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Wind Versus Water Damage to Buildings: A Meteorological Perspective

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1. INTRODUCTION

No sooner than a hurricane has dissipated, than another storm begins to brew about whether the damage done to buildings was caused by wind, rising water, or both. This controversy arises due to various insurance coverages. Typically, private insurance companies pay for wind damage, whereas government insurance pays for rising water damage. The task to delineate the types of building damages is left to adjusters and engineers. Occasionally, meteorologists are asked to develop a timeline with regard to the magnitudes and directions of wind and rising water for particular building locations. While meteorological studies do not take the place of detailed site inspections, they can provide a better understanding of how wind and rising water damages occurred.

This paper will present certain data sources that are available to meteorologists after a hurricane and describe how to best utilize these data to establish a wind and water timeline for a particular building site. Among the most important meteorological data are surface wind and water observations. These data can be compared and extrapolated to certain sites within reasonable distances of the building in question. Numerical models may help fill in some of the gaps; however, the author has seen dramatic differences in model results based partly on initial assumptions. Dropsonde, radar, and satellite data might shed some light on the characteristics of the hurricane; however; these data have other limitations that will be described herein.

Finally, this paper will discuss what to look for when a site inspection is conducted. Analysis of the building site can provide clues on the magnitudes and directions of wind and water forces.

2. SURFACE WIND DATA

There are a number of sources where wind data can be obtained after a hurricane. The National Climatic Data Center (NCDC, 2007) assembles wind data from the National Weather Service (NWS) as well as certain military installations. These data are available a few days after the storm and can be accessed via subscription.

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Additional features on NCDC's web site are product date ranges and detailed station descriptions. Also, photographs of the wind towers from various directions are available for certain locations.

A number of private organizations deploy wind recording equipment in the paths of hurricanes. Among those groups are the Florida Coastal Monitoring Program (FCMP, 2008) and Texas Tech University (TTU, 2008). Plots of wind speed and direction can be found on their web sites for a number of hurricanes.

2.1 Wind data characteristics

The quality of wind data is related to the type of equipment and its location. There are a variety of anemometer types and qualities on the market today. The most common anemometers are cup, propeller, hot-wire, and sonic.

The location of an anemometer is crucial to obtain the best quality data. Typically, anemometers are placed on booms or cross arms connected to a tower. The idea is to position the anemometer out in the wind stream and minimize turbulence from the tower. According to NOAA (2008a), standard tower heights should be 10m and the tower should be located in open, unobstructed terrain such as an airport. Obstructions can create large errors in wind speed and direction as shown in Fig. 1. Plotted are three wind speed measurements from three different anemometers in Pascagoula, MS during Hurricane Katrina.

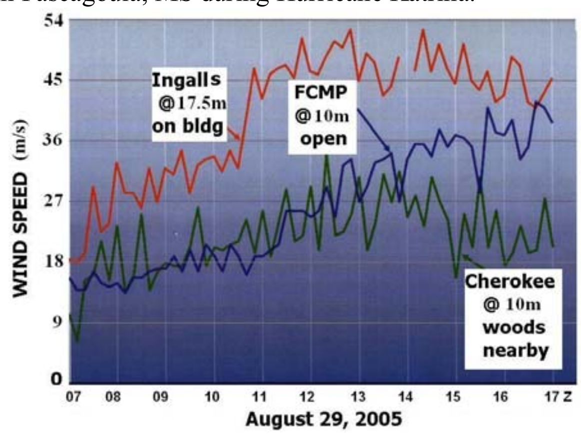

Figure 1. Three-second wind gusts from three different sites in Pascagoula, MS during Hurricane Katrina.

Note the higher wind speeds at the Ingalls site compared to the other two sites. The anemometer at the Ingalls site had been installed 1.5m above the southeast roof corner on a 16m high building (Fig. 2). This anemometer recorded wind speeds up to 53 m/s, or more than twice as high (at times) as the other two sites. Also, wind damage at the Ingalls site was not indicative of 53 m/s winds per the EF-scale (see WSEC, 2006) (i.e. surrounding buildings did not have failed columns). This author believes that the higher elevation of the anemometer as well as the accelerated airflow over the building contributed to the higher winds speeds, especially with easterly and southerly winds. Unfortunately, in certain legal cases, some meteorologists and engineers used the raw wind data from Ingalls to calculate the wind speeds and wind loads on nearby homes without correcting these data for height and exposure. These homes were not more than 5m high, and were located in wooded areas where the wind speeds naturally would be lower.

Figure 2. Wind velocities were affected by placing this anemometer at the southeast corner of a tall building at Ingalls Shipyard.

In contrast, the FCMP portable wind tower at the Trent Lott International Airport was located 10m above the ground at the north end of the a 1981m runway (Fig. 3). The wind tower was positioned at this location in order to obtain the greatest open fetch across open land when the strongest winds were from the south (Gurley, 2006) and was at the standard height and exposure. They recorded a peak three-second wind gust of 41.6 m/s at 10m. This was a much better location in terms of data quality although it was farther away from the buildings in question.

The wind tower at Cherokee Elementary School was located at 10m, but had pine forests 100 to 150m to the east, south, and west. Wind speeds from this anemometer were slightly lower than at the Trent Lott International Airport due, in part, to the affects of the increased surface roughness from nearby forests.

Figure 3. Portable wind towers like this one yield the best data when placed in open, unobstructed terrain. Source: FCMP.

Powell (1996a and b) described the problems with anemometer locations in his study of Hurricane Andrew data. He presented a five step method on how to adjust wind speeds to a common height, exposure, and averaging time. Only in this way can anemometer data be compared directly to each other. It is important that meteorologists understand how wind data should be corrected especially when these data are being extrapolated to particular building locations. There usually are a number of useful data sets available from hurricanes. Such was the case with Hurricane Katrina, when Texas Tech University personnel deployed three mobile wind towers at the north end of Stennis International Airport in Bay St. Louis, MS (Fig. 4). These data show good agreement between all the three recording platforms.

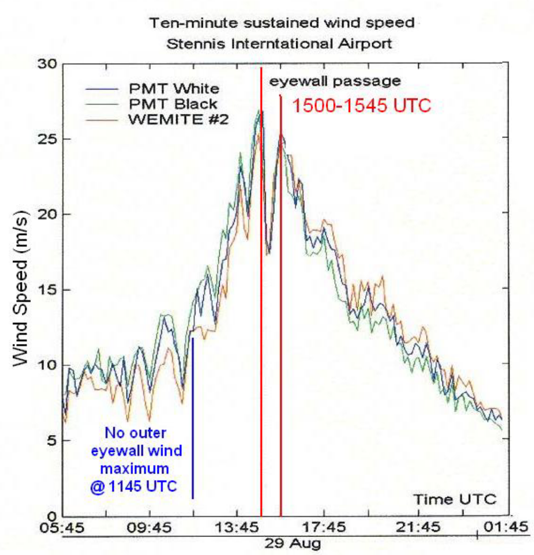

Figure 4. Observed ten-minute sustained wind speed time history from all three wind platforms at the Stennis site. Source: Giammanco et al. (2006).

2.1 *Corrections for height*

Corrections for different heights can be made by using the Power Law which can be expressed as:

$$V = V_r\,(Z/Z_r)^{1/\alpha}$$

where V is the wind speed (in m/s) at height Z (in meters), and V_r is the known wind speed at reference height Z_r. The exponent α is the roughness coefficient which varies by exposures per the American Society of Civil Engineers (ASCE, 2005) and are shown in Table 1. Exposure B is suburban or wooded terrain, Exposure C is open, unobstructed terrain, and Exposure D is along water surfaces. For example, the 41.6 m/s wind at 10m at the FCMP site would equate to 38.7 m/s for a nearby 5m roof top in Exposure C.

Table 1
Terrain-Exposure Coefficients per ASCE (2005)

Exposure	α	Zg (m)
B	7.0	365.76
C	9.5	274.32
D	11.5	213.36

2.2 *Corrections for exposure*

To correct for different exposures, it is first necessary to obtain the gradient wind using the Power Law equation:

$$V_g = V_r\,(Z_g/Z_r)^{1/\alpha}$$

where V_g is the wind speed (in m/s) at the gradient height Z_g (in meters), and V_r is the known wind speed at reference height Z_r. Then, the wind speed can be converted to other exposures or heights. Continuing with our example, the 41.6 m/s wind at 10m in Exposure C would equate to a gradient wind of about 59 m/s at Z_g (274.32m) in the same exposure. If converting to a rooftop in Exposure B at 5m, the coefficients for Exposure B are utilized in the Power Law formula:

$$V_B = V_g\,(Z_r/Z_{gB})^{1/\alpha}$$

Thus, a 41.6 m/s wind at 10m in Exposure C would equate to about 32 m/s for a 5m roof top in Exposure B, a reduction of 23 percent.

2.3 *Corrections for time-averaging period*

The relationship between short-duration gusts and the average wind speed is important in calculating the wind loads for a building. The ASCE (2005) standard employs the Durst (1960) curve whereas Krayer and Marshall (1992) developed a curve using 11 wind records taken from four different landfalling hurricanes. Conder et al. (2006) measured the winds in four additional hurricanes and found their gust factors were close to the Krayer-Marshall curve (Fig. 5).

These gust factor curves indicate that a three second wind gust is about 30 percent higher than a one-minute mean wind speed. Three-second gusts are currently used as the design wind speed in ASCE (2005). Thus, knowing the time duration of the wind is important. As Powell et al. (1996a and b) noted, uncorrected wind speeds can lead to exaggerated claims of wind speeds that caused the damage. They further indicated that failure to implement correction procedures to wind data may lead to errors as much as 40 percent.

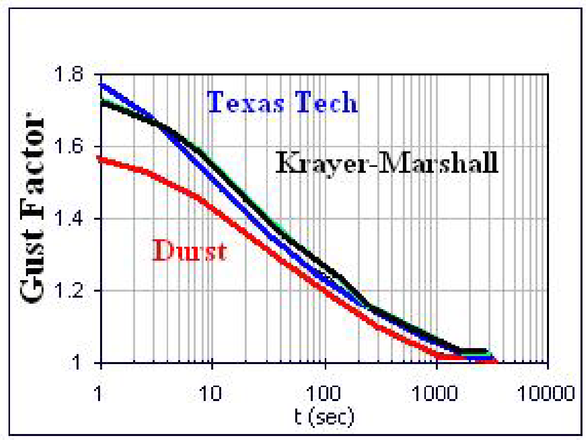

Figure 5. Comparison of gust factor curves from Texas Tech, Krayer-Marshall, and Durst. Source: Conder et al. (2000).

2.4 *Wind direction*

Wind direction changes with time during a hurricane. Thus, wind forces on a building will vary with the changing wind direction. In some instances, the wind direction may switch 180 degrees during the course of the storm.

A wind rose plot of the changing wind direction with time may be helpful in understanding the time that the wind damage occurred (Fig. 6). This figure shows that winds began out of the east, then switched to the south (as the hurricane eye made landfall to the west), and then ended up out of the southwest. Since the direction of the roof damage was from the south, the author concluded that wind damage must have occurred around 10 AM. However, it was deduced that inward failure of the large west facing door likely occurred during the early afternoon when the wind direction shifted to a more westerly direction.

The same wind rose plot can be utilized to delineate water damage if it can be shown that water submerged the damaged portion of the building before the wind blew from the direction indicated by the damage. Thus, a site inspection would be helpful in order to determine the directions of wind and water forces and resultant building damage.

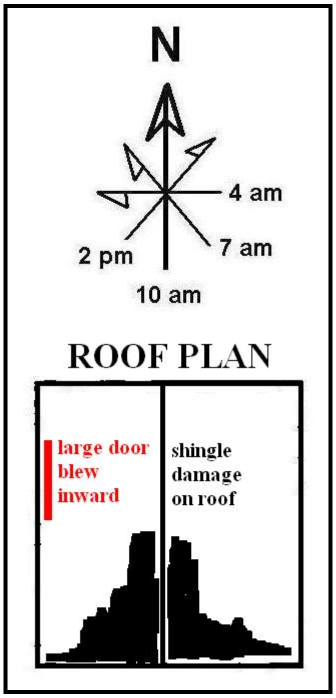

Figure 6. Example showing the importance of plotting wind direction with time to determine when building damage occurred.

2.5 Other wind data

Powell et al. (1996a and b) mentioned that the accuracy of eyewitness observations of digital or analog displays without recorders were extremely difficult to confirm. Also, wind estimates by the public tend to have a high error rate (Marshall, 1991). Thus, the meteorologist should refrain from utilizing such data unless it can be corroborated by other data, such as the extrapolation from recorded anemometer measurements and by the degree of the surrounding wind damage.

When evaluating wind damage for a particular building site, it might be important to know the history of wind that the building might have experienced from past hurricanes. If the building survived higher winds in past hurricanes, but did not survive the current hurricane, then rising water might have been a major factor in the buildings destruction.

3. RISING WATER DATA

There are a number of sources where rising water data can be obtained. The National Oceanic and Atmospheric Administration (NOAA, 2005a) archives tide levels throughout the United States coastline including some islands, inland rivers, and lakes. The United States Corps of Engineers (USCE, 2004) also records such data as do a number of municipalities and private organizations.

According to NOAA (2008b), while older tidal measuring stations used mechanical floats and recorders, a new generation of monitoring stations uses advanced acoustics and electronics. Today's recorders send an audio signal down a half-inch-wide sounding tube and measure the time it takes for the reflected signal to travel back from the water's surface. The sounding tube is mounted inside a six-inch diameter protective well, which is similar to the old stilling well.

Some tide gauge stations also measure wind speed, wind direction, and barometric pressure. These data are helpful to compare the wind and water levels during the storm. Figure 7 shows the wind and water levels for Dauphin Island, AL during Hurricane Katrina. These data clearly show that wind and water levels rose together and peaked about the same time. However, these data do not show wave action or storm run-up which did occur on the coast.

When evaluating water damage for a particular building site, it is important to know the elevation of the property in order to establish a timeline for water inundation. It also might be important to know the history of water levels that the building might have experienced from past hurricanes. If the building survived higher water levels in the past, but did not survive the current storm, then wind might have been major factor in the buildings destruction.

The National Buoy Data Center (NBDC, 2005) has deployed moored buoys in the ocean that measure and transmit barometric pressure; wind direction, speed, and gust; air and sea temperature; and wave energy spectra from which significant wave height, dominant wave period, and average wave period are derived. Even the direction of wave propagation is measured on many moored buoys. However, there are different types of buoys and the height of the wind measuring equipment may vary with buoy type. Thus, height corrections might be needed with these data.

In addition, the NBDC also has Coastal-Marine Automated Network (C-MAN) stations which measure barometric pressure, wind direction, speed and gust, and air temperature. Some C-MAN stations also measure sea water temperature, water level, waves, relative humidity, precipitation, and visibility. These data are processed and transmitted hourly in a manner almost identical to the moored buoy data. Again, height and/or exposure corrections might be needed with these data.

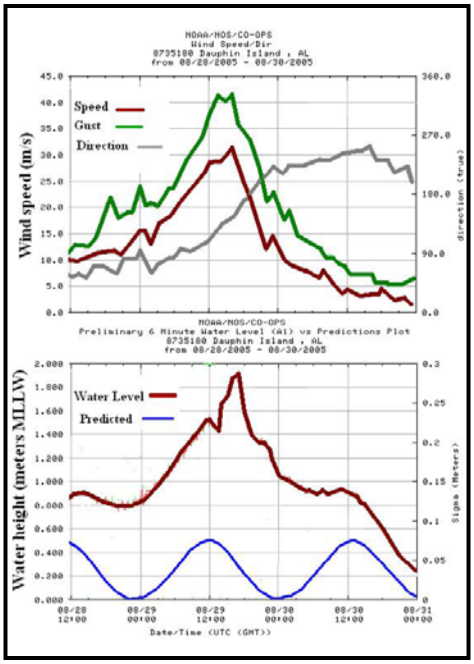

Figure 7. Wind (top graph) and water (bottom graph) data from the Dauphin Island, AL tide gauge station during Hurricane Katrina. Source: NOAA.

FEMA (2006b) along with the United States Geological Survey (USGS) typically measure high water marks after a hurricane. These water marks appear as dirt lines on the interiors of enclosed buildings. The datum level used is the North American Vertical Datum Level in 1988 (NAVD 88). It is important to note that this datum level is usually different than tide gauges and a correction to other datum levels might be warranted. Fortunately, NOAA (2005a) provides the various datum levels. Also, high water mark measurements do not include wave action or runup which can actually be higher than the high water mark on the inside of a building.

4. DATA FROM AIRCRAFT

Wind measurements are obtained by NOAA and hurricane hunter aircraft through the use of dropsondes and stepped-frequency microwave radiometers (SFMRs).

Dropsondes are cylindrical tubes that are ejected from aircraft. Dropsondes contain a global positioning system (GPS) receiver, along with pressure, temperature, and humidity sensors to obtain atmospheric profiles. Typically, these relay data to a computer in the aircraft by radio transmission. The device's descent is usually slowed by a parachute, allowing for more readings to be taken before it strikes the water. As noted by Uhlhorn and Black (2003), the sondes often fail to measure winds all the way to the sea surface, especially under the highest wind conditions.

Figure 8 shows a dropsonde profile that occurred at 1422 UTC over Pass Christian, MS during Hurricane Katrina. These data show a 68.4 m/s wind at 350m decreasing rapidly to 47 m/s at just below 100m before ceasing. Unfortunately, the author has encountered certain meteorologists concluding that boundary layer wind speeds, as shown on dropsonde profiles, were transported to the surface by downbursts, destroying buildings at certain sites before the storm surge arrived. The author found these conclusions were unsupported by actual "ground-truth" data. For instance, wind towers at nearby Stennis International Airport did not record winds greater than 47 m/s at 10m at that time.

Meteorologists must recognize that dropsonde wind speeds represent a "snapshot" of what occurred during the storm. Thus, dropsonde winds may not be representative of the winds that occurred at a particular building site.

The SFMR shoots microwave pulses at six frequencies onto the ocean, then measures those microwave returns. As the aircraft flies through a storm, the SFMR senses microwave radiation naturally emitted from foam created on the sea by winds at the surface. The SFMR directly measures the surface winds and is not confined to a single point like the dropsonde. While the SFMRs give a more complete picture of the storm, these wind speeds may need to be adjusted to the height and exposure of any involved building site.

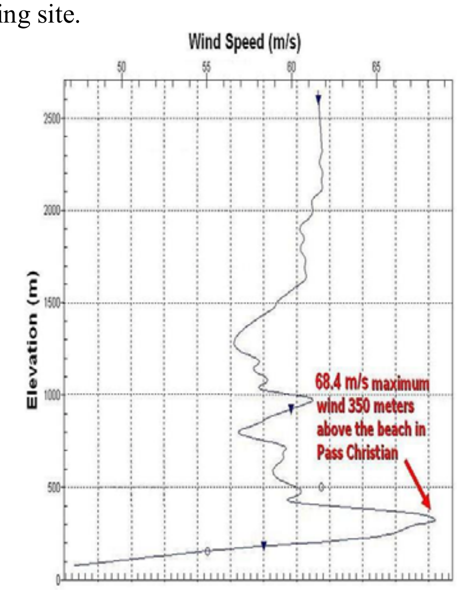

Figure 8. Dropsonde wind profile from AF 302 release at 1422 UTC on 29 August into Hurricane Katrina at Pass Christian, MS. Source: Henning, 2006.

5. RADAR DATA

Analysis of Doppler radar data can provide important information about the hurricane. The location of the eye, eyewall, and spiral bands can be plotted with time. Radar reflectivity provides information on the locations and intensities of convective cells, the stratiform regions, areas of dry air intrusion, and estimates of rainfall accumulation. Radial velocity reveals instantaneous wind speeds over a given region, wind profiles with height, and changes in wind over time. Spectrum Width measures the variability of the wind speed which can yield information on turbulence and rotation. Cross sections of the storm can provide information such as growing precipitation cores, descending precipitation cores, and vertical wind shear.

However, there are many limitations with regard to utilizing radar data when trying to determine what the wind velocities were at a particular building site. The elevation of the radar beam increases with range from the radar. Thus, at 100km range, the center of the beam is approximately 1600m above the radar level. Also, beam width increases with range. A one-degree beam widens about 1 km in width for every 60 km in range. Pulsed radar sampling is in range gates, typically 250 m to 1 km in length. All these dimensions mean that radar measurements (except for portable radars) are likely to represent areas much broader in width and length than any individual building and at a height significantly above the top of the building. Furthermore, current weather radars collect data in a series 9 to 14 elevation angles from low-levels to the height of tall storms. This means that each elevation angle recurs at intervals of from 3 to 6 minutes; sampling at any one height is not continuous.

With these limitations in mind, let us look at an example where a meteorologist erroneously used winds derived from radar to estimate what occurred at a particular building on the ground. Figure 9 shows a radial velocity image taken during Hurricane Katrina showing winds of about 59 m/s at 1250m above the ground. The meteorologist explained that these winds reached the ground by being transported through descending reflectivity cores or downbursts. However, a survey of the building site by the author revealed far less intensity winds had occurred.

Algorithms associated with radar have their limitations. As Fitzpatrick (2006) noted, the mesocyclone detection algorithm does not detect all circulations within hurricanes and only a small percentage of detected mesocyclones produce tornadoes. So, it would not be accurate for a meteorologist to conclude that a downburst, tornado, mini-swirl or other small-scale meteorological phenomenon produced damage to a particular building based on the radar signature alone. "Ground-truth" verification should be done. As noted by Holmes et al. (2006), radar data should be coupled with surface weather observations, along with an analysis of surface damage patterns in order to determine whether extreme wind gusts occurred at a particular location and whether the building damage was caused by wind.

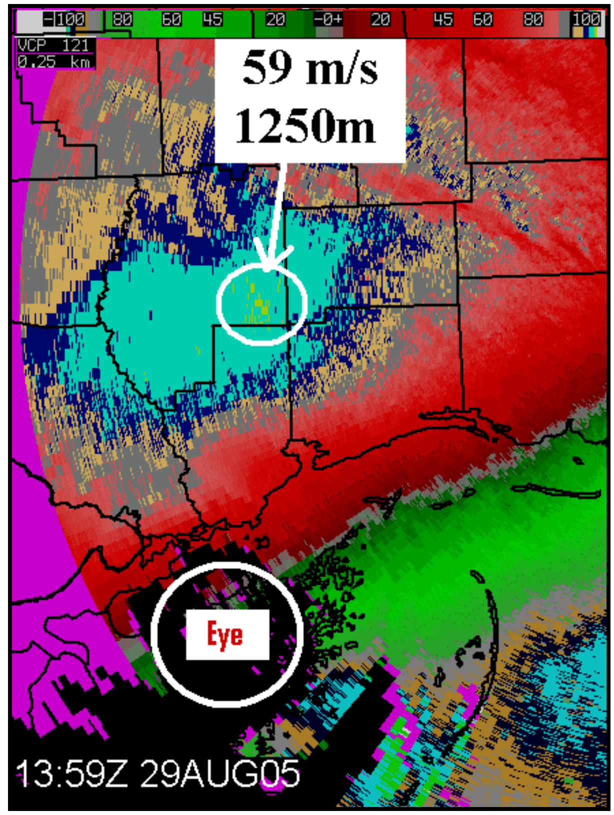

Figure 9. Radial velocity image of Hurricane Katrina at 1359UTC showing elevated winds. Source: Mobile, AL. NOAA/NWS.

6. SATELLITE DATA

There are several satellite-based remote sensing instruments which can be helpful in determining the characteristics of a hurricane: visible, infrared, water vapor, and microwave. According to Kidder et al. (2000), microwave remote sensing has the following advantages over other types of imagery: 1) microwave radiation penetrates clouds, and 2) microwave radiation is sensitive to a wide variety of geophysical parameters which includes estimates of surface wind speeds. The microwave signal can penetrate through obstructing ice clouds that are common in tropical cyclones and uniquely reveal the structure of the eyewall and organization of the spiral bands.

One type of satellite derived product is the Morphed Integrated Microwave Imagery (MIMIC) developed by at the Cooperative Institute for Meteorological Satellite

Studies (CIMSS). According to Wimmers and Velden (2007), the MIMIC product is a synthetic blend of tropical cyclone imagery from five low-Earth orbiting satellite instruments. MIMIC creates an animated sequence of images with 15 minute time steps.

A MIMIC image of Hurricane Katrina is shown in Figure 10. A meteorologist erroneously concluded that the presence of a spiral band or outer eyewall on MIMIC imagery meant that "extreme" winds occurred at a particular building site on the Mississippi coast at 1145 UTC, hours before the storm surge reached its peak. Had the meteorologist looked at surface wind records (see Fig. 4), it would have become apparent that no secondary wind maximum occurred. Also, winds on the Mississippi coast were out of the east at that time, whereas the strongest winds and bulk of the wind damage occurred later when winds were from the southeast and south.

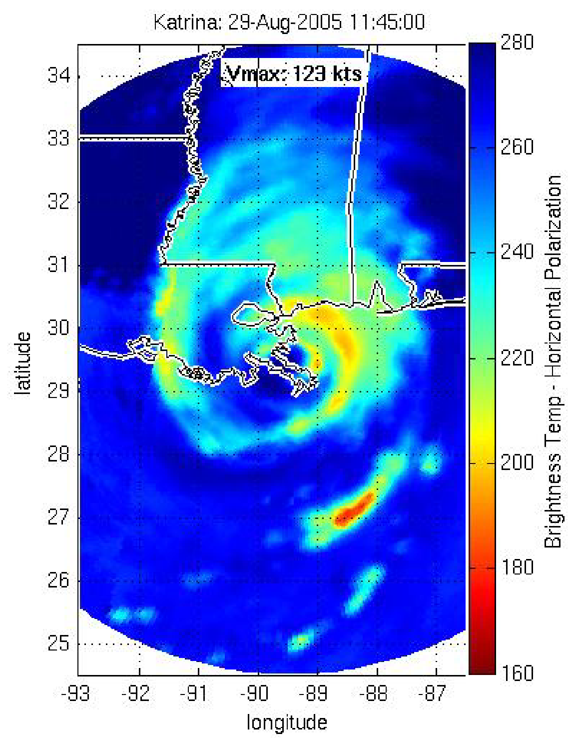

Figure 10. MIMIC image of Hurricane Katrina taken at 1145 UTC on 29 Aug. 2005 showing outer band. Source: MIMIC (2005).

Satellite derived estimates of wind speeds have low resolution and are likely to represent areas much broader in width and length than any individual building. Therefore, meteorologists using satellite-based estimates of wind speeds (like radar estimates) need to compare their results with surface-based weather observations as well as conduct an inspection of the building site to determine whether extreme wind gusts occurred at a particular location.

7. NUMERICAL MODELS

There are various types of numerical models used to simulate wind and/or water levels from a hurricane. Among the most popular models are the ADCIRC (Advanced Circulation), SLOSH (Sea, Lake, and Overland Surges from Hurricanes), and HRSM (High Resolution Surge Model). There are also a number of private consulting companies that have their own models, the details of which remain unknown since their models are proprietary. Regardless, all models have pros and cons but ultimately their accuracy relies upon verification.

Figure 11 shows an ADCIRC model solution for Biloxi, MS during Hurricane Katrina published on the Internet by the Commander of Naval Meteorology and Oceanography Command (CNMOC, 2005). Several meteorologists have utilized these "preliminary" outputs to base their opinions that hurricane force winds destroyed buildings along the coast prior to the storm surge reaching those buildings. However, comparison of the model results with actual data indicated that the maximum winds were predicted too early. Also, the peak storm surge predicted by the model arrived about an hour later than measured data showed. Therefore, it is important that the meteorologists verify their conclusions by using actual data and conducting site surveys.

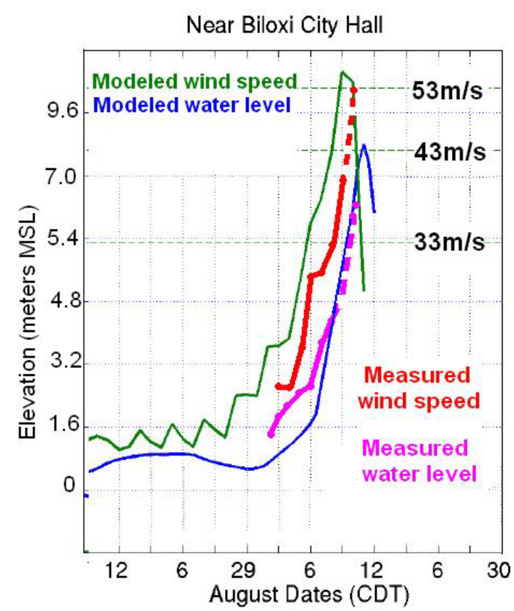

Figure 11. ADCIRC model prediction of wind and water levels at Biloxi, MS during Hurricane Katrina compared to actual wind measurements at Keesler Air Force Base in Biloxi and tide gauge data at Ocean Springs, MS (about 10km east of Biloxi). Dashed lines are approximate to peak. Source: (CNMOC, 2005).

8. SITE INSPECTION

A detailed inspection of the building site and surrounding properties remains the best way to determine the magnitude and direction of the wind as well as the heights of the water levels. As Bunting and Smith (1993) noted, damage vectors of downed trees, building items, and other debris should be determined. Such vectors show the final direction of the wind and water forces. As mentioned earlier, a comparison of these damage vectors along with meteorological data can help establish a timeline of when wind and water forces occurred. However, care should be taken to consider those damage vectors that could have been altered by storm influences, such as debris being deposited by receding water.

Wind speeds can be estimated based on the degree of damage to the building site or lack of damage. Mehta et al. (1983) and Kareem (1984) utilized the concept of wind speed-damage correlation after Hurricanes Frederic and Alicia, respectively. More recently, FEMA (2006a) and NOAA (2005b) utilized the concept of wind speed-damage correlation in their analyses of Hurricane Katrina damage. Marshall (2008) used EF-scale, wind speed-damage correlation relationships to find that wind speeds along coastal Mississippi ranged between 41 m/s for the vast majority of structures, but on occasion reached 48 m/s at 10m. These wind speed values correlated well with ground-based wind records.

In essence, each building acts like an anemometer that records the maximum wind speeds. Thus, a range of failure wind speeds can be determined by analyzing building damage whereas undamaged buildings provided upper bounds to the wind speeds. The National Weather Service employs the concept of wind speed-damage correlation through the use of the EF-scale (see WSEC, 2006).

Analysis of aerial photographs can be helpful in delineating wind and water damage. Fujita and Smith (1992) have studied numerous aerial photographs of many events to determine whether tornadoes or microbursts had occurred. They found that tornado damage typically has long, narrow paths with converging damage vectors. In contrast, microbursts have diverging damage vectors that appear fan- or starburst-shape.

The details of the storm surge can be identified by alluvial deposits of sand or dirt that indicate wave wash zones. Debris or rack lines may be visible at the termination points of the wave action especially in more populated areas.

It is important for the meteorologist to recognize the myths that are associated with such windstorms. As Bunting and Smith (1993), NOAA (2003), and Marshall (1993) have pointed out, twisted trees do not indicate a rotating wind. Neither do broken tree tops prove that a tornado funnel occurred. Also, the fact that one building or tree stands while an adjacent one remains is not evidence of a skipping tornado. Furthermore, eyewitness reports of "roaring sounds" do not confirm the presence of a tornado. As McCaul (1991) noted, tornadoes are rare, even in hurricanes. Thus, the odds of a building site getting struck by a hurricane-spawned tornado are remote.

Figure 12 shows an aerial view of the destruction along the coast in Long Beach, MS after Hurricane Katrina. Homes were completely destroyed near the beach but remained intact inland. A debris line can clearly be seen along the boundary. Some meteorologists have erroneously concluded that the sharp gradation in building damage was caused by stronger hurricane winds along the coast and that storm surge merely washed away the debris. However, most trees remained upright and there was a lack of roof debris or insulation in trees, which usually occurs when wind destroys houses. Other meteorologists have stated in error that tornadoes or some other localized wind phenomenon gathered up the debris in "windrows" creating the observed debris line.

Recently, tornado warnings have been issued by the National Weather Service as high wind warnings for the eyewall. In these instances, the issuance of a tornado warning does not mean a tornado has been confirmed. According to the Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM, 2006), a tornado warning may be used in hurricanes to warn the public to immediately take shelter in an interior portion of a well-built structure due to the onset of extreme tropical cyclone destructive winds. Extreme tropical cyclone winds are defined as greater than or equal to 51.4 m/s and are expected to develop or occur within one hour from the time the warning is issued. The tornado warning valid time should be two hours or less and the tornado warning for extreme tropical cyclone winds will not be reissued or extended for the same county or parish. Thus, meteorologists should not rely on tornado warnings as proof that a tornado hit a particular building.

Figure 12. Sharp gradation in housing damage along the Mississippi coast after Hurricane Katrina left some people questioning whether the destruction was caused by wind or water. Source: NOAA

9. SUMMARY

Meteorologists are frequently called upon by the legal community to assist in delineating wind and water damages to insured buildings after a hurricane. Meteorologists must wade through a wealth of weather information. Some of these data are good quality while other data are contaminated or are poor quality. While surface weather observations remain among the most important information with regard to determining wind and water levels for a particular area, these sites are sometimes spaced far apart and/or only have a partial record. Problems with siting anemometers might necessitate employing some type of correction for height and/or exposure to the wind record.

Dropsonde data from aircraft may help fill in some of the gaps in the wind records. However, these data are not continuous records and have problems sampling the low-level winds on the coast. Radar and satellite imagery are crude and cannot determine what happened at a particular building site. Corroboration by additional detailed weather information and data from "ground-truth" inspections is needed. Therefore, a detailed inspection of the building site and surrounding properties remains the best way to determine the magnitude and direction of the wind and water forces.

10. ACKNOWLEDGEMENTS

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