to a strong category 3 hurricane during the traverse across the continental shelf to landfall. Two, the hurricane was large, with a RMW that varied by quadrant. In the right front or northeast quadrant the RMW was approximately 24 nautical miles (28 statute miles) and in the right rear or southeast quadrant the RMW was approximately 34 nautical miles (39 statute miles) during landfall. At the Mississippi landfall, sustained hurricane force winds were measured as far east as Dauphin Island, Alabama, a distance of approximately 100 miles from the center. Three, the hurricane was moving north or approximately perpendicular to the coastline. Four, it was moving at about 18 mph during landfall. Five, the continental shelf is shallow and broad in this area. Six, the hurricane track was optimum for driving water into the "corner" (see Figures 5 and 7). In addition, the maximum storm surge occurred near the time of high tide. This added approximately another foot to the water elevations.

1. Storm tide heights in southeast Louisiana

Katrina generated maximum observed storm tide heights of 10-18 feet above NAVD88 at many coastal areas adjacent to Breton Sound, Lake Borgne and Lake Pontchartrain. Waves superimposed on the storm tide added to these heights in many locations. Significant storm tide and wave overtopping occurred at many of the federal and parish constructed levees. Due to Katrina's extensive hurricane force wind field as shown in Figure 10, the storm tide rose rapidly over the entire Louisiana coastal area at nearly the

same time. Based upon eye-witness accounts and numerical storm surge models the peak storm tide occurred in middle Plaquemines Parish at approximately 0730 CDT, in St. Bernard Parish one hour later at 0830 CDT and in East Orleans Parish at 0845 CDT; all within one hour and 15 minutes.

Katrina's measured storm tide elevations along the east facing levees of St. Bernard and Orleans Parishes are the highest ever recorded for these locations compared to other hurricanes going back to 1909. In Plaquemines Parish, Hurricane Betsy (1965) a category 3 hurricane generated an observed maximum of 15.7 feet near Pointe-a-la-Hache (8). High water measurements for Katrina near Pointe-a-la Hache are 13 to 14 feet. However, inspection of the descriptions of the marks shows that these are measurements of wrack lines (marsh grass mixed with debris) on the sides of the levees. Since the levees were overtopped in this area these wrack lines were likely deposited as the water was going down. Just up river from this location are wrack lines on the side of the levee with values of 16.1 and 16.2 feet and a little further north is a wrack line of 17.0 feet on the river levee. It is very likely that the storm tide maximums in Plaquemines Parish reached at least 17 feet and possibly higher.

2. Storm tide heights in Mississippi

Katrina generated maximum observed storm tide heights of 18-28 feet above NAVD88 along the Mississippi coast. The maximum storm tide heights of 18 feet or greater covered a 55-mile wide swath that extended eastward from western Hancock County through all of Harrison County to near the town of Gautier in central Jackson County. The storm tide heights decreased eastward from Gautier, but 10-15 foot heights were still measured as far as the Alabama coast, 15 miles further east. The storm tide penetrated up to six miles overland and 12 miles up bays and rivers over portions of coastal Mississippi.

Katrina's measured maximum storm tide elevations of 18-28 feet in Mississippi are the highest ever recorded along the United States Gulf of Mexico and Atlantic coastlines. Hurricane Carla (1961), a category 4 hurricane on the Saffir-Simpson Scale, generated an observed maximum of 22.0 feet inside Matagorda Bay, Texas. Hurricane Hugo (1989), also a category 4 hurricane, generated an observed maximum of 20.1 feet near Awendaw, South Carolina. Hurricane Camille (1969), a small intense category 5 hurricane, generated an observed maximum inside high water mark of 22.6 feet in Pass Christian, Mississippi (an outside mark of 24.6 feet was also recorded nearby) (9). Since Hurricanes Katrina and Camille made landfall near the same location a comparison of the observed coastal high water mark profiles can be made (Figure 11). Of interest is that Katrina's large RMW placed the strongest winds near Pass Christian, Mississippi. Camille had an RMW of approximately 7 miles and because it made landfall east of Katrina's landfall location its strongest winds were also near Pass Christian. The area inside of the RMW (i.e. area inside the eye) of each hurricane can give a feel for the size difference. The area inside of Camille's RMW was 154 square miles and Katrina's was 2462 square miles (using a conservative 28 statute miles for the RMW). Katrina's eye area was 16 times larger than that of Camille.

3. Standard Project Hurricane versus Katrina

The standard project hurricane, SPH, is a hypothetical hurricane that is intended to represent the most severe combination of hurricane meteorological parameters that is reasonably characteristic of a specified geographic region. From the SPH meteorological parameters, the SPH storm surge can be calculated. The height of the hurricane generated storm surge is the critical factor. This is mainly dependent on the speed and direction of winds as a hurricane nears and enters the coast. Thus, the most important parameter of the SPH is the hurricane wind field. The SPH is intended as a practicable expression of the maximum degree of protection that should be used as a general rule during the planning and designing of coastal structures for the protection of human life and minimizing of property destruction.

In order to determine the hurricane wind field, the following SPH parameters are required:

1. Central Pressure Index (CPI). This is the lowest sea-level pressure at the storm center.

2. Peripheral Pressure (Pn). This is the sea-level pressure at the outer limits of the hurricane wind circulation.

3. Radius of Maximum Wind (RMW). This is the radial distance from the hurricane center to the location of the highest winds.

4. Forward Speed (T). This is the rate of translation or movement of the hurricane center from one geographical point to another.

Based upon hurricane climatological data from 1900 to 1956, the U.S. Army Corps of Engineers in cooperation with the U.S. Weather Bureau determined meteorological parameters for the SPH for the coastal region of Louisiana. The parameters are a central pressure index, CPI, of 27.6 inches of mercury (935 millibars) , a Pn of 29.92 inches (1013 mb), a maximum 10-minute average wind velocity of 100 mph at a radius of 30 nautical miles (approximately 35 statute miles) and a forward speed that can be slow (approximately 5 mph), medium(approximately 12 mph) or high(approximately 30 mph).

Note: Based on recent detailed measurements of hurricane wind speeds in many hurricanes, a statistical relationship between the 10-minute and 1-minute average wind speeds has been established and is V(1-min) = 1.12V(10-min). Thus, the 100 mph 10-minute wind speed equates to an estimated 112 mph 1-minute wind speed. This is a category 3 wind speed on the Saffir-Simpson Hurricane Scale.

How did Katrina's observed meteorological parameters compare to the SPH values?

Hurricane Katrina's observed landfall parameters in southeast Louisiana were: CPI of 918 millibars south of Buras, LA to 928 millibars at the Pearl River landfall. Average of

923 millibars. Peripheral pressure of 1012 millibars. Maximum 1-minute sustained wind of 125 mph near Buras and 120 mph at the Pearl River landfall. Average of 123 mph. Radius of the maximum wind (in right rear quadrant) of 38 nautical miles near Buras to 30 nautical miles near the Pearl River landfall. Average of 34 nautical miles. Forward speed of 18 mph during landfall. Table 1 is a comparison of the SPH and Katrina meteorological parameters.

Table 1

Parameter	SPH	Katrina
CPI	935 mb	923 mb
Pn	1013 mb	1012 mb
RMW	30 nm	34 nm
T	5-30 mph	18 mph
Max 1-min wind	112 mph	123 mph

Katrina was stronger than the SPH as noted by the lower CPI and higher maximum 1-minute wind speed and slightly larger, as noted by the RMW comparison. The 18 mph translation speed of hurricane Katrina during landfall is above the average of about 13 mph based on the climatological record.

In 1956, the SPH wind surge computations were done by hand using a parametric equation that related wind surge height to wind speed, wind direction, fetch of the wind and average depth of the fetch. Additional water height adjustments were made for the inverted barometer effect, pressure differential in the water surface and astronomical tide (high tide condition). The SPH storm surges were calculated for several locations in Louisiana and are listed in Table 2. Also listed in Table 2 are the observed Katrina values at the same locations.

Table 2

SPH calculated storm tide (ST) heights and Katrina observed storm tide (ST) heights (NAVD88) for several locations in southeast Louisiana.

Location	SPH (ft)	Katrina (ft)
S. Shore of Lake Pontchartrain	11.2	9-13
Mandeville	12.5	8-9
Chamette area	11.9	17-18
Citrus and New Orleans East	12.5	15-18
Rigolets and Chef Menteur Pass	13.0	17-18

Table 2 shows that Katrina exceeded the SPH storm tide heights in the Chamette area, Citrus, New Orleans East and the Rigolets and Chef Menteur Pass. On the S. Shore of

Lake Pontchartrain it exceeded the SPH heights in many locations. Katrina did not exceed the SPH values for Mandeville.

Based upon the comparisons in Table 1, it is quite clear that Katrina had a lower central pressure, a higher maximum 1-minute wind speed and a larger RMW than the values used for the SPH. Because of this and the method of computation used in 1956, Katrina exceeded the SPH storm tide values in locations along the east facing levees in St. Bernard and Orleans parishes as shown in Table 2.

4. Probable Maximum Hurricane versus Katrina

The probable maximum hurricane, PMH, is a hypothetical hurricane that is intended to represent the worst combination of hurricane meteorological parameters that is reasonably characteristic of a specified geographic region. From the PMH meteorological parameters, the PMH storm surge can be calculated.

Table 3 lists the PMH meteorological parameters along with the Katrina values.

Table 3

Parameter	PMH	Katrina
CPI	911 mb	923 mb
Pn	1013 mb	1012 mb
RMW	30 nm	34 nm
T	5-30 mph	18 mph
Max 1-min wind	129 mph	123 mph

Table 3 shows that the PMH CPI was lower than Katrina and is near the CPI of 909 millibars that was recorded in Hurricane Camille (1969) at landfall along the Mississippi coast near Bay St. Louis. The PMH maximum 1-minute sustained wind is 6 mph higher than Katrina. Because of the very small RMW in Camille the maximum 1- minute sustained winds were estimated at 190 mph.

Table 4 lists the PMH calculated storm tide heights for selected locations and Katrina values.

Table 4

PMH calculated storm tide (ST) heights and Katrina observed storm tide (ST) heights (NAVD88) for several locations in southeast Louisiana.

Location	PMH (ft)	Katrina (ft)
S. Shore of Lake Pontchartrain	12.7	9-13
Mandeville	14.7	8-9

Chamette area	13.8	17-18
Citrus and New Orleans East	14.6	15-18
Rigolets and Chef Menteur Pass	15.2	17-18

Although the PMH storm tide values are larger than then SPH values, they are still not larger than the Katrina observed values for the Chamette area, Citrus and New Orleans East and the Rigolets and Chef Menteur Pass. The PMH storm tide values are larger than Katrina observed values in Mandeville and comparable to values observed at the South Shore of Lake Pontchartrain.

5. Saffir-Simpson Scale Wind and Storm Surge Disconnect for Hurricane Katrina

As mentioned above, the maximum 1-minute wind speeds in Hurricane Katrina during its two landfalls in Southeast Louisiana and Mississippi were 125 and 120 mph respectively. The Saffir-Simpson Scale rating is based on the maximum 1-minute winds. Thus, viewing the scale below shows that Katrina was a Category 3 hurricane during landfall. However, Katrina's storm surge exceeded the values of 9 - 12 feet that appear in the scale for a Category 3. In fact, much of the observed maximum storm surge heights in Mississippi were greater than 18 feet or Category 5. The reason for this disconnect is caused by the fact that the storm surge ranges for each category in the Saffir-Simpson scale are based upon the average storm surges heights that would occur along the U. S. Gulf of Mexico and Atlantic coastlines (i.e. Texas to Maine) for hurricanes with the winds in the corresponding category. Because of different widths and slopes of the continental shelf from Texas to Maine, a wide range of storm surge values are possible for a particular wind speed range. For example, hurricane Katrina's first U.S. landfall was near Miami, Florida, as a minimal Category 1. If it had been similar in size and intensity (Category 3) as it was in southeast Louisiana and Mississippi it would have produced a storm surge of 3 to 5 feet from Miami northward. This is in the Category 1 range on the scale. This is due to the fact that the continental shelf north of Miami is only 3 to 5 miles wide and drops off very quickly. Other locations on the U.S. coast will fall in the category 3 range using the Katrina landfall parameters. Because of this disconnect all of the U.S. Gulf of Mexico and Atlantic coastlines have had their storm surge floodplain determined and the storm surge heights calculated. The results are saved by emergency managers and the appropriate areas are evacuated when a hurricane threatens. Emergency managers do not depend on the storm surge values in the Saffir-Simpson scale for their decision making.

The Saffir-Simpson Hurricane Scale: The Saffir-Simpson Hurricane Scale is a 1-5 rating based on the hurricane's intensity. This is used to give an estimate of the potential property damage and flooding expected along the coast from a hurricane landfall.

Saffir-Simpson Hurricane Scale			
Category	*Winds (MPH)*	*Damage*	*Storm Surge*
1	74 - 95	**Minimal**: Damage to unanchored mobile homes, vegetation & signs. Coastal road flooding. Some shallow flooding of susceptible homes.	4 - 5 feet
2	96 - 110	**Moderate**: Significant damage to mobile homes & trees. Significant flooding of roads near the coast & bay.	6 - 8 feet
3	111 - 130	**Extensive**: Structural damage to small buildings. Large trees down. Mobile homes largely destroyed. Widespread flooding near the coast & bay.	9 - 12 feet
4	131 - 155	**Extreme**: Most trees blown down. Structural damage to many buildings. Roof failure on small structures. Flooding extends far inland. Major damage to structures near shore.	13 - 18 feet
5	More than 155	**Catastrophic**: All trees blown down. Some complete building failures. Widespread roof failures. Flood damage to lower floors less than 15 feet above sea level.	Greater than 18 feet

6. Hurricanes Gustav and Ike

During the 2008 North Atlantic hurricane season, hurricanes Gustav and Ike made landfall on the U.S. northern Gulf of Mexico coastline after causing major destruction to many locations in the Caribbean, especially Cuba. Gustav made landfall to the southwest of New Orleans, Louisiana, and Ike made landfall at Galveston, Texas. Both hurricanes had maximum sustained winds of 110 mph at landfall which made them Category 2 hurricanes, although at the upper end of the Category 2 scale. Accordingly, the Saffir-Simpson scale would give a storm surge elevation of 6 to 8 feet. FEMA high water marks are available for Ike and show a maximum storm tide value of 17.48 feet near where the strongest winds blew onshore. Storm tide values ranged from 11 to 15 feet inside of Galveston Bay. Higher water values were measured inside the bay but include additional height due to wave effects. Although the final FEMA high water mark survey report for Gustav was not available at the time of this report, the estimates of the maximum storm surge values range from 11 to 15 feet. Again, this shows the disconnect that can occur in the Saffir-Simpson Scale. Besides the width and slope of the continental shelf discussed above, both of these hurricanes had large RMWs (see discussion of RMW under Part III.) which resulted in large wind fields and large total kinetic energy and increased storm surge. This is similar to what happened in hurricane Katrina except these two hurricanes had lower maximum sustained wind speeds.

V. Summary

The size and scope of Hurricane Katrina makes it one of the most catastrophic hurricane events in recorded U.S. weather history. The Gulf Coasts of Louisiana and Mississippi suffered the brunt of the hurricane, with record-breaking storm tide heights causing extreme to catastrophic damage to most established structures in its path.

The right-angle nature of the geographical and man-made features of the southeastern Louisiana and Mississippi coastlines contributed greatly to the extremely large storm tide values associated with Hurricane Katrina. In the past several decades, human construction of protective levee systems and altered waterways have been undertaken to provide a means of preventing complete inundation of inhabited areas in the parishes of southeast Louisiana, specifically around the Mississippi River and the city of New Orleans.

Hurricane Katrina made landfall at Buras, Louisiana, and then again at the mouth of the Pearl River, moving north at 18 mph, and possessing 120 to 125 mph sustained wind speeds. As the storm approached from the Gulf of Mexico, it weakened in terms of its maximum sustained wind speed, but expanded its wind field to extend hurricane force winds almost 100 miles from its center. The kinetic energy associated with this expansion was calculated to be an unprecedented 122 TJ (terajoule, or one trillion joules), allowing the storm to transfer a huge amount of energy to the ocean, providing another contributing factor to the higher storm tides.

Besides the geographical makeup of the impacted area and the size of the storm's wind field, there were four other major contributions that resulted in Hurricane Katrina's massive storm tide. First, the sustained wind speeds of 120 to 125 mph during landfall allowed for the transfer of energy into the water for wave and current production. Next, Katrina's near-perpendicular track as it approached the coastline focused its wind field over a large area during landfall. The third factor, the storm's speed of approach, resulted in additional wind energy being transferred to the water. Finally, the wide and shallow continental shelf bathymetry of the coastline areas in Katrina's path did not allow any room for the storm tide to move or dissipate, pushing it inland while piling it upward at the same time.

The storm tide generated by Hurricane Katrina caused extensive flooding throughout all of the areas affected by the storm. The combination of the storm tide and the superimposed wave field on top of it resulted in an unprecedented amount of water being pushed inland during the storm, causing many areas to remain flooded for several days after the storm's passing. In Mississippi, storm tides ranging from at least 18 to 28 feet occurred over 55 miles of coastline, establishing new record maximum storm tide heights at most of these locations. Similarly, in Louisiana, locations along several east-facing parish levee systems also established new record maximum storm tide heights. Nearly all of the protective levee systems were overtopped and damaged by the combination of storm tide and wind driven wave fields.

Hurricane Katrina's storm tide elevations exceeded both the SPH and PMH storm tide elevations for locations along the east facing levees of St. Bernard and Orleans Parishes.

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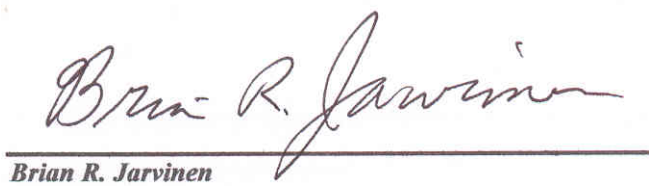
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Respectfully submitted,



Brian R. Jarvinen
Consulting Meteorologist

December 22, 2008

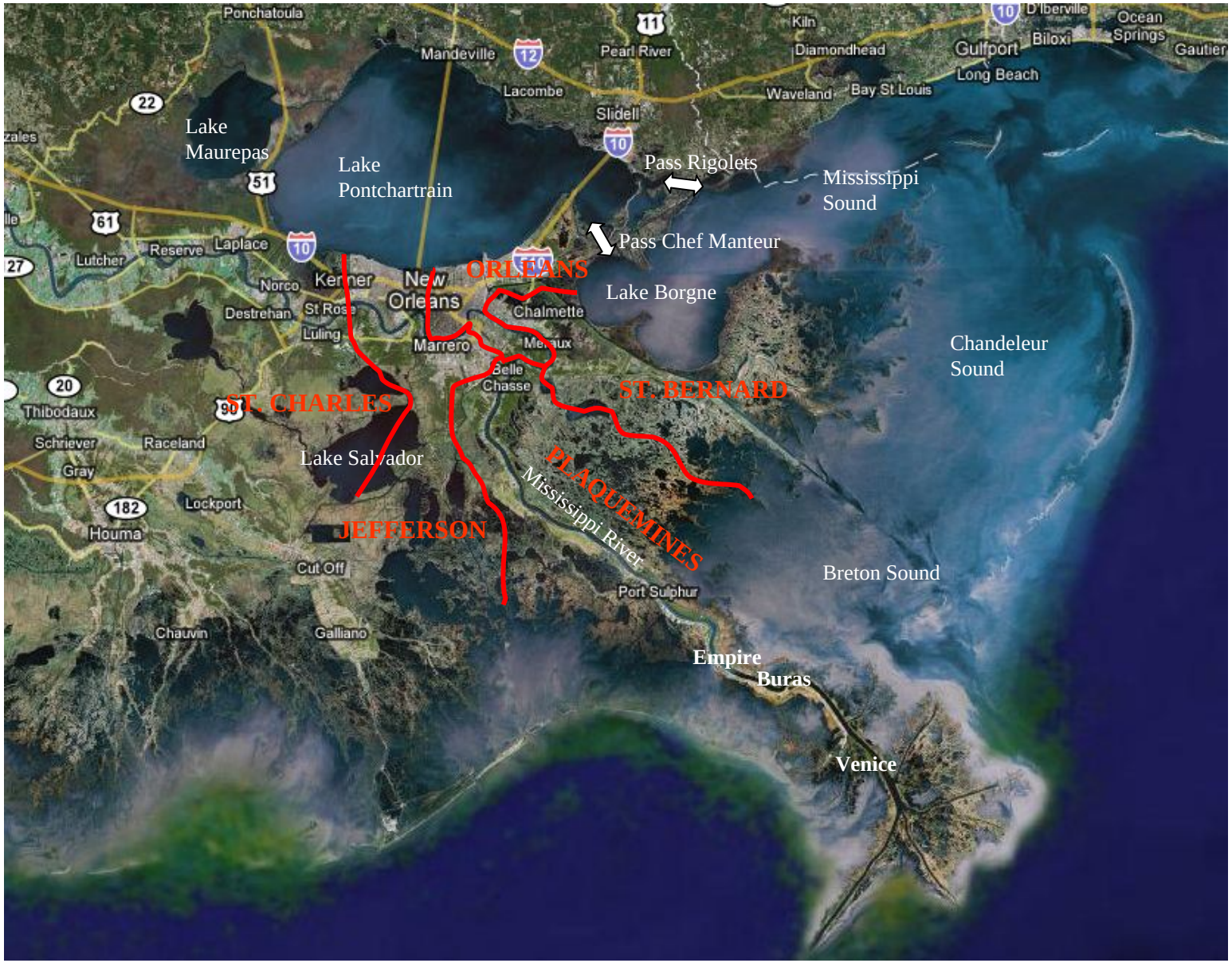


Figure 1. Geographical overview of southeast Louisiana
(Courtesy of Google Maps)

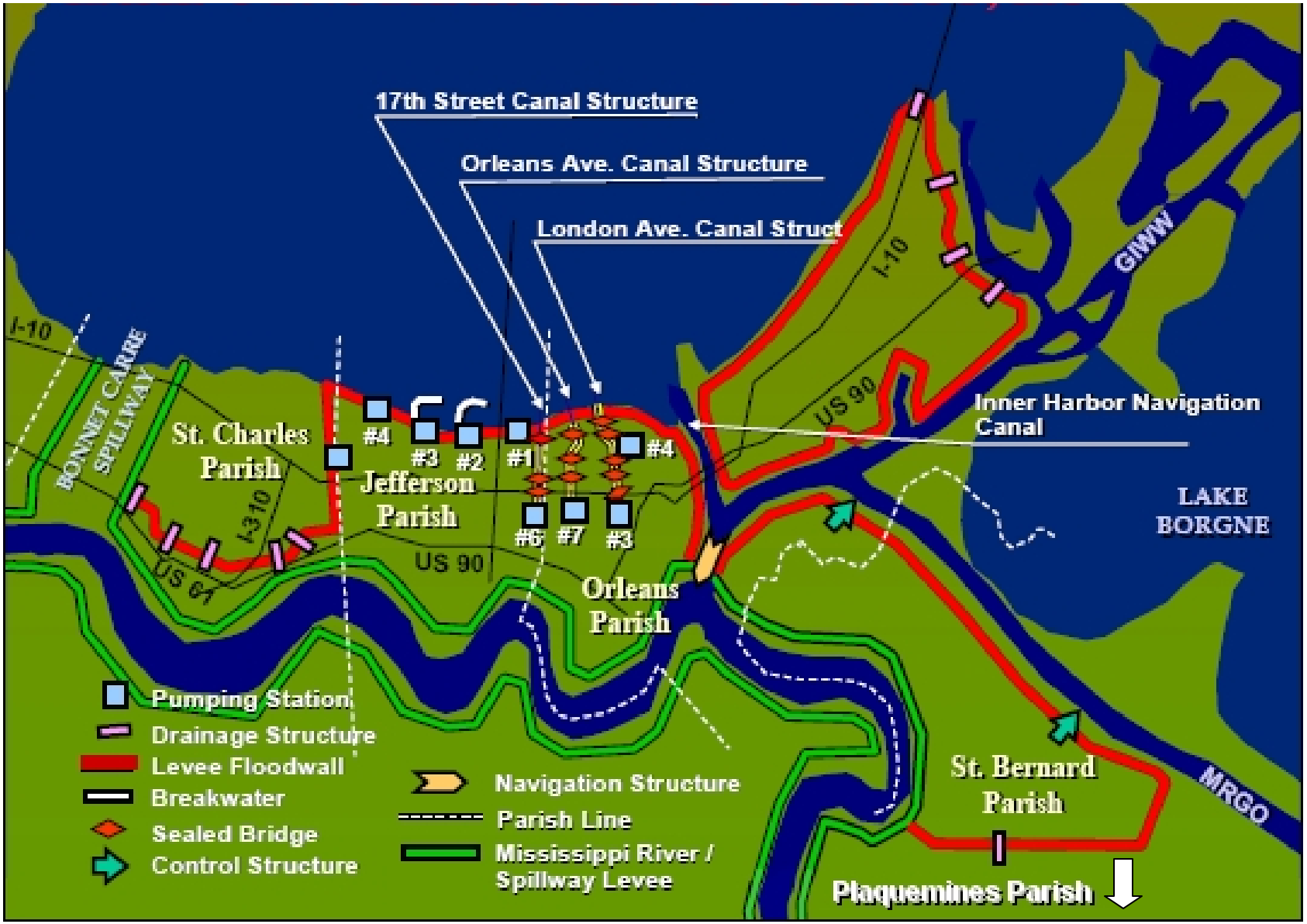


Figure 2. Mississippi River and Hurricane Flood Protection System for New Orleans and Vicinity

(US Army Corps of Engineers – *IPET Report (March 2007)*)

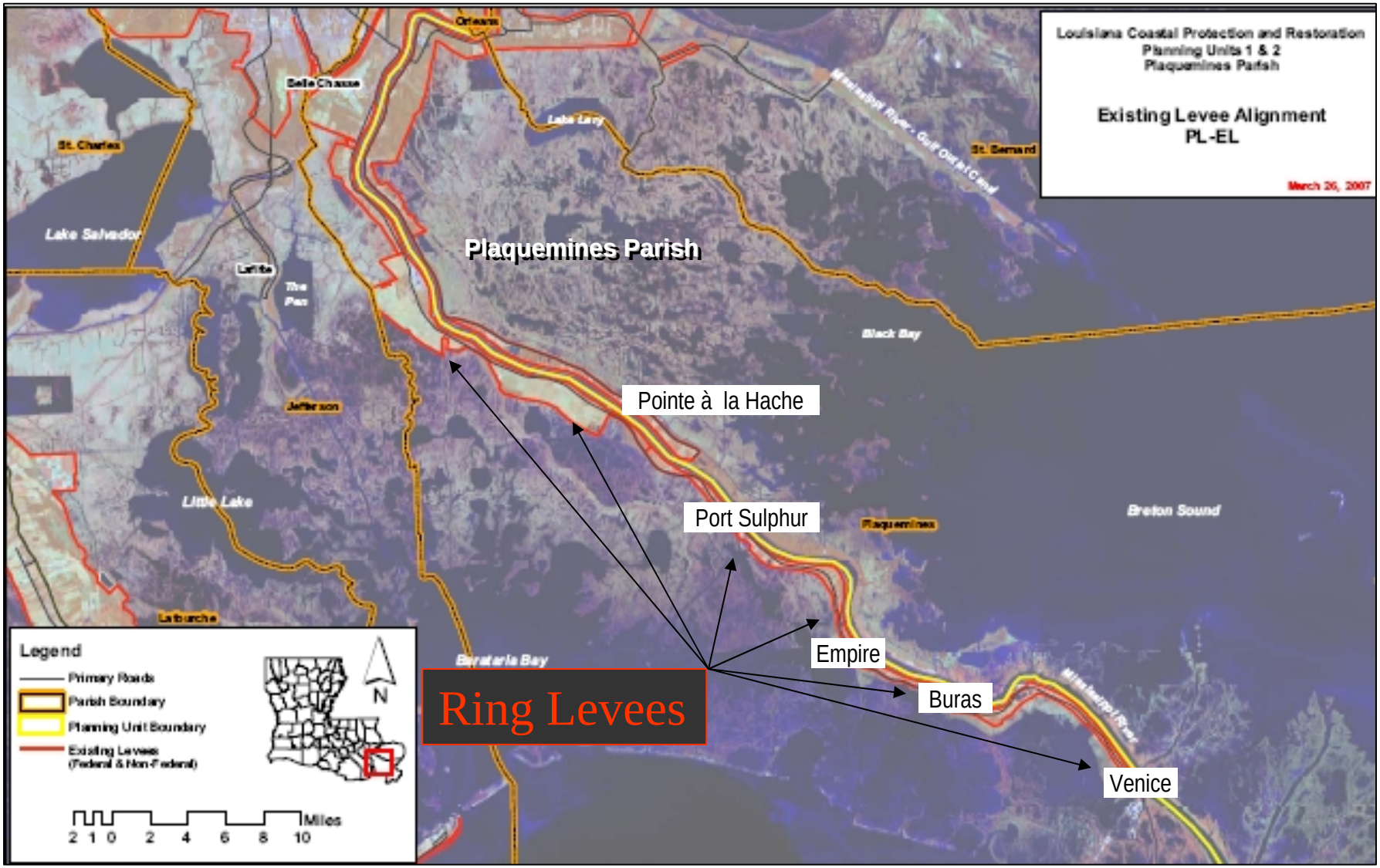


Figure 3. Mississippi River and Hurricane Flood Protection System for Plaquemines Parish

(US Army Corps of Engineers – *Louisiana Coastal Protection and Restoration Technical Report (Draft February 2008)*)



Figure 4. Natural and manmade barriers in southeast Louisiana and Mississippi
(Courtesy of Google Maps)



Figure 5. Visualization of the right angle created by natural and manmade barriers in southeast Louisiana and Mississippi

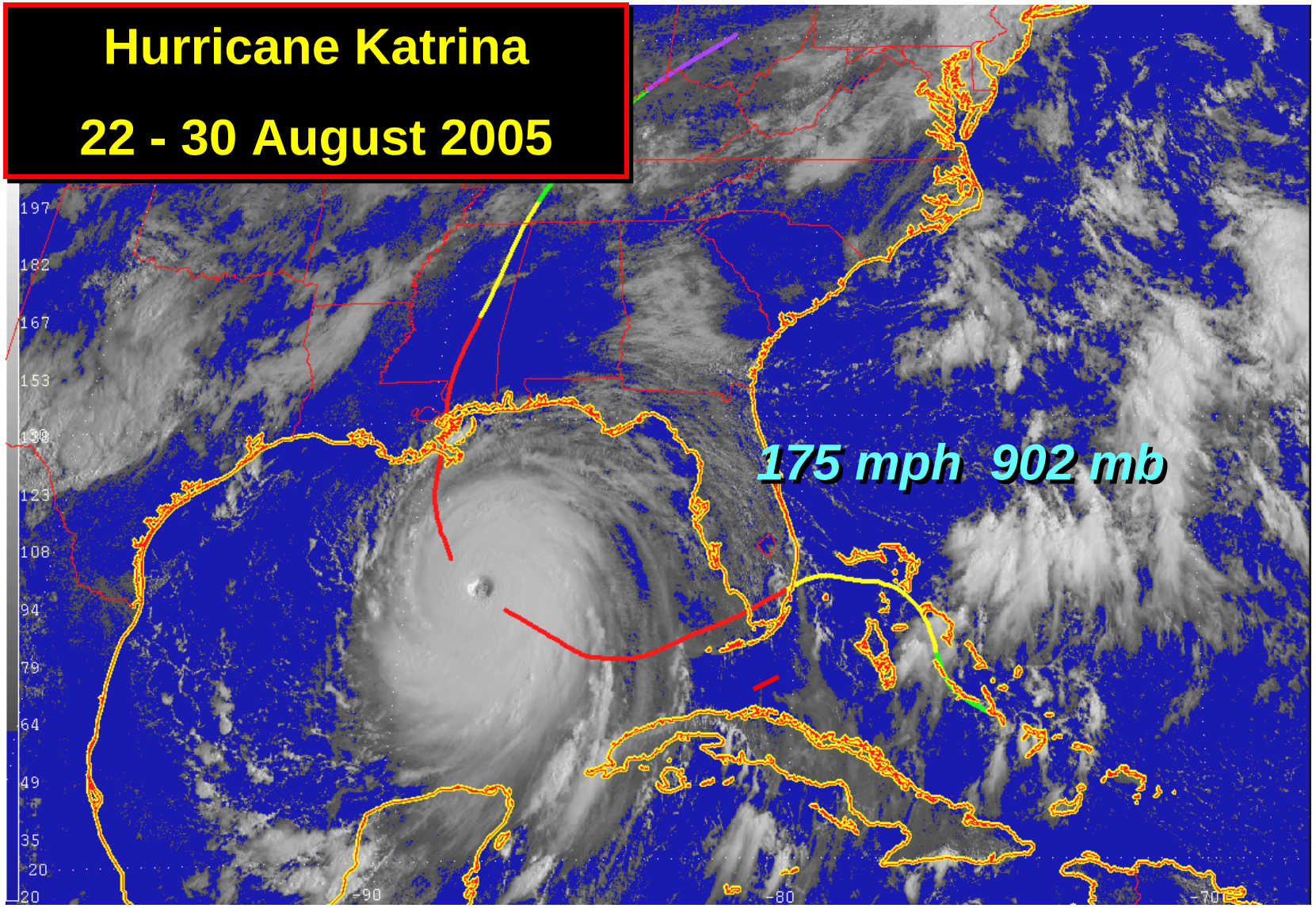


Figure 6. NHC best track estimate for Hurricane Katrina, overlayed with satellite image of the storm at peak intensity

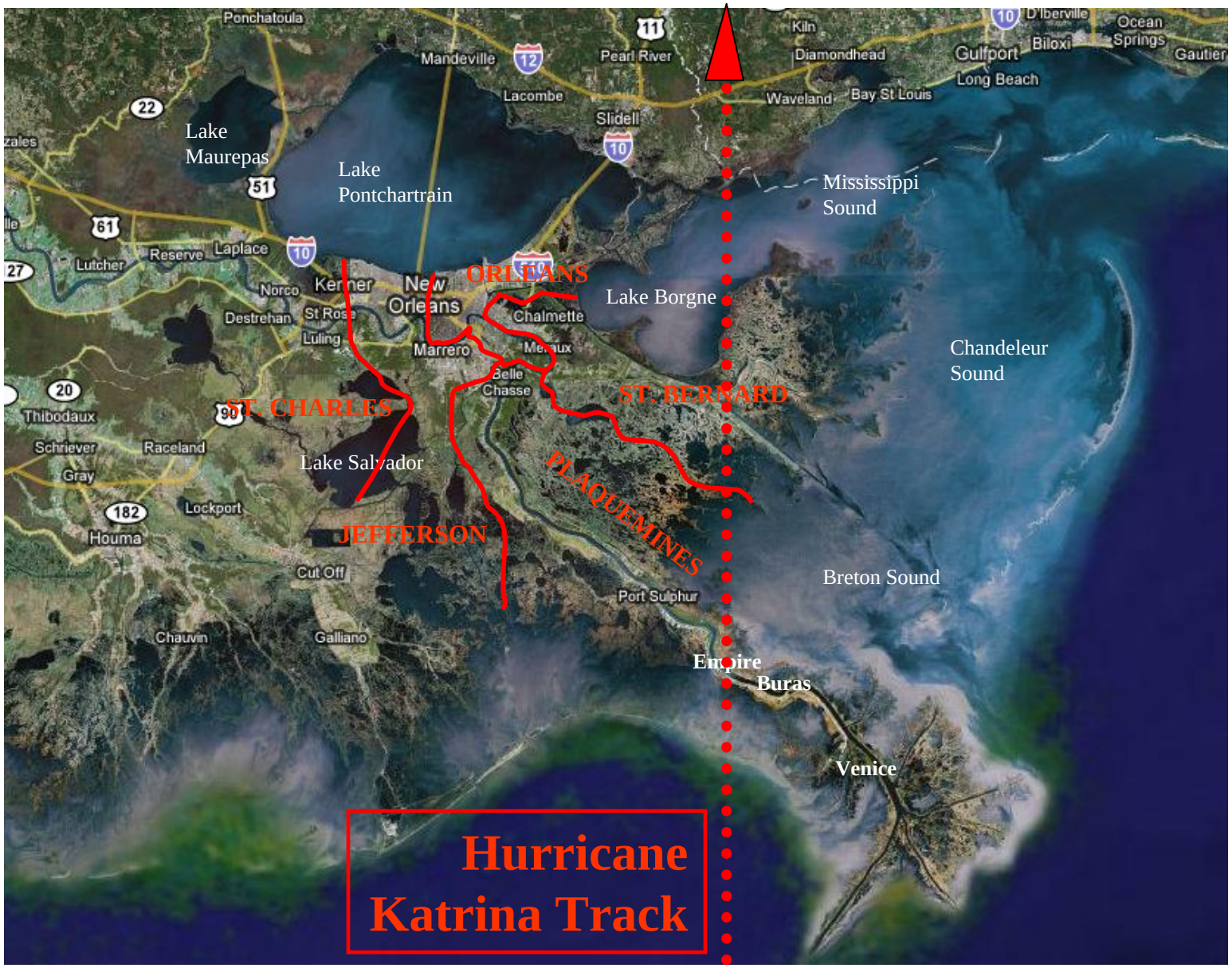


Figure 7. Hurricane Katrina track through southeast Louisiana

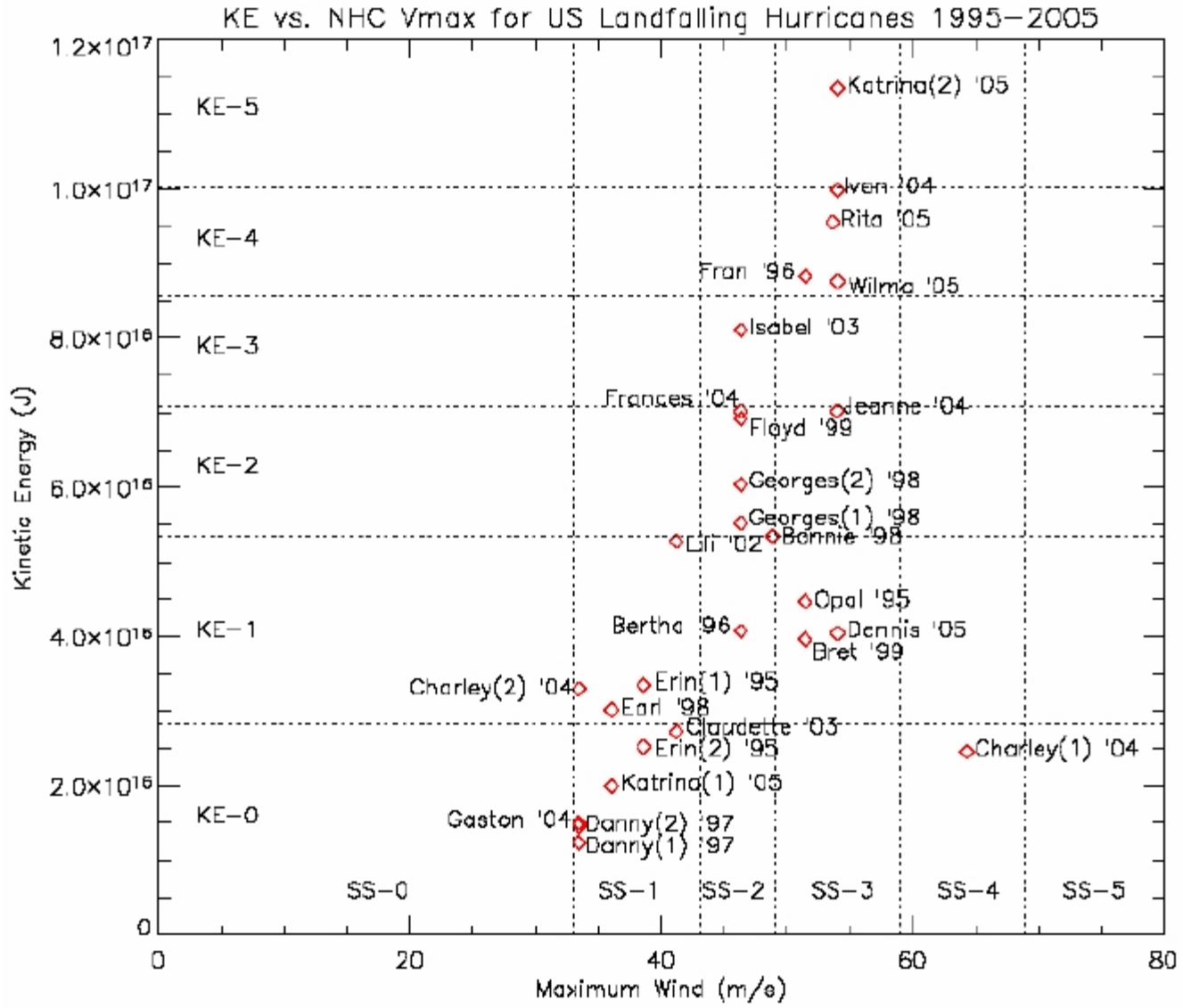


Figure 8. Plot of the approximate inner core Kinetic Energy versus the NHC intensity at land fall for all US land falling hurricanes from 1995-2005.

Courtesy of Maclay (Colorado State University)

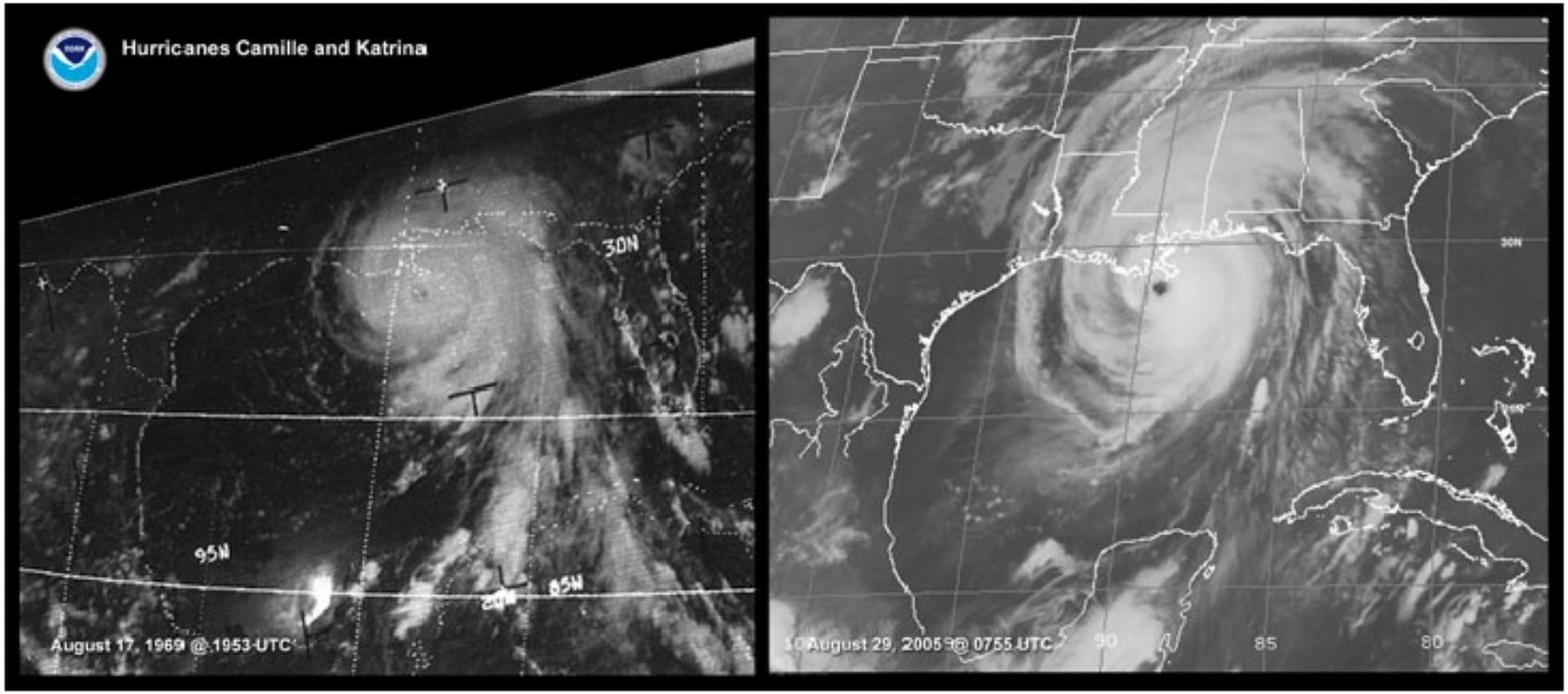


Figure 9. Side-by-side satellite image comparison of Hurricane Camille (left) and Hurricane Katrina (right)

Courtesy NOAA National Climatic Data Center

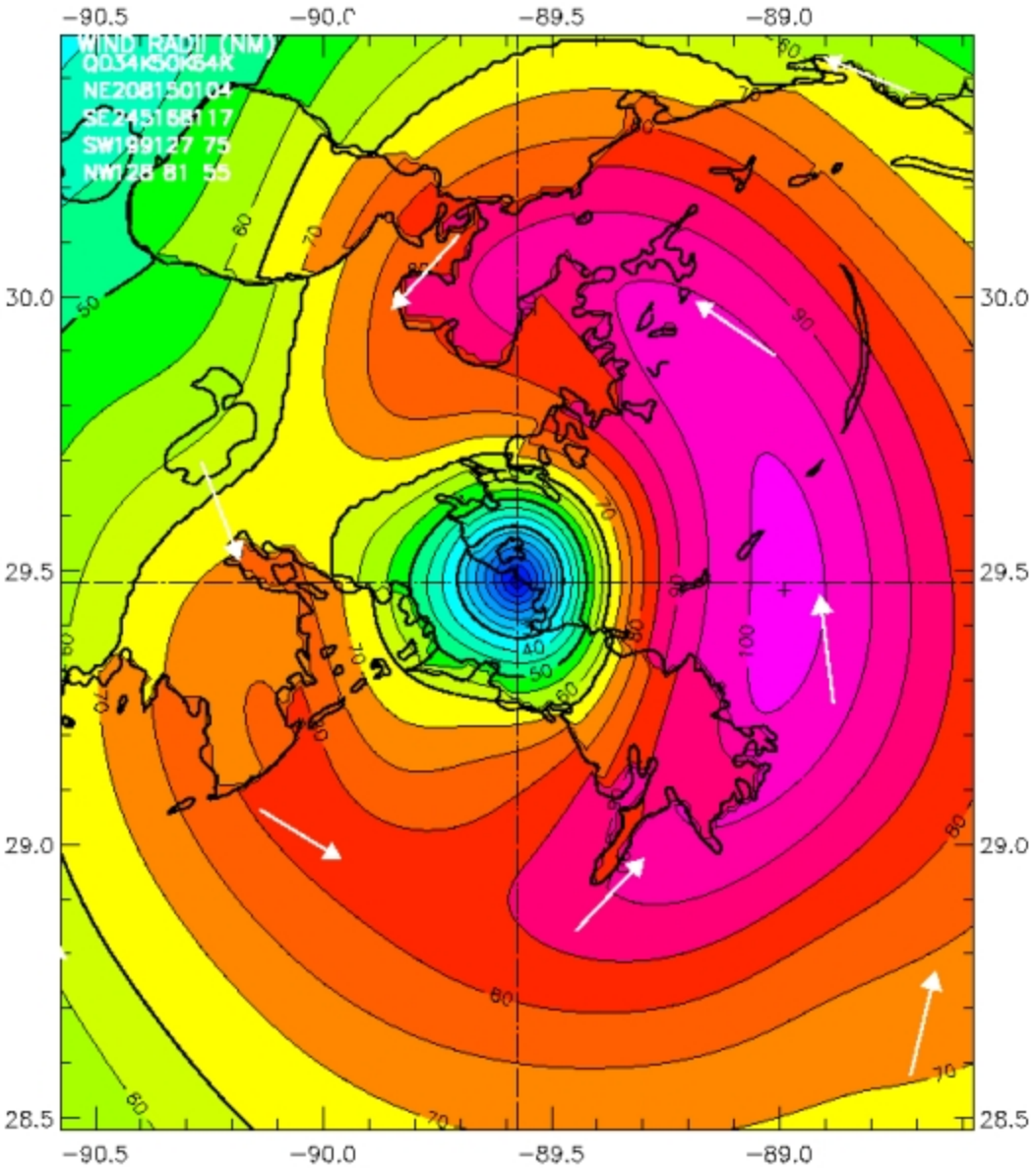


Figure 10. Hurricane Katrina 1200 UTC 29 AUG 2005 Maximum 1-min sustained surface winds (knots)

Courtesy NOAA/AOML/Hurricane Research Division

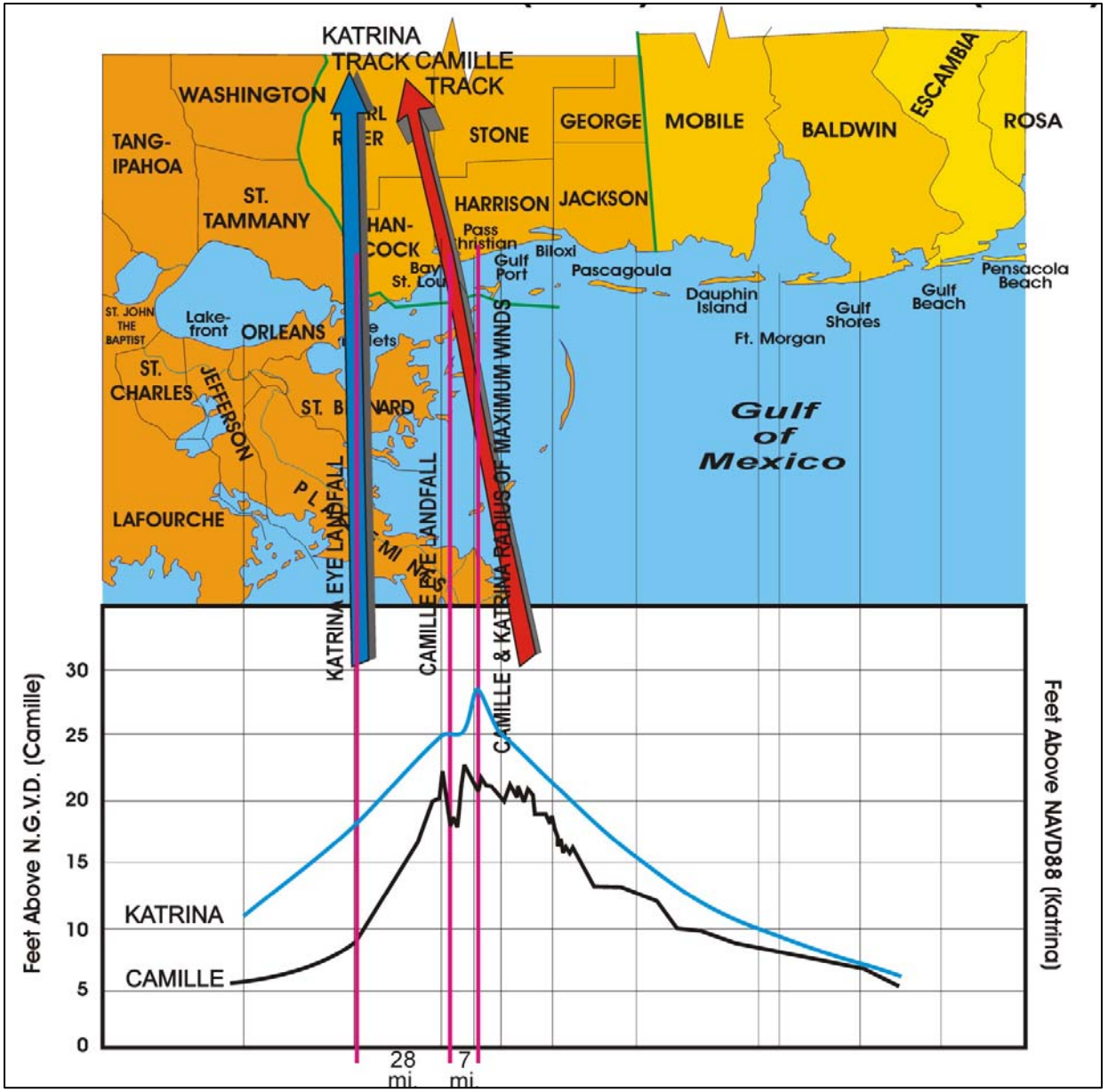


Figure 11. Observed coastal profiles for Hurricane Camille (1969) and Hurricane Katrina (2005)

Courtesy NOAA/National Hurricane Center