3.3 FINE SCALE ANALYSIS OF THE CONVECTIVE SCALE WIND FIELDS OF KATRINA AND THEIR RELATIONSHIP TO THE SURGE EVENT

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1. INTRODUCTION

On 29 August, 2005, the landfall of Hurricane Katrina became the costliest natural disaster in U.S. history with more than 352,000 homes destroyed and nearly 140,000 others suffering major damage (National Association of Home Builders (NAHB) and the American Red Cross collected by FEMA). There is no debate as to the overall net scope of the event. However, there remains considerable debate as to the relative magnitude and importance, as well as the timing, of the different physical forces that acted to damage thousands of these properties. The owners remain embroiled in litigation with their insurance carriers as to whether it was wind or water, or what was the relative contribution of either, that should be to blame for their losses. The author of this presentation has written over 200 reports for locations (see Figure 1) along the Mississippi Coast attempting to reconstruct the timeline of events at each spot. This paper will briefly explain the methodology employed to use surface measurements, aircraft reconnaissance, satellite, and radar data to create neighborhood-specific estimates of wind magnitude and duration, and how those estimates are integrated with ADCIRC and other tools to re-create the temporal relationship between these winds and the associated episode of surge and wind driven waves.

2. SURFACE WIND ESTIMATE METHODOLOGY

During the morning of 28 August, 2005, USAF Reserve (AFRES) reconnaissance aircraft AF302, (with the author of this paper onboard flying Mission 1712A as a crewmember performing reserve duty), and then later NOAA 43 flying mission 1812A, recorded some of the strongest winds ever measured in a Gulf of Mexico hurricane as Katrina rapidly intensified from a MSLP of 935 millibars (mb), down to 902 mb, in less than 12 hours. Ten second averaged 700 mb wind values as high as 85 m/sec or 166 knots (with a peak one second value of 179 knots) were measured in the northeast eyewall. Dropsondes released into the inner edge of that northeast eyewall measured a peak max of 95 m/sec or 185 knots (213 MPH) at 501 meters. Mean winds in the lowest 150 meter interval captured above the surface (from 63 to 213 meters) were 81 m/sec or 158 knots (182 MPH). Less than 24 hours later the eye made landfall, first in Plaquemines Parish, LA around 1100 UTC, then for a final time about four hours later in extreme western Hancock County, MS near the Pearl River which borders LA. MSLP at landfall in LA had filled to 920 mb.

An even greater degree of weakening was conveyed in the NHC report on Katrina issued 20 December, 2005 (then updated 10 August 2006) regarding the maximum sustained winds (MSW) of Katrina at landfall in LA (110 knots) and in MS (105 knots). As stated on page 7 of the NHC report: the 110 knot figure, when associated with the 920 mb landfall pressure, would assign Katrina the lowest winds ever seen with a 920 mb hurricane in the Atlantic Basin.

An examination of reconnaissance data (both flight level and dropsonde) in conjunction with WSR-88D reflectivity and radial velocity archives from the Mobile, AL and Slidell, LA sites suggests that many waterfront neighborhoods along the MS coast saw localized MSW higher than 105 knots for brief periods underneath areas of the most intense convection. Conveying the degree of wind damage potential from a large hurricane impacting so many locations can be a daunting task. The NHC report and HRD's H*Wind plots best express the broad scale tangential wind field associated with the parent vortex. Convective scale features, when superimposed onto this field, would suggest higher absolute wind peaks in many locations. However, simply showing a few forensic examples of damage suggesting higher winds can easily be refuted through the use of nearby examples just as easily suggesting much lower winds (ie: Figure 2 contained in Marshall 2006 showing the type of frail items that survived Katrina intact in areas exposed to very high winds). Therefore, it is not as simple as asking one to believe that evidence of wind damage is easiest to see on the smallest scales (as indeed, Figure 3 from Chambers et al does just the opposite, showing the massive swath of 320 million dead and dying trees, extending far inland, left in the wake of Katrina as seen from satellite).

As is the case with all hurricanes, there existed a distinct horizontal gradient of MSW in Katrina along the MS coast. The reduction in wind speed as a function of distance from the coast depends to some degree upon the character of the terrain over which it flows (Howard and Schroeder). Any attempt at estimating surface winds over a point on land (even for a location near the waterfront) whether made from use of a dropsonde or any value implied within the planetary boundary layer (PBL) using measurements made at higher levels (ie: flight level), if the measurement was taken over water, must be a blend of considering both the horizontal and vertical gradients at the land-sea interface. Parameterization of this vertical gradient can be made using any number of methods including simple log wind profiles:

$$u_z = \frac{u_*}{\kappa} \ln\left(\frac{z-d}{z_0}\right) + \varphi(z, z_0, L)$$

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Monin-Obukhof Length:

$$L = -\frac{u_*^3 \bar{\theta}_v}{kg(\overline{w'\theta_v'})}$$

or more recent work done by Mark Powell, James Franklin and others at HRD (well summarized in Dunion et al) which takes advantage of the wealth of data gathered in the last ten years by GPS dropsondes. After examining more than 200 locations along the MS coast impacted by Katrina, empirically determined best fit curves, roughly proportional to the appropriate roughness length parameter (z_0) and thereby, to the erosion of MSW, can be assigned based on classifying terrain character (Figure 4). Characterization of the terrain into roughness categories (ie: low-lying grassy wetlands, low, medium or high intensity urban development, evergreen versus deciduous forest etc) using USGS Multi-Resolution Land Characteristics (MRLC) charts can be made along the trajectories of air flowing off the Mississippi Sound onto the coast (see Figure 5). Using those MRLC charts and Figure 4, trajectories can be reconstructed to approximate the erosion of sustained wind values with increasing distance from the water's edge.

A significant amount of reduction in wind speed is evident within the first several hundred meters inland of the Mississippi Sound. For example, in Biloxi and Gulfport, sustained winds along the CSX railroad line which runs parallel to Highway 90 less than 500 meters further north, saw sustained winds of 10 to as much as 15 knots less than at the immediate shoreline. The consequences are that: a) The wind estimates along the shore are "contaminated" by those just further inland and b) The footprint of this horizontal gradient of winds is almost entirely within the surge zone in most areas, making it difficult for a forensic examination of damage and debris patterns to distinguish between surge and the very high winds confined only to the waterfront.

It is important to also examine how winds may be allowed to increase again when they emerge back over a significant fetch of inland waterways. The MS coast is laced with many such features (ie: Saint Louis Bay, The Back Bay of Biloxi). As convection sweeps inland, parcels blowing off the Mississippi Sound that had been decelerated by passage over the coastal terrain are re-invigorated by the added momentum of downbursts and other localized phenomena. This can explain secondary wind maxima in places such as the Eagle Point neighborhood of North Biloxi (adjacent to the western end of The Back Bay of Biloxi where it meets the expansive wetlands at the mouth of the Biloxi River) and portions of southwestern Diamondhead (well displaced inland from the Mississippi Sound but near Saint Louis Bay).

The importance of this horizontal wind gradient is most pronounced when discussing sustained (one minute average) winds associated with the larger scale ambient wind field. The effect of this gradient is less apparent in examination of what are largely convectively modulated three second gusts (responsible for a significant portion of wind damage). It should also be pointed out that the hurricane wind field is, by its nature, inherently chaotic in its boundary layer flow with a great deal of gustiness separate from the effects of convection. Therefore, gusts can, to the first order, be approximated from sustained values using statistical parameterization. In my reports, I endeavored to distinguish between the statistically expected gusts factor and gusts that can be attributed to distinctly identifiable convective structures.

Examination the thermodynamic stability of the boundary layer flowing onshore from the Mississippi Sound, with sea surface temperatures of around 31 degrees C, suggests it was likely that the near-surface layer remained strongly coupled to higher winds flowing 300-500 meters aloft. With those very warm SSTs yielding a highly unstable near-surface environment , it is unlikely that the PBL became as decoupled as was seen in more stable major hurricane landfall environments (ie: Mitch at landfall in 1998 after stalling just off the coast of Honduras and upwelling cooler water for two days). In cases like Mitch, a sharp delineation develops between very high tangential winds still spinning rapidly around the eye in a balanced, near-laminar fashion (relatively absent of deep convection) at around 500 meters and the rapid erosion of winds closer to the surface in the PBL caused from friction below. Black et al describe how such highly sheared environments may have resulted in the formation of roll vortices in Katrina. While it is possible that such structures may have formed in temporarily CAPE-depleted areas of stratiform rain, the majority of extreme straight line wind gust potential came from convectively fueled inflow into mesovortices and their subsequent collapse into wet microburst shafts as described in several post-Katrina papers by Blackwell et al.

3. CORRELATION OF WSR-88D & RECON DATA

AFRES AF300 (flying mission 2212A) flew at 700 mb from east to west, paralleling the MS coast just prior to the eye coming ashore in the marshes of southernmost Hancock County. At 1422 UTC the crew measured 30 second average winds of 125 knots at flight level just southeast of the Long Beach/Pass Christian beaches. Thirty seconds is an eternity in recon considering the aircraft is moving through the sampled package of winds at a rate of three miles per minute. Flight level winds exceeding 110 knots were measured continuously for eight minutes suggesting a 25 mile wide band poised to sweep above the communities around Henderson Point. There were two AFRES WC-130J aircraft flying at landfall along with a W-P3 (NOAA 43) conducting a landfalling TC experiment. NOAA 43 released 36 sondes. An in-depth analysis of these drops along with those made by the two AFRES missions (along with a third that was completed just prior to landfall) can be read in Henning 2008 (another paper delivered in a different session of this same AMS Annual Meeting). Summarizing the other paper, all of the sondes released show a marked drop-off in wind speed near the surface with much higher winds around 300 to 500 meters above the surface. The highest winds seen in any of the sondes dropped by these aircraft on the morning of 29 August was at 1030 UTC by NOAA 43 over the Mississippi River Delta showing 71 m/sec or 138 knots (159 MPH) a little over 300 meters above the surface with a corresponding surface wind of 52 m/sec (101 knots or 116 MPH). There were two other sondes of particular interest. The first was released by NOAA 43 just south of Pascagoula at 1306 UTC that measured 63 m/sec (123 knots or 142 MPH) about 300 meters above the surface that failed to transmit any more winds below 241 meters (at which time winds were 112 knots or 129 MPH). The other was released by AFRES AF300 in the leg described at the top of this paragraph just south of Pass Christian, MS. That sonde found winds of 68 m/sec (133 knots or 153 MPH) about 350 meters above the beach as the instrument was carried onshore and landed a mile inland in the Timber Ridge neighborhood. Prior to reaching the surface, winds dropped off rapidly to 49 m/sec at 77 meters (the last wind reading).

When comparing these drop locations with NEXRAD archives from Slidell and Mobile, in only the case of the first sonde mentioned (over the Delta) was the drop made in such a way that it fell through active convection near the surface. Due to the slope of eyewall convection, while the Pascagoula and Pass Christian sondes were released close to max wind bands at altitude (about 650 mb and 700 mb respectively), they both fell into weaker, stratiform rain as they approached the surface. After 10 years of examination of GPS dropwinsondes released into TCs there is a clear relationship that can be drawn between how much wind reduction is seen in the planetary boundary layer and the character of the precipitation just above that layer (whether it is convective versus stratiform). Several studies (including Campo and Rickenbach) of NEXRAD radial velocity products from Katrina show the 60-70 m/sec winds seen in the boundary layer in these and other dropsondes were consistent with radial velocity-derived wind speeds 0.5 km above the MS coast.

4. TIMING OF WIND AND SURGE MAXIMA

The temporal relationship between the maximum wind event and the maximum surge is key to hundreds, if not thousands, of Katrina property cases in litigation. The courts consider it materially important if it can be shown that a significant amount of damage was likely to have been done to a structure by the wind, even if subsequent surge reduced what remained to a concrete slab. For much of the MS coast outside of Hancock County and western portions of Harrison County, where the more intense, innermost eyewall came onshore (basically any location east of Downtown Gulfport) the wind maxima can be attributed to the larger, older and more established outer eyewall that arced across the three coastal counties and pushed inland north of Interstate 10 well before the eye was completely onshore. Figure 6 stamps large scale MSW that in Jackson and eastern Harrison County were all associated with this outer eyewall. Due to the highly ageostrophic nature of the surface wind flow, the direction of which reflects the significant effect of friction with the Earth (especially at, and inland of, the land / sea interface), this inward spiral of the winds means that the onshore winds in Biloxi and Pascagoula maintained an easterly component well after the eye's landfall in Hancock County. The large scale ambient winds associated with the parent vortex did not veer through a southerly direction (180 degrees) until the eye was well inland, delaying the orientation of the winds with relation to the coast into their most perpendicular fashion. It is that time of greatest perpendicularity between the coastline and the fetch of the wind driven surge and wave action when we see the peak inundation values. The further east one travels along the coast, away from the landfall point, the greater the lag seen in that veering of the winds to southerly. As a result, these locations further east, while seeing generally lower maximum winds, saw a more pronounced lag (see Figure 7) between their maximum wind event and the highest surge event (as much as 90-120 minutes in the Pascagoula area). ADvanced CIRCulation (ADCIRC) numerical simulations of the Katrina surge event have been performed at many laboratories. Dr Reinard Flick, of the Scripps Institute of Oceanography at the University of California at San Diego, has produced one of the more detailed representations of the surge event. The sharpest, most "jagged" representations of the event are more representative of what was seen in nature that morning along the MS coast. ADCIRC and SLOSH depictions of the Katrina event that show a more gently sloped, Bell-like curve unrealistically place too much inundation along the coast too early in the timeline of events. There were no tide gauges along the MS coast that were able to successfully record the entire surge event. All failed at some point while the water was still gradually rising in the early hours well prior to the sudden, massive increase in inundation values that resulted in the catastrophic, record peak event later that morning. Nearly all eyewitness reports, as well as the limited amount of video evidence, confirm the Flick ADCIRC depiction that much of the rise in sea level occurred within an approximately 90 minute interval.

5. SEQUENCE OF EVENTS: Waveland

The most extreme winds associated with the landfall of Katrina in MS occurred in southern Hancock County around the remote communities of Jackson Landing and Ansley (approximately midway between New Orleans and Gulfport) where sustained winds of 115 knots and three second gusts of more than 140 knots were likely during the passage of the most intense convective bands seen during the interrupted reformation of an inner eyewall around 1338 UTC (see Figure 9). For all practical purposes, the winds in Waveland (just a few miles to the northeast) were effectively as strong with estimated MSW between 110 and 115 knots and gusts also in the range of 140 knots associated with the passage of the inner eyewall convection a few minutes later around 1354 UTC. Earlier, a mesovortex moved directly overhead at 0859 UTC, with two crossing the shore just to the north around 0810 and 0927 UTC (see Figure 8). These cells which moved across Bay St Louis may have been responsible for hundreds of trees that were splintered in The Oaks and Salt Breeze neighborhoods between Dunbar and Engman Avenues in the Cedar Point area.

Just after 1430 UTC, the eye began to reach Waveland and winds rapidly subsided. Due to the orientation of the coast in this portion of Hancock County (where southeasterly rather than southerly winds create a fetch on the Mississippi Sound perpendicular to the shore, as is the case elsewhere

where the coast is oriented more in an east-west fashion) the interval between maximum winds and arrival of the highest surge was the shortest of anywhere on the MS coast. The highest surge measured by NOAA gauge 8747766 in Waveland was at 0912 UTC with a reading of 8.98 feet (about seven feet above what would be expected on the tidal charts for that morning), the gauge obviously failing well before the inundation reached the catastrophic proportions that would soon follow. Figure 10 shows the maximum value around 31.5 feet above what would have been the normal tide at around 1430 UTC or 0930 CDT. This is when the center of the eye was still a few miles south of making its final landfall. This suggests around 30 minutes of lag between the MSW and the peak of the surge. Note that the orientation of the coast in Waveland also allowed for a more gradual build-up of the surge rather than the more abrupt, jagged shaped curve that will be seen further to the east. Figure 10 shows that the surge built from around 3 feet above normal tide at 0130 CDT to the 7 feet measured by the NOAA gauge just prior to it going offline around 0400 CDT, to over 12 feet by 0600 CDT. There was an 18 foot rise in water during the final three hours prior to the extreme peak then a very abrupt fall after the center of the eye passed the latitude of Waveland and winds swung into a WSW (offshore) direction, pushing most of the inundation quickly back into the Mississippi Sound. In short, Waveland suffered the worst of both wind and water that Katrina had to offer and it is not surprising that nearly every structure in the community within a kilometer of the Sound was either severely damaged or destroyed.

6. SEQUENCE OF EVENTS: Diamondhead

The southwestern neighborhood of Diamondhead (south of Interstate 10 built around the Airport) is an example of a community set five miles inland from the Mississippi Sound but directly adjacent to the inland waters of Saint Louis Bay as well as the expanse of grassy wetlands around Cutoff and Umbrella Bayous. This location was also only 12 miles east of where the center of the eye tracked inland across Hancock County. The most intense inner eyewall convection reached Diamondhead about 30 to 45 minutes after passing over Waveland (see Figure 11 from 1443 UTC). The eastern portion of the eye came overhead after 1500 UTC. Based on tracing wind parcels passing across the coast over Henderson Point then traveling across more than three miles of water traversing Saint Louis Bay, where they were allowed to accelerate back to close their original velocity, MSW could have easily reached 110 knots with gusts between 130 and 140 knots. Earlier, two mesovortices passed over the Airport neighborhood at 0900 and 1103 UTC (see Figure 8). The forest along the border between easternmost Hancock and westernmost Harrison Counties shows swaths of hundreds of large pine trees blown over and splintered by tornadic or straight line winds.

Figure 12 shows the peak surge event in Diamondhead occurred significantly later than what was seen along locations in Hancock County that directly faced the Mississippi Sound but the magnitude was still enormous with a 26 foot max between 1030 and 1045 CDT. The rate of increase in inundation values was much slower through the night than what was seen in Waveland (about 7 feet above normal tide by 0800 CDT versus 19 feet at that time down in Waveland). Half of the surge came after 1000 CDT as inundation level doubled from 13 to 26 feet in less than an hour as the center of the eye passed abeam this latitude. The surge receded much slower in Diamondhead since veering of the winds past southerly to a westerly component still maintained a strongly onshore fetch on the Bay.

7. SEQUENCE OF EVENTS: Pass Christian

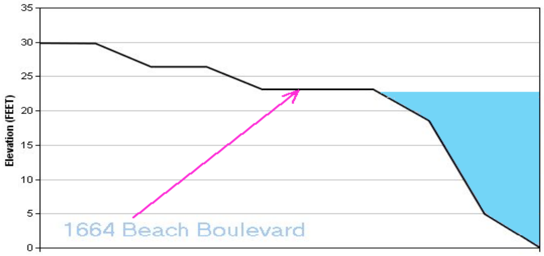
Unlike the previous two locations discussed, Pass Christian, further to the east, never saw the eye of Katrina. As was the case 36 years earlier in Camille, the Henderson Point area was pounded by the eastern semicircle of Katrina as the center passed 20 miles to the west around 1530 UTC. The multiple eyewalls of Katrina came into play here with the outer eyewall reaching Pass Christian at 1200 UTC and the inner eyewall hitting about two hours later. This community was also the most mesovortex prone of any along the MS coast during the landfall of Katrina with four well-defined rotational events depicted on Slidell radial velocity archives at 0806, 0853, 0925 and 1354 UTC (again, see Figure 8). MSW were nearly as high (110 knots with three second gusts near 140 knots) as what was seen across the inlet to Saint Louis Bay in Hancock County as the neighborhoods within a couple of miles of Henderson Point had the highest winds seen anywhere in western Harrison County.

Figure 13 shows the surge in Pass Christian occurred later than in Waveland but just prior to that in Diamondhead. Between 0630 and 0700 CDT it rose across Highway 90. Then the rate of inundation began rapidly accelerated with a doubling in depth from 11 to 22 feet in the 90 minutes between 0830 and 1000 CDT with a peak value of 29 feet above normal tide around 1030 CDT. As the winds veered to southwesterly (paralleling the shoreline of Hancock County to the WSW of Henderson Point), the surge quickly receded back into the Sound over the next few hours.

8. SEQUENCE OF EVENTS: Biloxi

As one moves further to the east, to greater distances from where the eye crossed the MS coast, two things become clear. First, the outer eyewall (which was the primary, more well-established and older of the two) was the only eyewall which affected locations east of the Port of Gulfport in western Harrison County. While the inner eyewall contained the most extreme winds, the outer eyewall pounded the coast for an extended period with MSW anywhere from 95 to 105 knots and cells embedded within this outer eyewall generated three second gusts well in excess of these values over many neighborhoods. Secondly, the interval between the episode of maximum sustained winds and the peak of the surge event grows considerably larger the further one travels eastward with a 45 minute lag between the two evident in the Point Cadet neighborhood of Biloxi. The magnitude of wind driven wave run-up onto the beachfront, especially for properties just north of Highway 90 (Beach Boulevard) that are close to the same elevation as the

23 foot surge peak shown in Figure 14, is critical in determining the degree of water damage that may have occurred. It is vital in these cases to understand that the highest wind driven waves occurred as the most intense convection along the trailing edge of the outer eyewall swept across the Biloxi coast (as the surge was rising rapidly but had not yet peaked). It was about 45 minutes later, after the winds had decreased significantly, that the surge peaked. Since the two events were out of phase, it is unrealistic to superimpose anything more than around 2 to 3 feet of wind driven waves on top of the peak surge depth.



9. SEQUENCE OF EVENTS: Pascagoula

Jackson County, furthest to the east, still saw significant winds along the coast associated with the strongest core feeder bands and then the outer eyewall (see Figure 15 from 1133 UTC and Figure 16 from 1416 UTC). An anemometer at the Ingalls Shipyard recorded 117 MPH gusts between 1240 and 1250 UTC then again between 1410 and 1420 UTC. Wind gusts of 124 and then 137 MPH were reported at the Jackson County Emergency Operations Center prior to the roof being peeled off by the wind around 0830 CDT.

The surge did not peak in Pascagoula until approximately 1100 CDT at 18-19 feet above normal (see Figure 17), so in some areas of Jackson County (especially inland waterways such as the Pascagoula River) there was as much as a 90 to 120 minute lag behind the strongest winds. In deference to NOAA tidal gauge 8743281 in Ocean Springs, which continued to record data later than any other in the path of Katrina, every effort was made to fit a realistic inclusion of this ground truth into the ADCIRC-based curve depicted in Figure 17. The Ocean Springs gauge was up to 13 feet (around 11 feet above normal high tide) at 0818 CDT when it ceased recording any further data.

10. DISCUSSION

A key component of the argument that wind caused only a limited amount of the damage in MS (even near the waterfront) is data collected by surface anemometers. There were a small number of permanent weather stations with wind measurement capability existing prior to Katrina that were augmented by additional research towers erected by Texas Tech University (at the Stennis International Airport) and the Florida Coastal Monitoring Program (FCMP) at Trent Lott Airport north of Pascagoula. The ASOS station at the Gulfport Airport failed at 1025 UTC. Data collected at Keesler AFB by the FMQ-19 system became sporadic and suspect as the full force of Katrina struck the base with many missing and incomplete observations in the NCDC database. Other observations, both from permanent ASOS stations or the research towers, were all collected north of Interstate 10, some as much as nine miles inland from the Mississippi Sound. Using these inland data points to definitively characterize winds further south along the coast, or using the incomplete data sets from stations that failed well prior to the peak winds, would make as much sense as using the surge values measured by tidal gauges in Waveland and Ocean Springs, as they both failed, to suggest the later surge peak wasn't much greater than nine feet in Waveland or 13 feet in Ocean Springs.

Blending surface based anemometer data with other tools such as Doppler radar, CIMSS MIMIC microwave satellite imagery, and aircraft reconnaissance (not only flight level and dropsonde data but also the Stepped Frequency Microwave Radiometer (SFMR)) creates a more coherent, realistic reconstruction of Major Hurricane Katrina.

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Figure 1 Plot of the locations of more than 200 reports written by Henning for properties along the MS Coast:

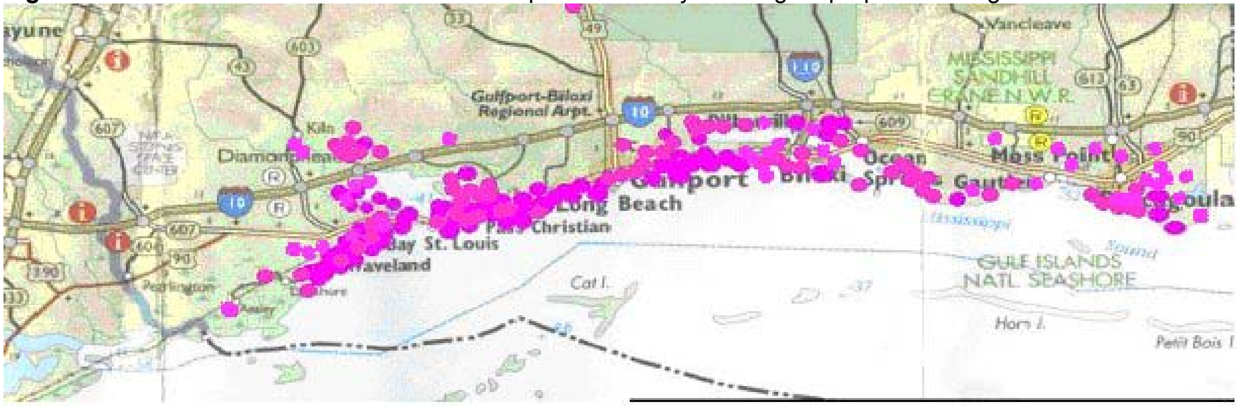
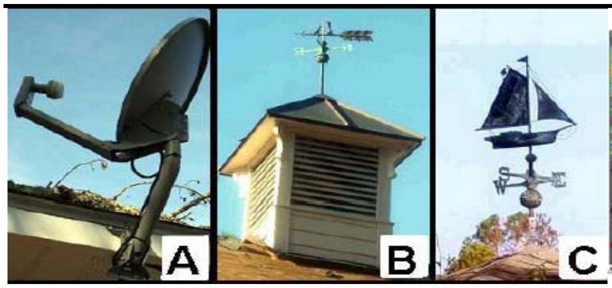


Figure 2 (left) Examining the smallest forensic scales: Examples of items that survived the extreme winds in Bay St Louis and Pass Christian (from Marshall). **Figure 3** (right) On the other end of the forensic scale, we see a swath of 320 million dead or dying trees from space in the wake of Katrina representing 105 teragrams of carbon or between 50 and 140 percent of the total annual US forest carbon sink (from Chambers et al)



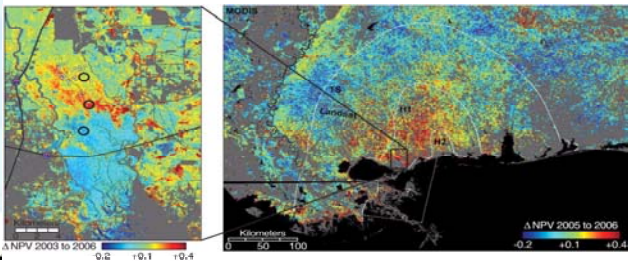


Figure 4 A plot of reduction in sustained (one minute avg) wind speed versus distance from open water exposure for approximately 100 locations along the Mississippi Coast. Assignment of best-fit curves to the scatter of points results in approximate grouping into the terrain categories shown. The reduction in wind speed shown is for quasi-laminar flow in a stable boundary layer characterized by stratiform precipitation. With active convection and turbulent mixing, as with a highly unstable boundary layer, the erosion of sustained wind with distance inland is far less predictable.

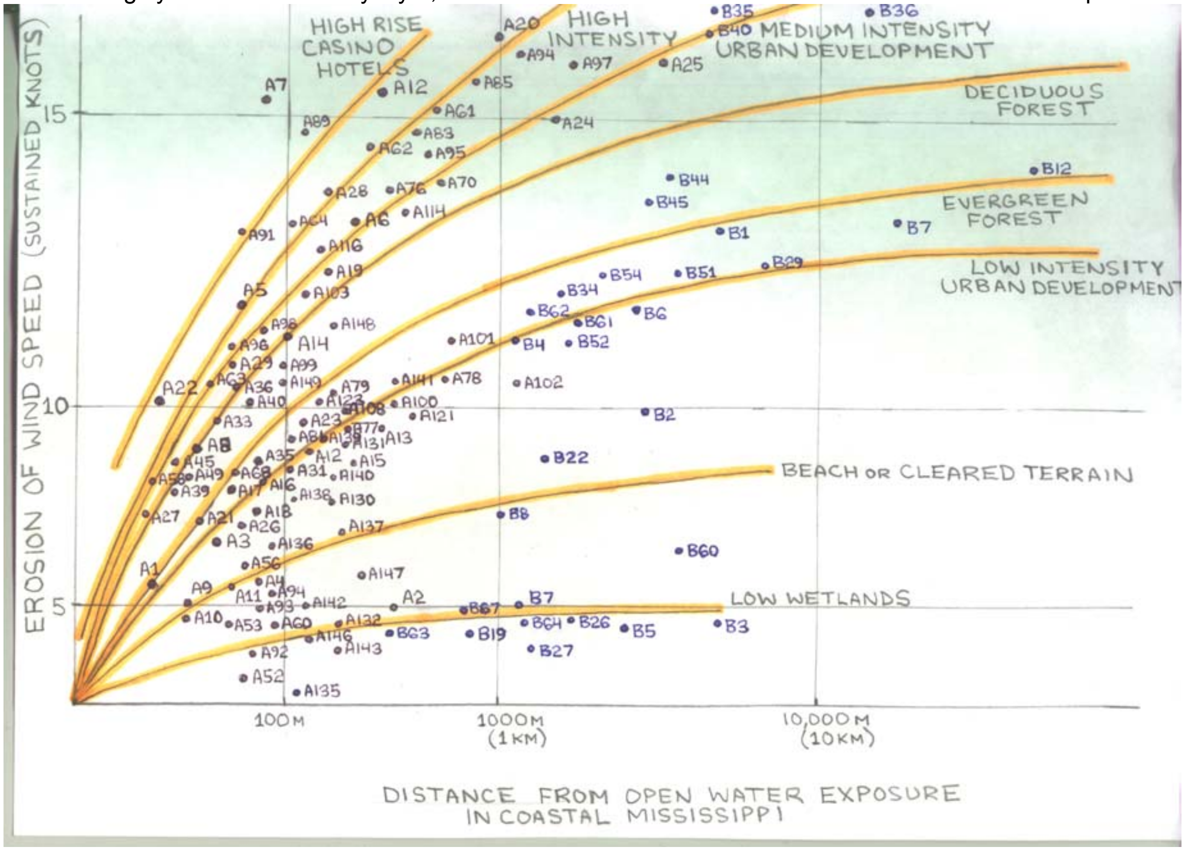


Figure 5 US Geological Survey Multi-Resolution Land Characteristics (MRLC) imagery of the Biloxi, MS area. The cross section from A to B traces the path of southeasterly wind parcel from the Mississippi Sound, across the beach, then a densely packed collection of low rise condominiums, apartments and hotels along Highway 90 southwest of Keesler AFB. Several low intensity neighborhoods, open urban areas and businesses along Pass Road cover the next 2.5 kilometers before reaching the expanse of The Back Bay of Biloxi. The final portion of the trajectory moves across the wetlands of Big Lake, the mouth of the Biloxi River and into the Eagle Point neighborhood of North Biloxi.

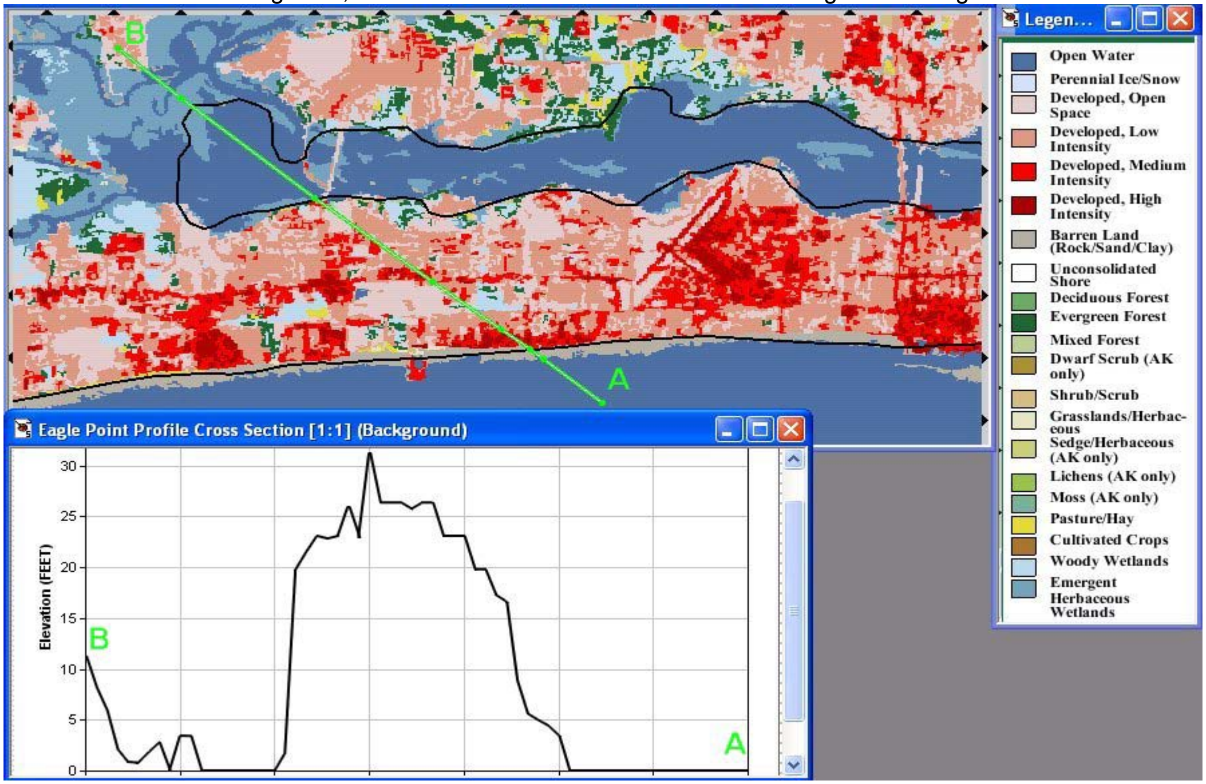
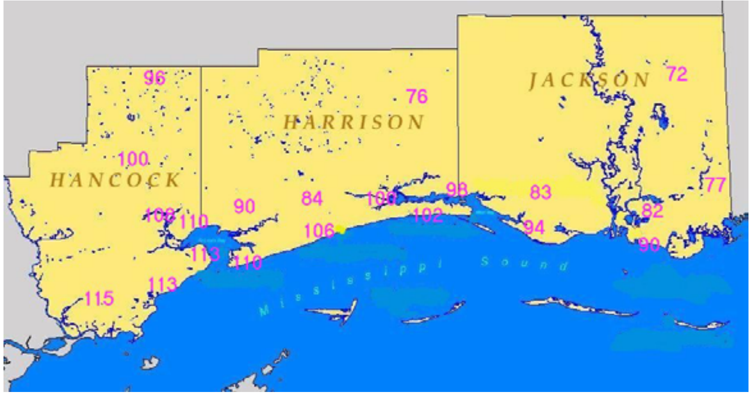


Figure 6 (left) Maximum sustained winds at various location in the three county area. **Figure 7 (right)** shows the lag between max winds in the outer eyewall around Biloxi and the subsequent surge as calculated by CNMOC Stennis Space Center ADCIRC:



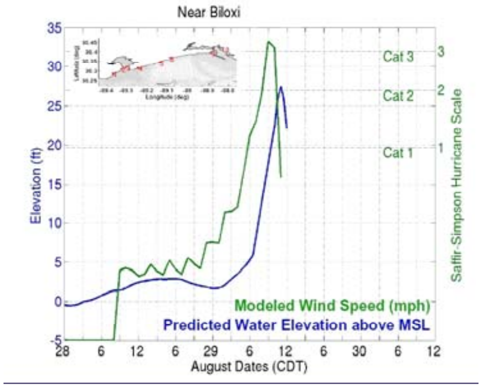
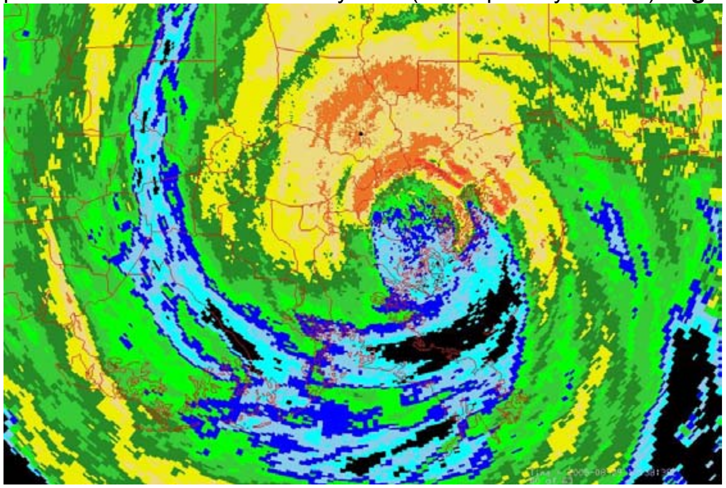


Figure 8 Plot of the paths of 13 mesovortices as detected by radial velocity products from the Slidell and Mobile sites

Figure 9 (left) 1338 UTC Slidell radar imagery of intense convection moving over Waveland, MS associated with the partial reformation of an inner eyewall (interrupted by landfall). **Figure 10 (right)** surge timeline in Waveland.



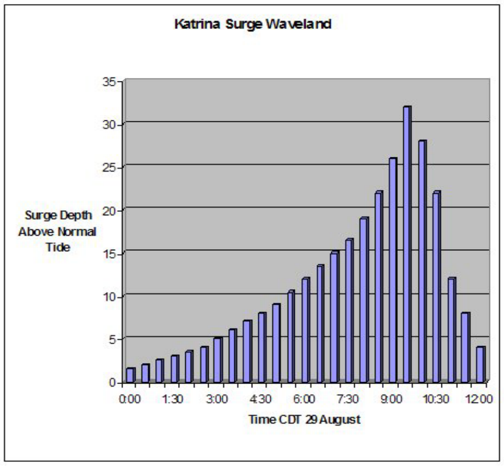
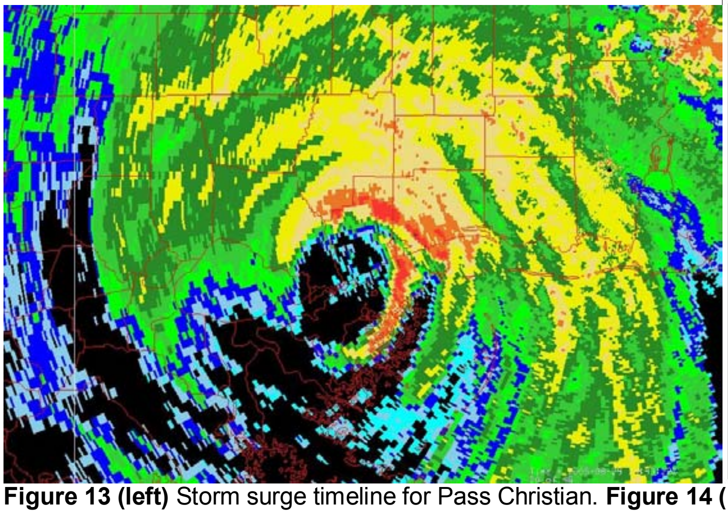


Figure 11 (left) 1443 UTC Slidell radar imagery of the inner eyewall convection moving inland across Saint Louis Bay into Diamondhead **Figure 12 (right)** The surge timeline in Diamondhead shows a peak 60 min later than Waveland.



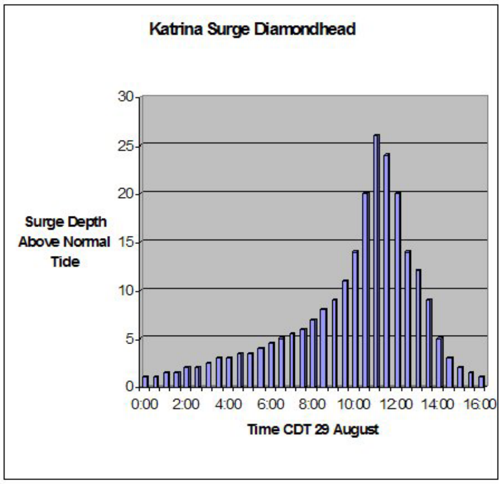
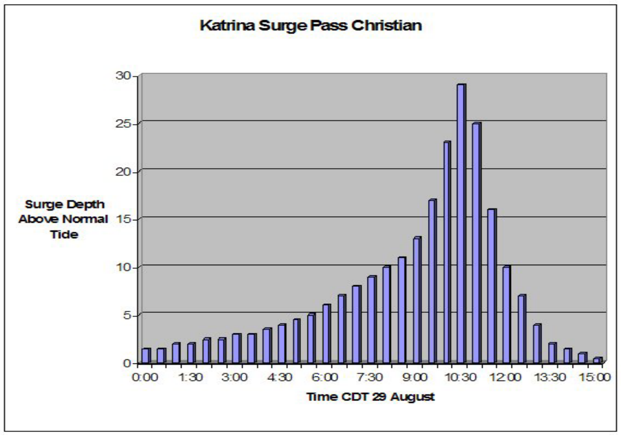


Figure 13 (left) Storm surge timeline for Pass Christian. **Figure 14 (right)** Storm surge timeline for Biloxi.



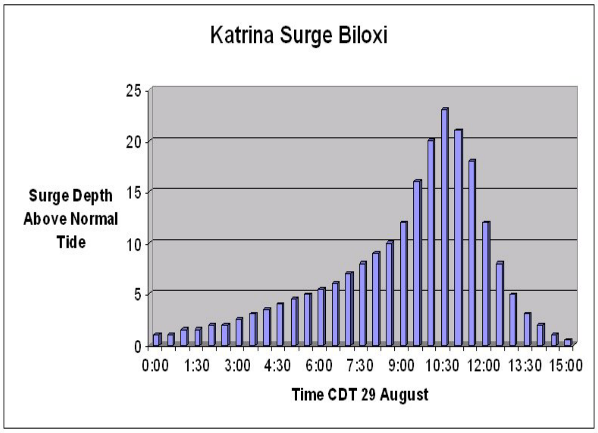
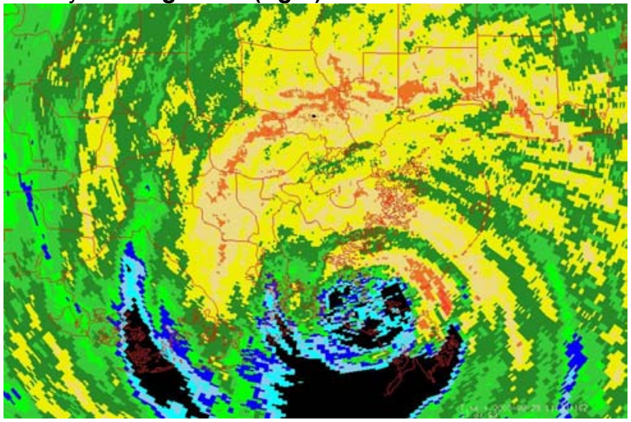


Figure 15 (left) Mobile radar imagery from 1133 UTC showing an intense feeder band sweeping across Jackson County then **Figure 16 (right)** from 1416z shows the outer eyewall moving in.



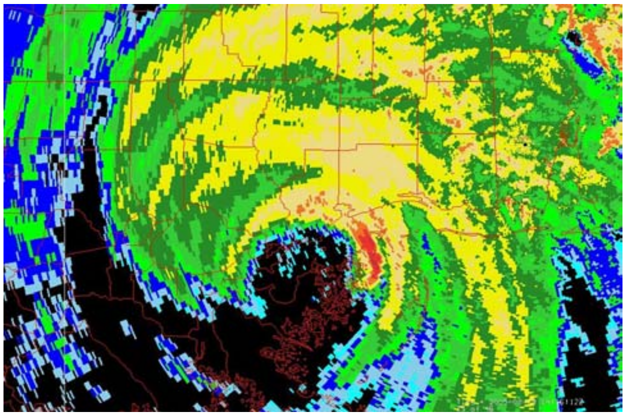


Figure 17 (left) Storm surge timeline for Pascagoula.