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Hurricanes: A Primer for the Aviation Professional

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HURRICANES: A PRIMER FOR THE AVIATION PROFESSIONAL

Randell J. Barry

Abstract

This article has been written in response to the recent increase in hurricane activity within the Atlantic basin and the expectation that this heightened activity will continue for another 20 to 30 years. Its purpose is to educate aviation professionals on the hurricane phenomenon. The topics presented are focused, keying on information that will help these individuals better protect their aircraft and other resources. The issue of aircraft evacuation in response to a threatening hurricane is addressed throughout this paper.

Introduction

The number of hurricanes per season in the Atlantic basin, and therefore the potential for destruction from these storms, has shown a cyclical pattern with activity varying on the scale of decades. The period from the late 1920s through the 1960s was a time of relatively high activity in the Atlantic. Then activity decreased from about 1970 through the early 1990's (Goldenberg, Landsea, Metas-Nunez, and Gray, 2001). This region is now approximately ten years into another period of increased activity. This most recent period has been highlighted by many unusual events. This includes the record setting 2005 season in which there was an unprecedented occurrence of 28 named storms (NOAA News Online, April 13, 2006). The unofficial record up until 2005 was 21 set in 1933 and the official record was 19 set in 1995, a year also within this latest period of heightened activity (NOAA/AOML, October 19, 2005). Given the historical pattern in storm frequency, the recent increase in activity is expected to last up to another 30 years.

Aircraft are particularly vulnerable to the destructive force of these storms, especially those

in the general aviation class. For example, when Charley moved through central Florida in August 2004 several aircraft in its path from Punta Gorda to Daytona Beach experienced significant damage (Anonymous, 2004/2005). When Wilma moved through south Florida in October 2005 both general aviation and larger jet transport aircraft were severely damaged at the Opa-locka Airport (Boyd, 2006).

Therefore, motivated by this recent increase in hurricane activity, the high probability that this period of high activity will persist, and the destructive impact these storms can have on aircraft this article has been written. My goal is to provide aviation professionals located along the hurricane prone East and Gulf Coasts of the United States with knowledge that will help them better protect their resources.

Having an understanding of the hurricane phenomenon is essential to making informed decisions on how to limit the impacts of these storms. A basic but thorough understanding of the hurricane phenomenon is presented in this paper. This information will be focused, keying on those aspects of hurricanes that the decision maker in aviation needs to understand to better protect their

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aircraft and other resources.

One particular issue faced by the individual responsible for aircraft when a hurricane threatens is whether to evacuate their aircraft or stay put. This issue is an important part of this paper and is addressed throughout as we look at the hurricane phenomenon.

Hurricanes: A Definition

A hurricane is a surface low pressure center of tropical origin producing a distinct cyclonic (i.e., counter-clockwise) surface circulation that spirals in towards the storm's center. Surface wind speeds within a portion of the storm must be greater than 64 knots (74 mph) for the storm to be classified as a hurricane (Ahrens, 2003; NOAA/AOML, October 19, 2005). Note that the wind speeds reported with a hurricane or developing storm are sustained wind speeds (i.e., the average wind speed within a certain time period). The averaging period for winds reported with hurricanes is one minute. The implication of

this is that wind speeds above the reported value (i.e., gusts) may also be present. If significant gusts are present, however, they are usually reported with the sustained wind speeds (NOAA/AOML, October 19, 2005).

An example of a hurricane as seen on a surface weather map is shown in Figure 1. This map shows surface conditions for 15 September 2004 at 18 UTC when Hurricane Ivan was approaching the Gulf Coast. The surface low pressure center and cyclonic circulation associated with Ivan is easily seen in this image. While this mean sea level pressure analysis indicates a central pressure somewhere between 988 and 992 mb, the central pressure of Ivan was in fact down to 937 mb at this time. This is a value 76 mb below the standard sea level pressure of 1013 mb. The maximum sustained wind speed that resulted from this "deep" low pressure center was 115 knots easily giving this storm hurricane status.

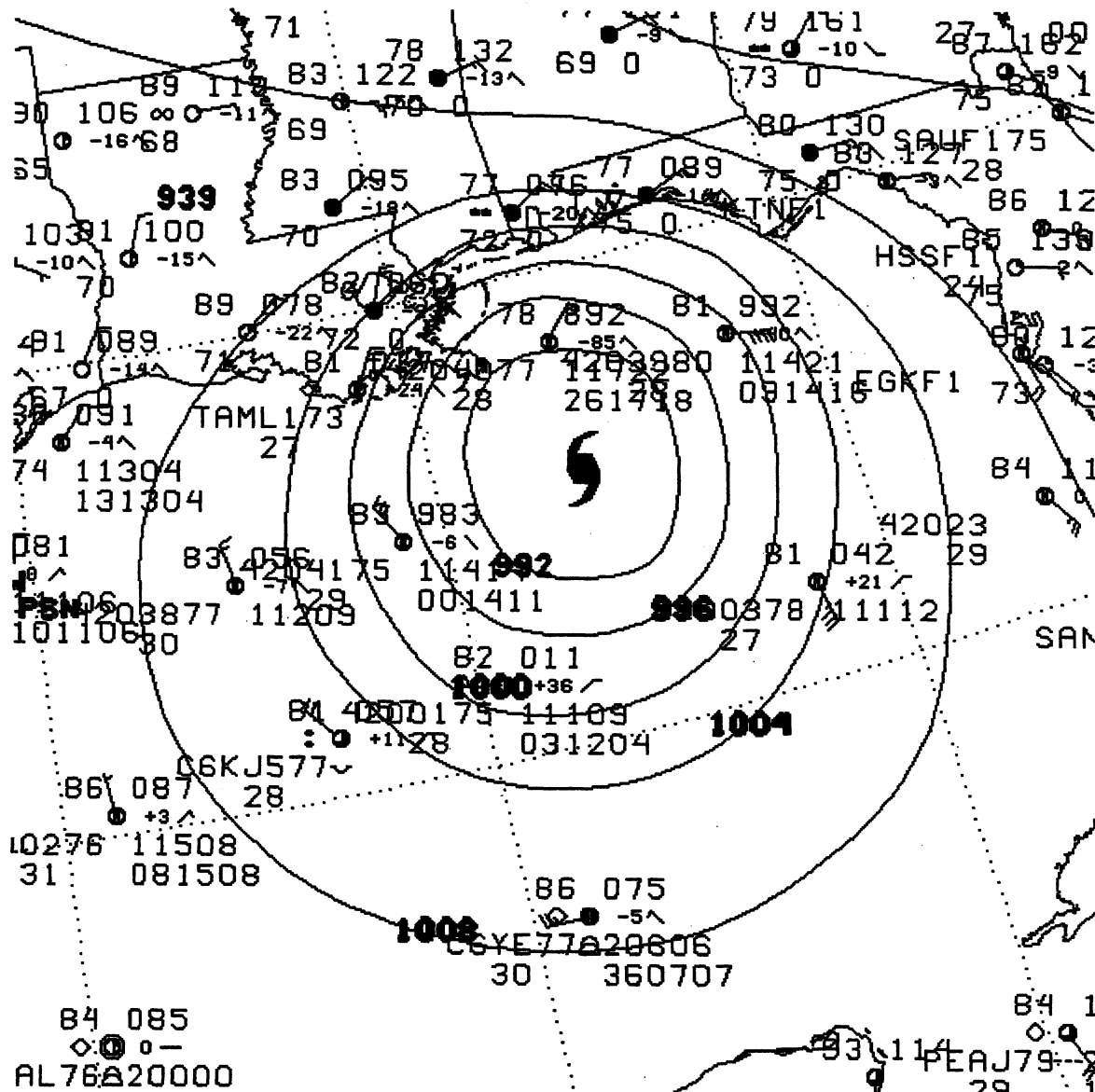


Figure 1. Surface weather conditions on 15 Sep 2004 at 18 UTC as Hurricane Ivan was approaching the Gulf Coast. Weather parameters (e.g., wind speed and direction) at surface observing locations are indicated using the standard surface station model. Lines of constant mean sea level pressure (i.e., isobars) are drawn every four millibars (mb) centered on the 1000 mb value. Ivan's position is indicated using the standard hurricane symbol.

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Hurricane Structure and Size

The structure of the hurricane circulation extends through a significant depth of the atmosphere as illustrated in Figure 2. Although not indicated in the figure, the overall circulation of the storm typically reaches upwards to 15 km (~50000 ft). As stated earlier, the winds near the surface are moving in a counter-clockwise direction around and converging into the storm

center. And this counter-clockwise motion predominates through almost the entire depth of the storm. Near the very top of the storm, however, the circulation reverses becoming clockwise and divergent (Ahrens 2003). This upper portion of the storm is often referred to as the storm's "divergent outflow region".

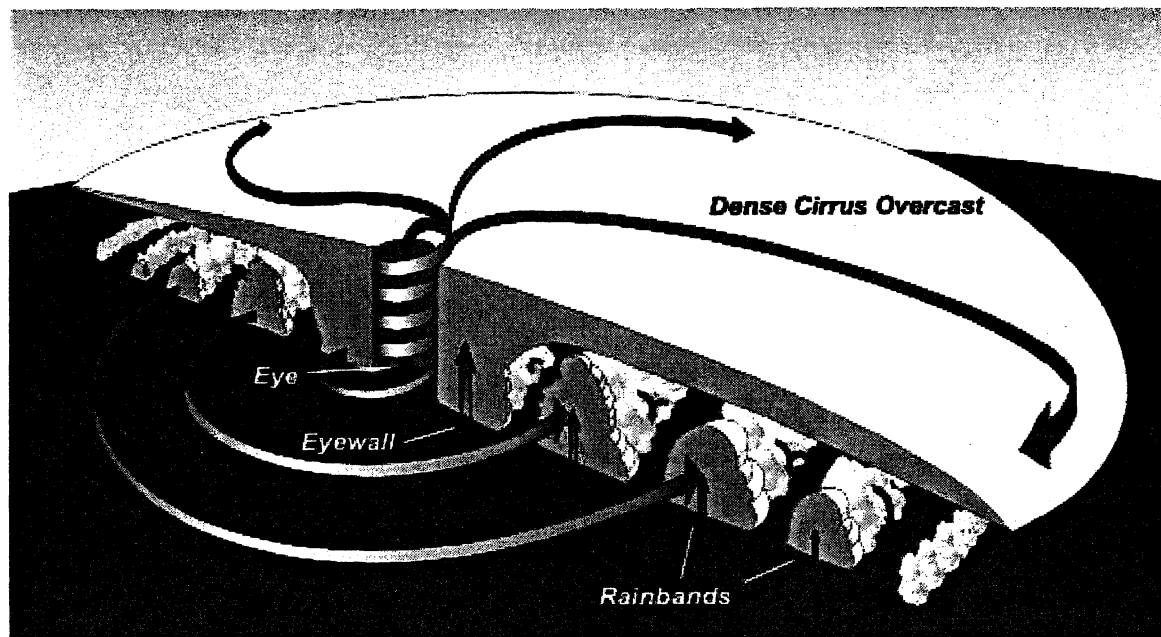


Figure 2. A three-dimensional representation of a hurricane. Credit: JetStream An Online School for Weather, NWS Southern Region; <http://www.srh.weather.gov/srh/jetstream/>

An interesting aspect of the vertical structure of the circulation is that the strongest winds within the storm occur near the surface. This differs from what we typically observe in the atmosphere, especially at midlatitude locations. In the midlatitudes wind speeds generally decrease with altitude and peak at the jet stream level (i.e., 20 to 40 thousand feet). In hurricanes, however, the maximum wind speeds occur approximately 500 m (~1500 ft) above the ground with wind speeds decreasing upwards from this altitude. Wind speeds experienced at the surface are generally 15 to 25 percent less than this maximum value (Franklin, Black, and Valde, 2000). Therefore, 100 knots at 1500 ft agl would typically result in 75 to 85 knots at the surface.

Other noteworthy features of the storm's structure include the eye, the eyewall, and the spiral rainbands. The eye is the generally cloud-free region at the storm's center of circulation (Ahrens 2003; Vescio, Cooper, and Cain, August 9, 2006). Over a large portion of the storm the air is rising producing the cloudiness and precipitation we observe. Within the eye, however, there is significant sinking motion leading to the distinct lack of cloudiness there. Winds within the eye are relatively light (less than 15 knots); especially when compared to the adjacent eyewall (Vescio et al., August 9, 2006).

The eyewall is the ring of towering convective activity (i.e., air moving rapidly upwards producing thick clouds and large rainfall amounts) that encircles the eye. It is within the eyewall that the deepest convection and clouds occur and where the strongest surface winds are

most often observed (Ahrens 2003; Vescio et al., August 9, 2006). It is for this reason a storm's most destructive impacts in terms of wind damage are near its center.

Like the eyewall, the spiral rainbands are areas of convection producing relatively thick clouds and heavy precipitation. As the name suggests, the rain bands move with the storm's circulation spiraling inwards towards the storm center (Vescio et al., August 9, 2006). These bands, compared to adjacent regions, are associated with heavier precipitation, stronger winds, and, from an aviation perspective, highly turbulent motion. The bands can exist well away from the center of the storm and are the first part of the storm to produce significant impacts at a location. The potential for IFR conditions and turbulent motion make the spiral rainbands a feature to be avoided by the aviator and their arrival often closes the window of opportunity for evacuating general aviation aircraft.

Figure 3 is a visible satellite image that coincides in time with the surface map presented in Figure 1. It is presented to illustrate the eye, eyewall, and spiral rainband structures; in this particular case, those structures associated with Ivan. Ivan's eye is the dark, cloud-free region at the center of the storm. The eyewall is the ring of brighter and therefore thicker cloudiness adjacent to the eye. The rainbands are also the brighter regions of cloud spiraling into the storm. A rainband beginning between the Yucatan peninsula and Cuba then stretching northward to Florida's panhandle is quite evident.

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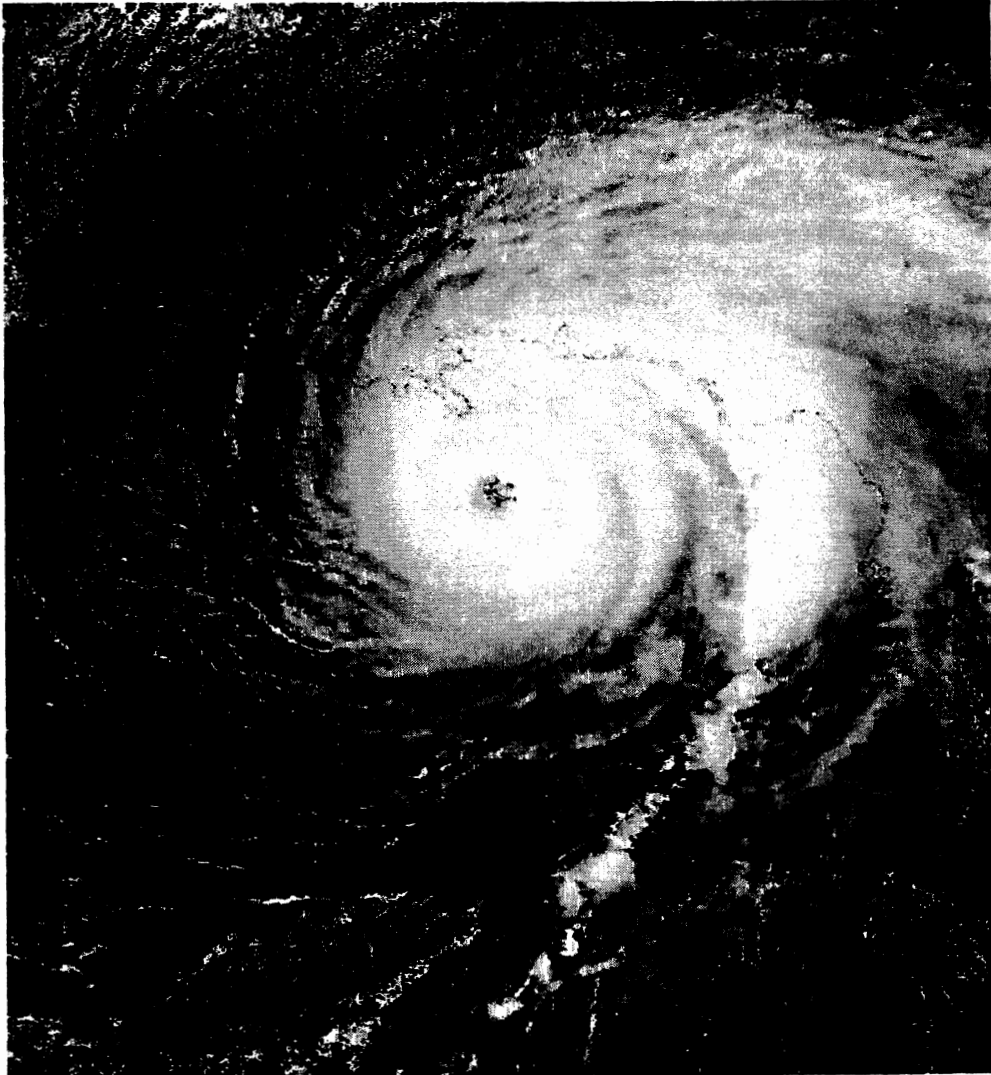


Figure 3. A visible satellite image of Hurricane Ivan on 15 Sep 2004 at 1830 UTC. Credit: Liam Gumley, Space Science and Engineering Center, University of Wisconsin-Madison; <http://www.ssec.wisc.edu/>

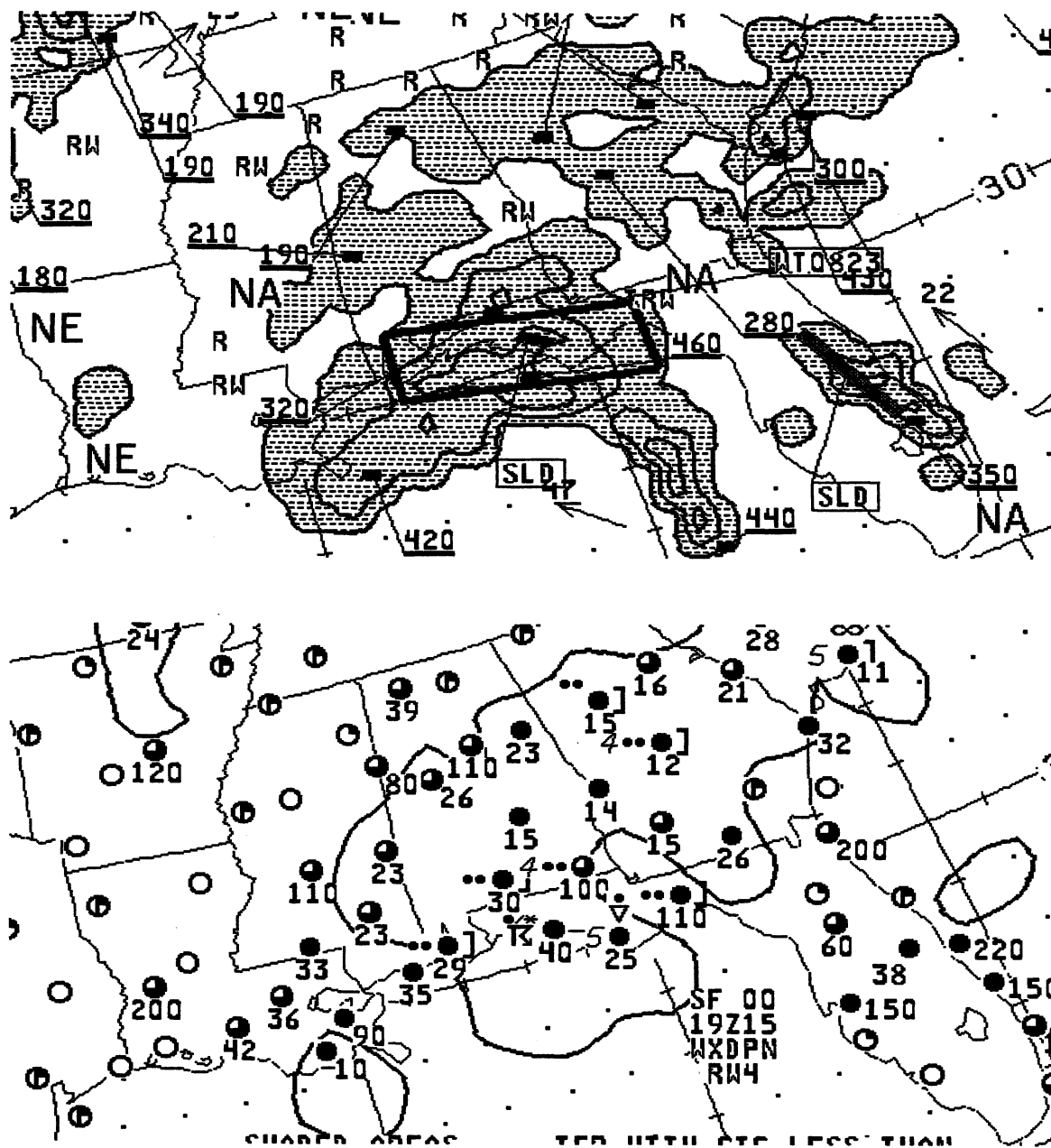


Figure 4.

- (a) A composite Radar image of the southeastern United States on 15 Sep 2004 at 1820 UTC.
 (b) Aviation weather conditions across the southeastern United States on 15 Sep 2004 at 19 UTC.

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Other outer rainbands are seen in Georgia, Alabama, and Mississippi. Figure 4, which contains both the radar chart and map of aviation weather conditions coincident with the satellite image in Figure 3, also shows these features. Precipitation and MVFR conditions associated with these outer rainbands extend into northern Georgia, northern Alabama, and central Mississippi. Note that these operationally significant impacts are occurring as much as 300 miles from Ivan's center and would be affecting any aircraft evacuations that may have been occurring in this region at this time.

While the worst conditions associated with any storm are typically near the storm's center (e.g., the maximum wind speeds), the weather produced by the outer rainbands can severely hamper one's ability to evacuate general aviation aircraft when threatened by a damaging storm. These outer rainbands can arrive a significant period of time ahead of the more destructive impacts one is trying to avoid. The time between the arrival of the outer rainbands and the storm's more destructive effects depends on a variety of factors such as the speed at which the storm is moving and the size of a storm's circulation.

In Ivan's case, the circulation had a diameter that was on the order of 500 miles and, as indicated earlier, led to rainshowers and MVFR conditions that extended well away from the storm center. Ivan would be considered a rather large storm. Areas in the panhandle of Florida and

Alabama that experienced the worst of this storm (e.g., significant structural damage) were feeling its effects (e.g., low ceilings and visibilities, gusty winds and turbulence) a significant period of time before the arrival of the more destructive parts of the storm. A smaller storm moving at a similar speed would have produced a longer period of time before conditions deteriorated and therefore a longer period of time to evacuate aircraft.

There is, in fact, large variability in storm size. To illustrate this variability, Figure 5 shows a composite image of visible satellite pictures that contained Hurricanes Dennis, Emily, Katrina, Rita, and Wilma from the active 2005 season. Storm sizes ranged from the relatively small circulation of Dennis, on the order of 200 miles in diameter, to the rather large circulation associated with Katrina. Katrina's circulation was more than double that of Dennis. The important point is the size of these storms affected the timing of the arrival of their outer rainbands relative to the arrival of the more destructive parts at the center of these storms. This then has an effect on the amount of time one has to evacuate aircraft.

The size of the storm circulation is also an important consideration when deciding whether the more destructive parts of a storm will affect your area, and therefore whether to evacuate aircraft in the first place. Simply put, bigger storms produce wider spread destruction compared to smaller storms. This topic will be addressed more thoroughly in the section on storm impacts.

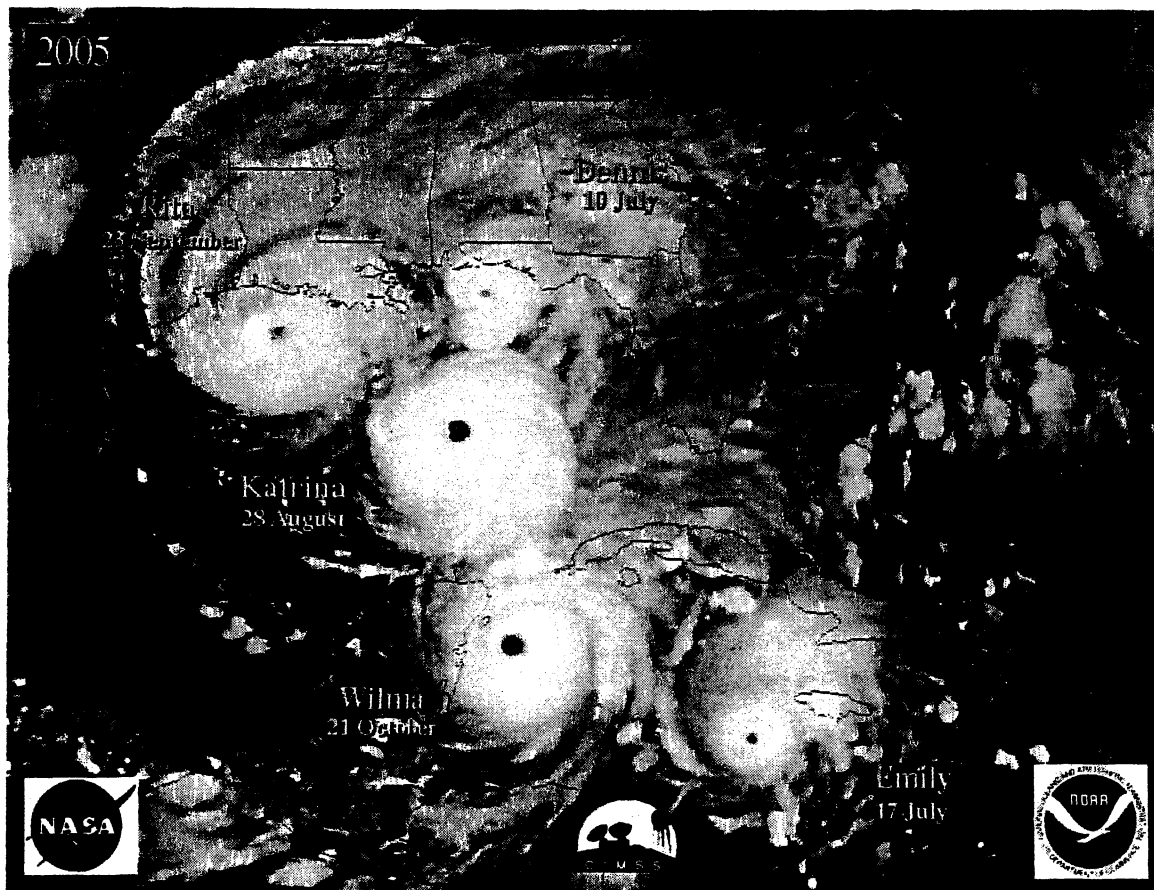


Figure 5. A mosaic of visible satellite imagery comparing the size of five storms (Dennis, Emily, Katrina, Wilma, and Rita) during the active 2005 hurricane season. Credit: Cooperative Institute of Meteorological Satellite Studies, University of Wisconsin – Madison Space Science and Engineering Center; <http://cimss.ssec.wisc.edu/>

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Hurricane Season

The hurricane season in the Atlantic Basin is designated as the period from June 1st to November 30th. The peak activity, however, typically occurs from late August until mid-October. It is also during this period of greatest activity that the strongest storms tend to occur (NOAA/NHC, July 27, 2006). Note, however, that there have been years with activity outside the time period of the aforementioned hurricane season. The 2005 season provides an example of this. The last storm of that season developed on the 30th of December (NOAA News Online, April 13, 2006).

The important point is that those with aviation interests along the East and Gulf Coasts should begin monitoring the tropics for activity in the early summer and continue through the late fall; this being especially true during the climatological peak – late August through mid-October. Furthermore, these same individuals should have preparations in place (e.g., the establishment of aircraft evacuation plans, procedures for protecting other resources, etc.) well before the season begins.

Hurricane Development, Evolution, and Movement

Hurricanes begin as clusters of convective clouds over the warm waters of the tropical Atlantic. If favorable environmental conditions exist, these regions of convection can then become organized into the convective structures that make up a hurricane. Favorable conditions include the presence of warm ocean water to a significant depth; a water temperature of 26°C is considered the lower limit. Winds in the region of development must be relatively light through the depth of the atmosphere. This latter condition is referred to as a “low wind shear environment” (Ahrens, 2003; Rauber, Walsh, and Charlevoix, 2002).

There are four stages to becoming a hurricane. These stages, listed in order of development, are tropical disturbance, tropical depression, tropical storm, and hurricane. Tropical depressions, tropical storms, and hurricanes are as a group referred to as tropical cyclones (i.e., low

pressure centers that have a defined cyclonic or counter-clockwise circulation) (Ahrens, 2003; NOAA/AOML, October 19, 2005; Rauber et al., 2002).

A tropical disturbance is an area of weak low pressure with active cloudiness that has persisted for over 24 hours and wind speeds less than 20 knots (23 mph). Westward moving easterly waves that come off of Africa are one type of tropical disturbance that, under the right set of conditions, can evolve into a tropical cyclone. Other types of tropical disturbances exist and lead to tropical cyclone development. But it is these easterly waves that are most often the precursors to tropical cyclones in the Atlantic basin (NOAA/AOML, October 19, 2005; Rauber et al., 2002).

As tropical disturbances strengthen, a low pressure center develops and the surface circulation about this center becomes better organized. By “better organized” we mean the circulation has developed a more defined cyclonic, counter-clockwise pattern about the low pressure center. A tropical disturbance becomes a tropical depression when the maximum surface wind speed within that area of cyclonic motion becomes greater than 20 knots (23 mph) (NOAA/AOML, October 19, 2005; Rauber et al., 2002). It is at this second stage that the National Hurricane Center (NHC), the organization tasked with monitoring and providing forecasts for tropical cyclones, assigns a number (e.g., Tropical Depression One) and starts issuing forecasts.

A tropical depression becomes a tropical storm when the maximum surface wind speed increases to greater than 34 knots (39 mph). NHC assigns a name to the storm at this stage. A tropical storm is then classified as a hurricane when the maximum surface wind speed increases to greater than 64 knots (74 mph) (NOAA/AOML, October 19, 2005; Rauber et al., 2002).

Once a storm becomes a hurricane it is further categorized according to the Saffir-Simpson Hurricane intensity scale. There are five storm intensity categories which are shown in Table 1. These categories are also based on the maximum

surface wind speed within a storm. Note that Category 3 storms or greater are classified as “major” hurricanes and are the most destructive. This scale was originally developed to give an estimate of damage expected from hurricane winds (NOAA/AOML, October 19, 2005; Rauber et al.,

2002). Later, in the section on storm impacts, there will be a discussion of the potential damage associated with the Saffir-Simpson hurricane categories as well as that associated with tropical storm force winds.

Table 1. Saffir-Simpson Hurricane Intensity Categories

Category	Maximum Surface Wind Speeds
One	64 – 82 knots (74 – 95 mph)
Two	83 – 95 knots (96 – 110 mph)
Three	96 – 113 knots (111- 130 mph)
Four	114- 135 knots (131 – 154 mph)
Five	greater than 135 knots (155 mph)

The track and stages of development of Hurricane Ivan are presented in Figure 6 as an example of storm evolution and movement. Ivan began as a tropical disturbance that moved off the west coast of Africa on 31 August 2004. On the 2nd of September at 18 UTC, as this disturbance moved westward, it was classified as Tropical Depression no. 9. Just 12 hours later this system became Tropical Storm Ivan. Ivan remained a tropical storm until 5 September at 06 UTC when it reached hurricane status over the central portion of the tropical Atlantic Ocean. Ivan subsequently

crossed the Lesser Antilles and then peaked in intensity as a dangerous Category 5 system while it moved northwestward across the Caribbean Sea. Maximum wind speeds of 145 knots occurred on the 11th of September just west of the island of Jamaica. Taking a more northward track, Ivan moved into the Gulf of Mexico around the 14th of September and decreased in intensity to Category 4. Sometime after 00 UTC on the 16th of September it made landfall on the Gulf Coast near Gulf Shores, Alabama as a Category 3 hurricane (Stewart, May 27, 2005).

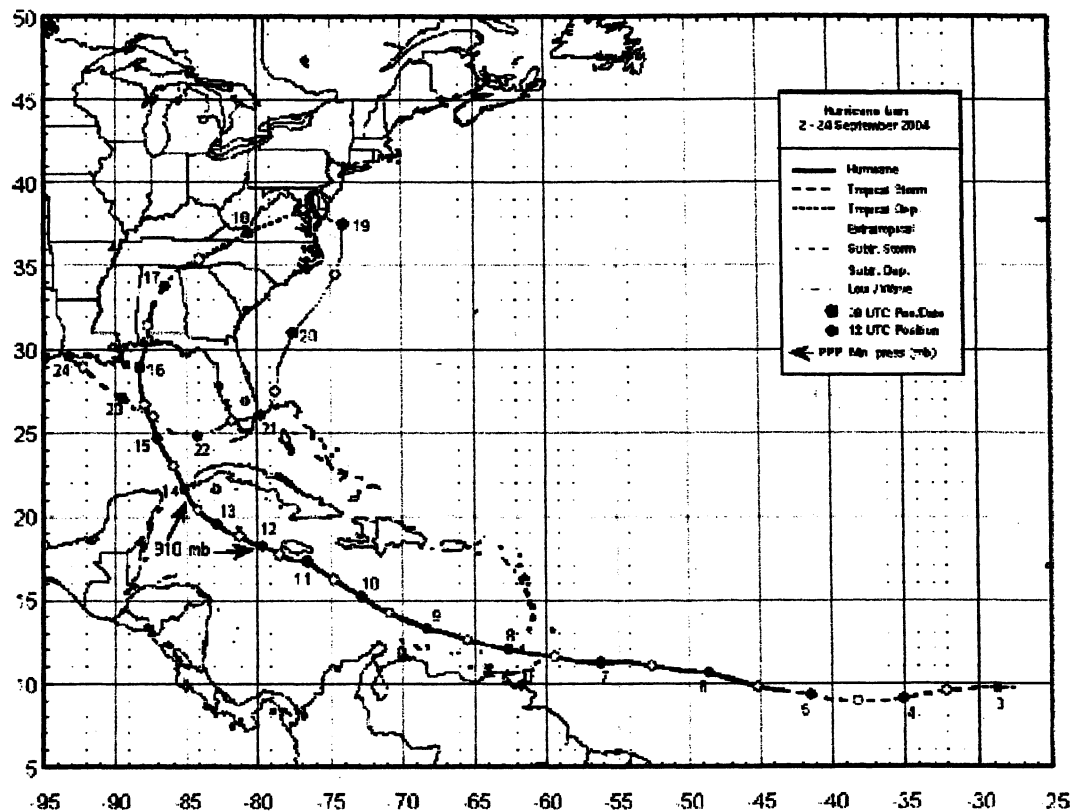
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Figure 6. The storm track for Hurricane Ivan from 2-24 September 2004. Credit: NOAA-National Hurricane Center; <http://www.nhc.noaa.gov>

The path taken by Ivan illustrates the classic “recurving” track taken by many of these storms. This recurving path has the storm’s initially moving westward across the tropical Atlantic but then turning northward towards the midlatitudes subsequently moving off towards the northeast.

This recurving phenomenon is further illustrated in Figure 7. This figure contains a summary of all the tracks taken by tropical cyclones during the 2004 season. Note that there were two predominant storm tracks during that year. One track had storms recurving into the central Atlantic while the second track had recurvature taking place near the southeastern

United States.

To understand the movement of these storms we must consider the overall motion of the atmosphere. Motion in general within the atmosphere occurs on a variety of scales or sizes (Ahrens, 2003). The diameter of the circulation associated with the hurricane itself varies from approximately one hundred miles up to hundreds of miles across. There are, however, larger scale circulations, on the order of thousands of miles across, within which tropical storms and hurricanes are embedded. It is these larger scale circulations that determine the movement of these storms (Rauber et al., 2002).

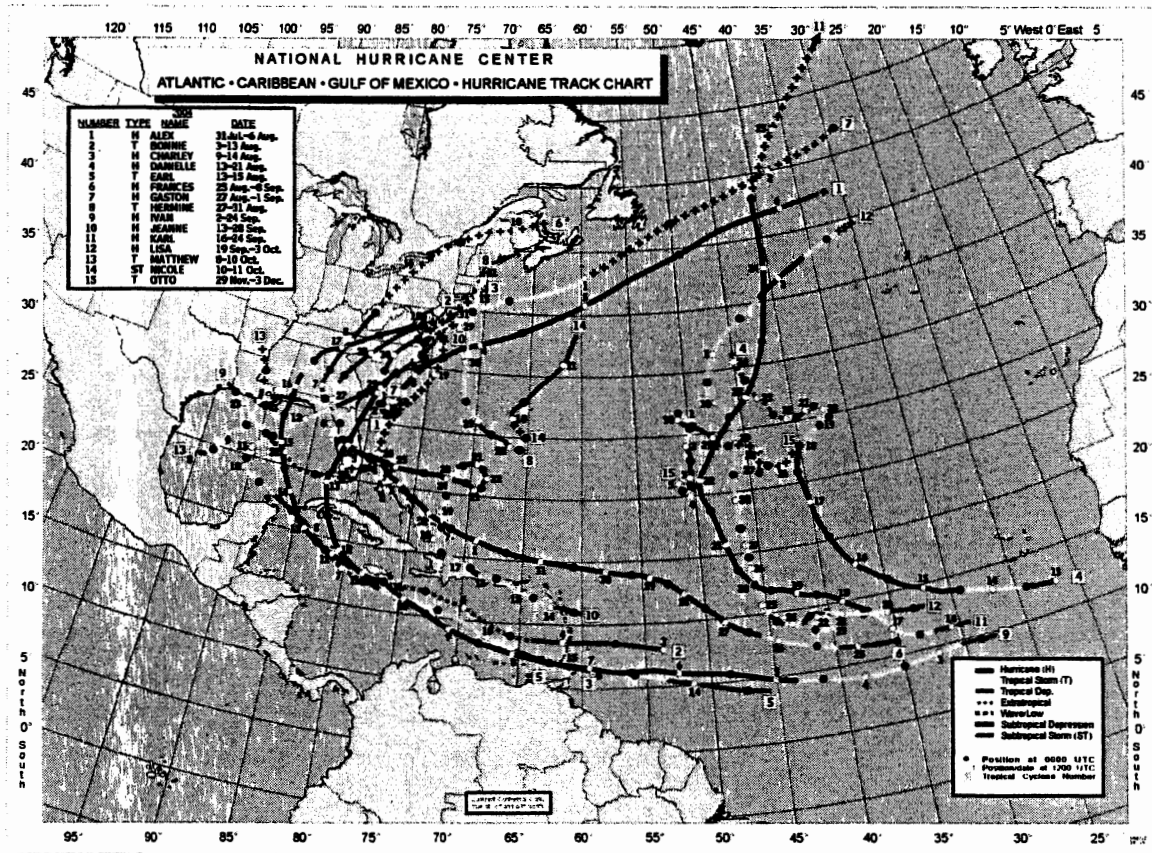


Figure 7. Tropical cyclone tracks during the 2004 hurricane season. Credit: NOAA- National Hurricane Center; <http://www.nhc.noaa.gov>

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Figure 8 contains a map of the average mean sea level pressure from 1 August to 30 September 2004, the period of time when a large majority of the storms occurred in 2004. A large high pressure center dominated the North Atlantic Ocean basin during this time period. This general pressure pattern is not unusual in the Atlantic. The

high pressure center shown in this figure is, in fact, a semi-permanent feature of the large scale circulation known as a subtropical high (Ahrens, 2003). And although only the surface representation of the subtropical high is shown in Figure 8, this circulation extends through a significant depth of the atmosphere.

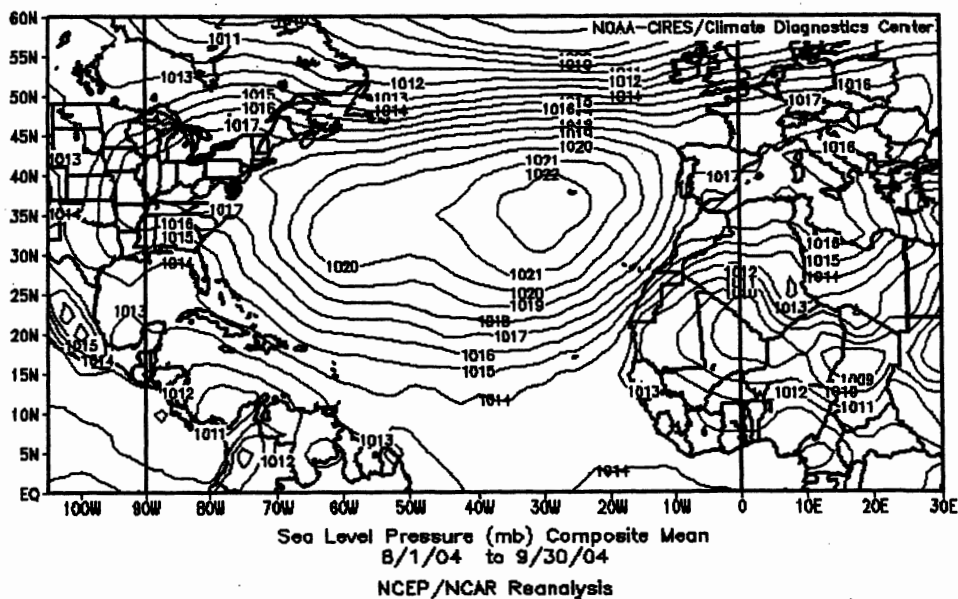


Figure 8. The average mean sea level pressure over the Atlantic Ocean basin from 1 August 2004 to 30 September 2004. Isobars are drawn every 1 mb. Credit: NOAA-CIRES/Climate Diagnostic Center; <http://www.cdc.noaa.gov>

Both the structure and location of the subtropical high in this region plays an important role in determining the track a tropical cyclone will take. Noting that highs have a clockwise circulation about their centers, smaller scale tropical cyclones embedded in the large scale circulation of the subtropical high often move around its southern, western, and northern periphery (i.e., they follow the classic recurving path).

In 2004 the subtropical high was centered near the Azores with the western edge extending across the state of Florida. There was also a weakness or area of somewhat lower pressure evident in the central Atlantic just west of the high center. Both the western edge of the subtropical high and this weakness in the central Atlantic are coincident with the two predominant storm tracks observed during 2004. Once again, the structure and location of the subtropical high across the Atlantic basin during any given season plays a crucial role in the paths storms will take during that season and what regions are affected.

An important issue when considering an evacuation due to a threatening hurricane is the amount of lead time one has before a storm impacts a particular location. Lead time is

determined by factors such as speed of movement, storm size, and where a storm first develops relative to the location being threatened. If a storm develops over the tropical Atlantic south of the subtropical high, locations along the Gulf and East coast of the United States will, generally speaking, have a longer time to prepare. In contrast, when storms develop along the western edge of the high, such as in the Caribbean Sea or over the Gulf of Mexico there is typically going to be less time to prepare.

Where storms tend to develop and the potential effect this has on available lead time does show some variation during the season. Figure 9 shows typical areas of development and storm tracks for the months of June, August, and September. In June development is more likely to take place along the western periphery of the subtropical high in the Caribbean Sea and Gulf of Mexico. As we move into the period of greatest activity in late August through September the area expands shifting eastward towards the tropical Atlantic. Remember, however, these are averages and hurricane development and track can significantly deviate from these averages (NOAA/NHC, July 27, 2006).

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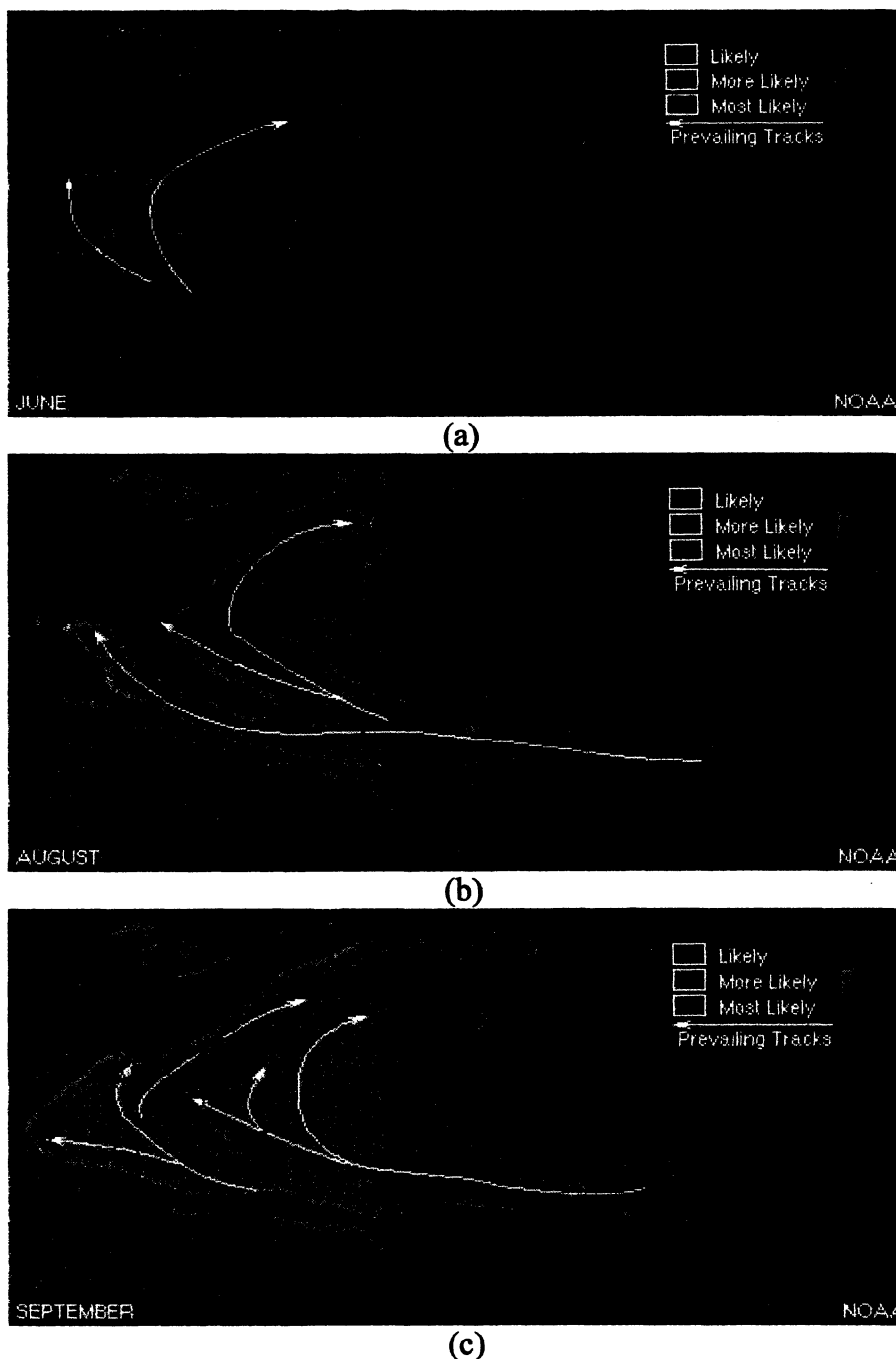


Figure 9. Average zones of origin and tracks of tropical cyclones for: (a) June, (b) August, and (c) September. Credit: NOAA- National Hurricane Center; <http://www.nhc.noaa.gov>

Hurricane Impacts

Hurricanes produce four destructive impacts. These impacts are strong surface winds, the storm surge phenomenon, heavy rains and the resulting flooding, and embedded tornadoes (Vescio et al., August 9, 2006).

Surface Winds

The strong surface winds associated with hurricanes can produce significant damage, especially to aircraft. Aircraft damage can come about in a variety of ways. At minimum, winds can torque and stress an aircraft that is tied down. In the worst case, however, these winds can dislodge an aircraft from its tie-downs, lifting and tossing it a significant distance. There is also the possibility of damage from flying debris when an aircraft is not sheltered. If an aircraft is housed in a hanger, there still can be a risk of damage as these structures can fail when exposed to the winds of stronger hurricanes.

There are two obvious questions that need to be considered when determining whether aircraft damage is likely due to strong wind speeds. These are "How fast are the winds expected to be at my location?" and "Will the aircraft be tied down or in a hanger?"

Generally speaking, if tropical storm force winds or greater are expected and there are no hangar facilities available, general aviation aircraft are vulnerable to damage. Evacuation should be considered; especially as wind speeds approach hurricane force. If structurally sound hanger facilities are available, then there is typically no need to evacuate when only tropical storm force winds are expected.

If hurricane force winds are expected and an aircraft can be placed in a hanger, there is a varying degree of risk of damage to the aircraft. For Category 1 and 2 storms (i.e., wind speeds of 64 to 95 knots) the potential for damage to aircraft in a structurally sound hanger is quite low (Rauber et al., 2002). The hanger may experience some external damage but generally will not fail. Note, however, there are examples of hangers having failed under Category 1 and 2 strength winds so this is not a completely risk free situation (Anonymous, 2004/2005).

According to the damage rating associated with the Saffir-Simpson scale it isn't until Category 3 storm strength or greater (i.e., major hurricanes wind speeds greater than 95

knots) that there is the potential for significant structural damage to buildings. And, of course, the potential increases as the wind speed increases (Rauber et al., 2002). Therefore, evacuation should be considered when threatened by the more destructive winds of a major hurricane, even if hanger facilities are available.

The strongest surface winds, and therefore the greatest damage from the wind, typically occur near the storm's center within the eyewall as indicated earlier. The strongest wind speeds, however, are not symmetric about the storm center but most often occur to the right of the storm when looking towards the direction the storm is moving (Rauber et al., 2002). As an example, the surface wind speed structure of Ivan as it was moving almost due north towards the Gulf Coast is presented in Figure 10. Wind speeds are contoured every 5 knots with the 35 knot (tropical storm force), 50 knot, and 65 knot (hurricane force) contours being highlighted. The storm's center is located where the two dashed lines in the figure cross. In the case of Ivan, the area of maximum wind speeds is occurring within the region of the storm's eyewall. And, as is typically the case, this area is located to the right relative to storm motion.

Figure 10 also illustrates the extent of destructive wind speeds associated with Ivan at this time. The area of highest wind speeds to the right of storm motion covers a relative small area compared to the overall circulation of Ivan. Recall that Ivan's overall cyclonic circulation was on the order of 500 miles across. The area of strongest winds that included wind speeds of Category 3 strength was on the order of only 50 miles across. The area of hurricane force winds had a diameter of approximately 100 miles. The area of tropical storm force winds had a diameter of approximately 250 to 300 miles. Ivan was therefore producing a rather broad threat of wind damage from southeastern Louisiana to the panhandle of Florida at this time. Note also that the overall area of strongest winds (i.e., speeds greater than tropical storm force) is not symmetric about the storm center but are skewed to the right of motion.

As the size of the overall circulation of tropical cyclones varies, so therefore does the size of the region of damaging winds associated with these storms. Hurricane Charley, also from the 2004 season, was a much smaller storm when

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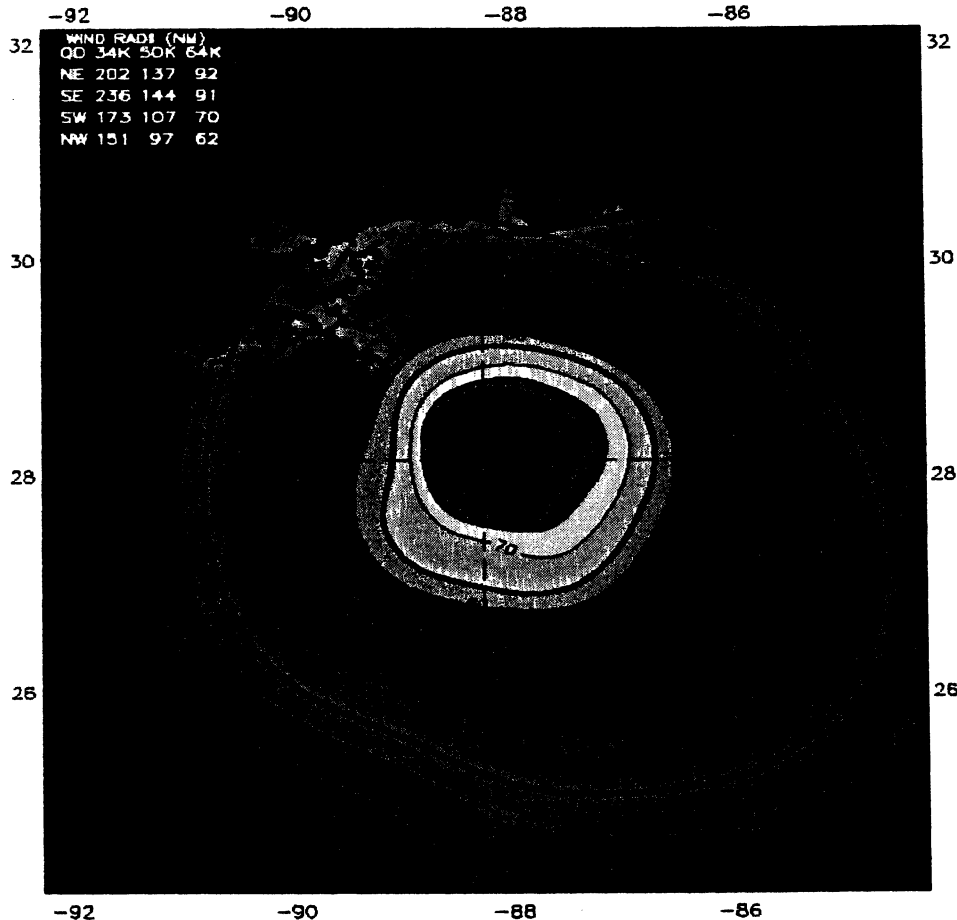
compared to Ivan. Charley's cyclonic circulation was less than two hundred miles across.

Hurricane Ivan 1930 UTC 15 Sep 2004

Max 1-min sustained surface winds (kt) for marine exposure

Analysis based on GPSSONDE_SFC from 2120 - 2120 z; MOORED_BUOY from 2209 - 2209 z;
 SFMR43 from 2329 - 2329 z; GPSSONDE_WL150 from 2120 - 2120 z;
 TOWER_LD_TO from 2326 - 2326 z; SHIP from 1809 - 2350 z; CMAN from 2254 - 2254 z;
 SFMR42 from 2321 - 2321 z; GOES from 1902 - 1902 z; CMAN_LD_TO from 2254 - 2254 z;
 ASOS_LD_TO from 2317 - 2317 z; GPSSONDE_MBL from 2120 - 2120 z;
 QSCAT from 2334 - 2334 z

1930 z position interpolated from 1745 Vortex; malp = 937.0 mb



Observed Max. Surface Wind: 106 kts, 19 nm NE of center based on 1854 z SFMR42 sfc measurement

Analyzed Max. Wind: 106 kts, 19 nm NE of center

Experimental research product of:

NOAA / AOML / Hurricane Research Division

Figure 10. Surface wind speed distribution about Hurricane Ivan at 1930 UTC on 15 September 2004. Wind speeds are contoured every 5 knots. The 35, 50, and 65 knot isotachs are highlighted. Credit: NOAA/AOML/Hurricane Research Division; <http://www.aoml.noaa.gov/hrd/>

Figure 11 contains the wind speed distribution of Charley as it was approaching southeast Florida on 13 August at 1630 UTC. Charley was moving towards the north-northeast at this time. Once again we observe the maximum wind speeds occurring to the right of the storm's motion. The wind maxima associated with Charley was on the order of 20 miles across while the hurricane force winds cover an area 40 miles across. The diameter of the area of tropical storm force wind was on the order of 150 miles. Furthermore, there was a large asymmetry in the wind field about the storm's center. Areas to the northwest of the storm (i.e., left of motion) are feeling minimal impacts while areas at the storm's center and off to the southeast of the storm track (i.e., right of motion) are feeling the worst of the conditions. This remained true as Charley made landfall near Punta Gorda, Florida and continued across central Florida to the Daytona Beach area (Pasch, Brown, and Blake, January 5, 2005).

The magnitude of the wind speeds are affected as a storm makes landfall. Landfall is defined as the location and point in time when the storm's center of the circulation first moves over land (NHC, May 4, 2007). When this happens the storm will weaken in intensity due to being cut off from its energy source, the warm ocean waters. This weakening takes time, however. As a result, locations well inland can still experience significant wind damage. There are two factors that determine how far inland destructive winds occur. These are the strength of the storm as it makes landfall and the speed at which the storm is moving. Stronger storms will have an effect further inland as will faster moving storms (NHC, June 28, 2006).

Charley from 2004 is an example of an intense, fast moving storm that produced destruction well inland from its landfall location. Charley made landfall as a destructive Category 4 storm. Maximum wind speeds at the time of

landfall were 130 knots. After coming ashore near Punta Gorda, Florida it moved rapidly across Central Florida at 20 to 25 mph passing over the Orlando and Daytona Beach areas. Figure 12 shows an analysis of wind speeds associated with Charley as it moved over the eastern portion of central Florida. Charley was still a minimal Category 1 hurricane with surface wind speeds up to 70 knots as it passed over Daytona Beach. This being true even though the storm had traveled a distance of 200 miles over land. It took Charley approximately 8 hours to cover this distance (Pasch et al., January 5, 2005). Once again, it takes time for these storms to weaken after landfall.

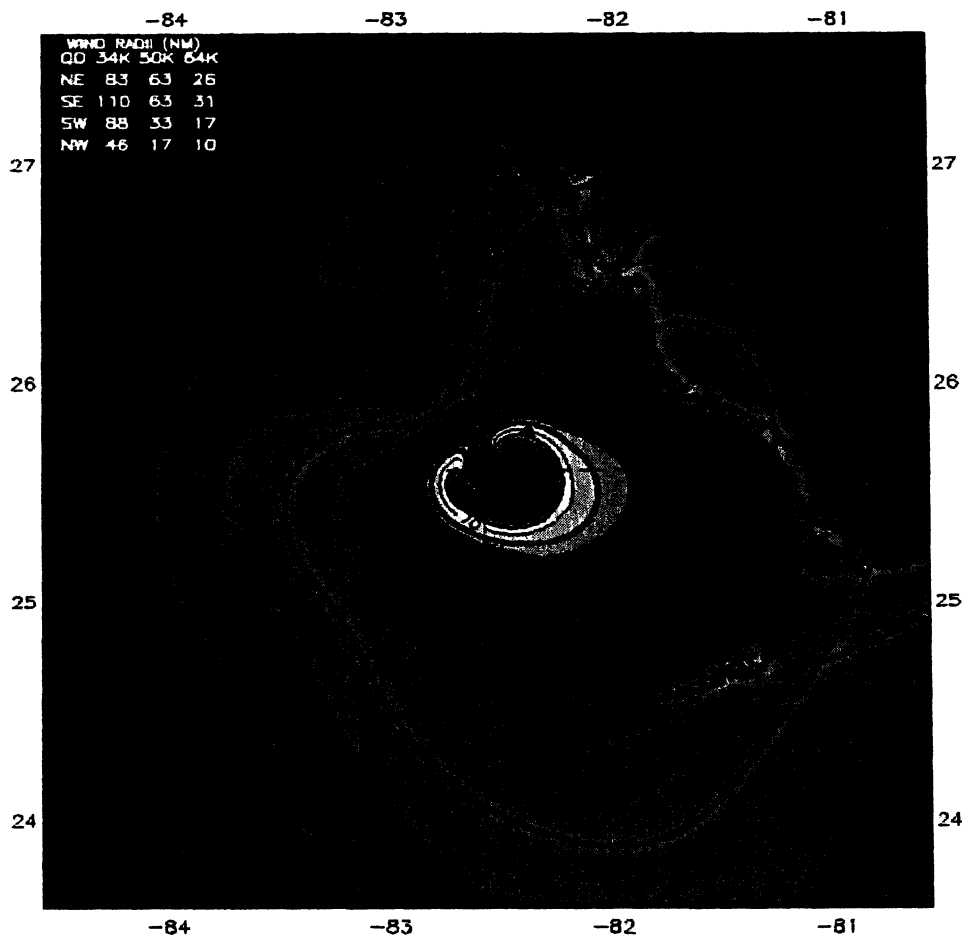
In summary, when considering the potential for wind destruction at a given location all of the following must be considered: (1) the intensity (i.e., maximum wind speeds) of a storm, (2) the size and structure of the area of potentially damaging winds (e.g., tropical storm force winds or greater) and ones location relative to that area, and (3) the speed which a storm is moving and ones distance from the shore. The stronger the storm, the greater the destruction associated with the storm. The bigger the damaging wind field, the larger the probability a location will be adversely affected. Where a location is likely to be relative to the storm center's track is also an important consideration. Locations falling along the center and to the right of the storm track generally experience the strongest winds and therefore the greatest amount of wind damage. Locations away from the storm center to the left of the track have a somewhat lower probability for destruction. How far inland a location sits will also affect the amount of destruction. Because storms deteriorate after making landfall, locations further inland are obviously safer. But one must consider the intensity of the storm and how fast it is moving to determine the potential for wind damage at inland locations.

Hurricanes: A Primer

Hurricane Charley 1630 UTC 13 Aug 2004

Max 1-min sustained surface winds (kt) for marine exposure

Analysis based on MOORED_BUOY from 1220 - 1220 z; GPSSONDE_SFC from 1219 - 1701 z;
 SHIP from 1220 - 1220 z; TOWER_LD_TO from 0000 - 0000 z;
 AFRES_FLT adj. to surface from mean height 3168 m from 1219 - 1219 z;
 GPSSONDE_WL150 from 1219 - 1219 z; GPSSONDE_MBL from 1219 - 1701 z;
 DRIFTING_BUOY from 1300 - 1300 z; GOES from 1302 - 1302 z; CMAN from 1230 - 1230 z;
 1630 z position interpolated from 1522 Vortex; mslp = 964.0 mb



Observed Max. Surface Wind: 118 kts, 8 nm SE of center based on 1658 z AFRES_FLT sfc measurement
Analyzed Max. Wind: 114 kts, 9 nm SE of center
 Experimental research product of:
NOAA / AOML / Hurricane Research Division

Figure 11. Like Figure 10 except for Hurricane Charley at 1630 UTC on 13 August 2004. Credit: NOAA/AOML/Hurricane Research Division; <http://www.aoml.noaa.gov/hrd/>

Charley Winds from HRD MAXSFC (MPH)

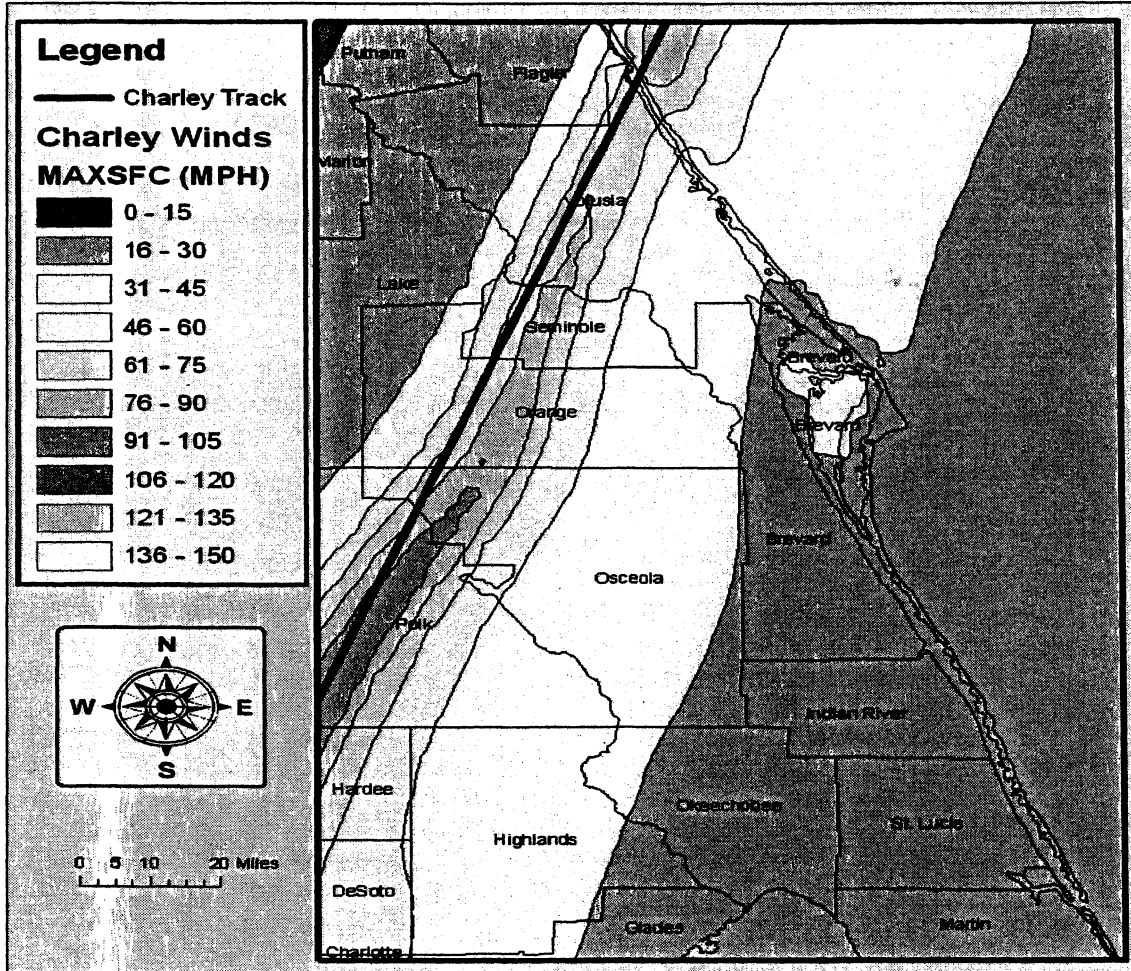


Figure 12. The storm track and surface wind speed distribution for Charley as it moved through the eastern portion of central Florida in 2004. Credit: Dave Jacobs, National Weather Service/WFO Melbourne; <http://www.srh.noaa.gov/mlb/>

Hurricanes: A Primer

Storm Surge

The storm surge is simply the water that is pushed ashore by the force of the storm's winds as it is making landfall. It is highly destructive. Part of its destructive nature is the significant flooding it produces. Another destructive aspect is the overall force of the water coming ashore and the repeated battering due to the waves superimposed on the surge. This produces significant structural damage. In fact, structures located near the shore can be completely destroyed by the storm surge phenomenon (NOAA/NHC, May 21-27, 2006).

Figure 13 shows a cross-section of a hurricane and the associated storm surge. In this figure the storm is moving out of the figure. Recall that the winds move in a counter-clockwise pattern about the eye of a storm with the strongest winds occurring to the right of the storm motion. It is in this region of strong, on-shore winds where the storm surge will be found. These strong winds provide the energy to lift and push the ocean water inland.

The depth of and how far the water moves inland is a function of the strength of the winds and the slope of the continental shelf. Stronger storms making landfall at locations with shallow coastal slopes will produce the deepest storm surges as well as the furthest inland penetration. The magnitude of the depth and inland penetration for the strongest storms is quite significant (NOAA/NHC, May 21-27, 2006). For example, a Category 5 storm can produce a surge of more than 25 feet above sea level along the coast and can easily push water on the order of 2 to 3 miles inland (see Figure 14 as an example).

When aircraft are located at airports along the shore, even if the aircraft are housed in hangars, evacuation should be considered if inundation due to the storm surge is expected at the facility. Once again, locations to the right of the storm's motion will experience the storm surge and the storm's strength and the nature of the coast line determine the magnitude of the surge. Information on the expected inland extent of the storm surge for a particular region as a function of storm strength can often be provided by the local emergency manager's office. An example of such a chart is shown in Figure 14.

Flooding

Tropical cyclones can produce large amounts of rainfall. Therefore, the threat of flooding and its associated damage exists as these storms move inland. In fact, inland flooding, from a human perspective, can be the most dangerous aspects of tropical cyclones. From 1970 to 2000 the majority of deaths from these storms were due to inland flooding (NOAA/NHC, May 21-27, 2006).

One important factor affecting how much rain occurs locally from a tropical cyclone, and therefore the potential for flooding by that cyclone, is the speed at which the storm is moving (NOAA/NHC, May 21-27, 2006). Slow moving storms will typically produce more rainfall locally than fast moving storms. Storm strength is generally not a factor in rainfall amounts. For example, a slow moving tropical storm will often produce more local rainfall than a faster moving hurricane.

An example of a slow moving storm that produced large rainfall amounts and significant inland flooding is Frances in 2004. Figure 15 shows the track taken by Frances with storm positions indicated every 12 hours at 00 and 12 UTC. Frances' forward movement was 12 to 14 knots while north of the West Indies. It slowed considerably, however, as it moved over the Bahamas on the 2nd, 3rd, and 4th of September and continued this slow movement across Florida on the 5th and 6th of September. Average forward movement during this time was 8 knots with the storm moving as slow as 4 knots on the 4th and 5th. This slow movement led to rainfall totals of over 15 inches in the central part of the Florida and a significant amount of flooding in that part of the state (Beven, December 17, 2004).

Although typically not a threat to aircraft at most airports, aircraft damage could occur at facilities in areas more prone to flooding; for example, in low lying areas or near the confluence of two rivers. Therefore, to avoid flood damage to aircraft, one must be aware of the general susceptibility of the airport to flooding. If the facility is located in a region that is prone to flooding then moving aircraft may be in order when threatened by a tropical cyclone; especially one that is forecast to move slowly across the region.

Tornadoes

In addition to the strong winds associated with the overall circulation of a hurricane, hurricanes can produce destructive tornadoes (NOAA/NHC, May 21-27, 2006). Tornadoes are rapidly rotating columns of air having a diameter that is usually less than half of a mile across and containing wind speeds up to 260 knots (300 mph) (Ahrens, 2003; Rauber et al., 2002). The tornadoes produced by hurricanes are generally smaller in scale and of the weaker class. Wind speeds in

tornadoes occurring with hurricanes are typically less than 130 knots (150 mph). When tornadoes occur with hurricanes they are often embedded in rainbands located in the right front quadrant of the hurricane as it is making landfall (NOAA/NHC, May 21-27, 2006). Once again, we are referring to the right of storm motion. As a result, any tornado development that occurs will generally take place in the vicinity of the strongest sustained winds thereby giving an additional reason for avoiding this portion of the storm.

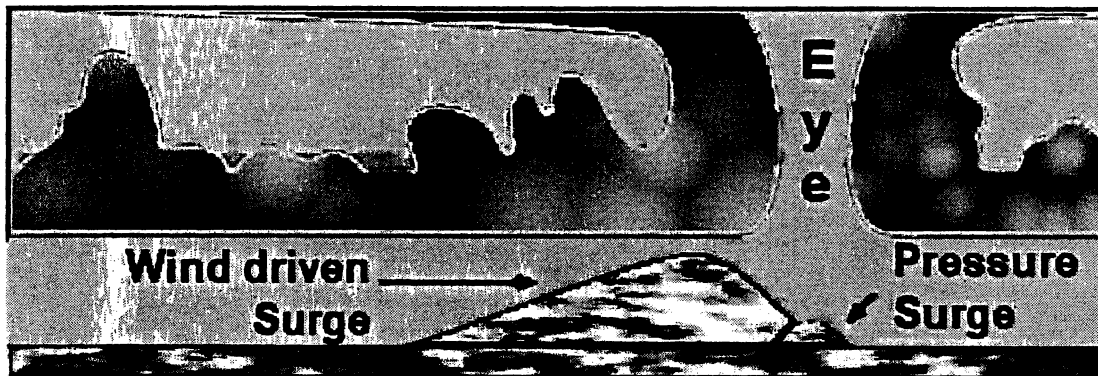


Figure 13. Cross-section through a hurricane illustrating the storm surge structure. Hurricane is depicted moving out of the image. Credit: The Weather Doctor; <http://www.islandnet.com/~see/weather/doctor.htm>

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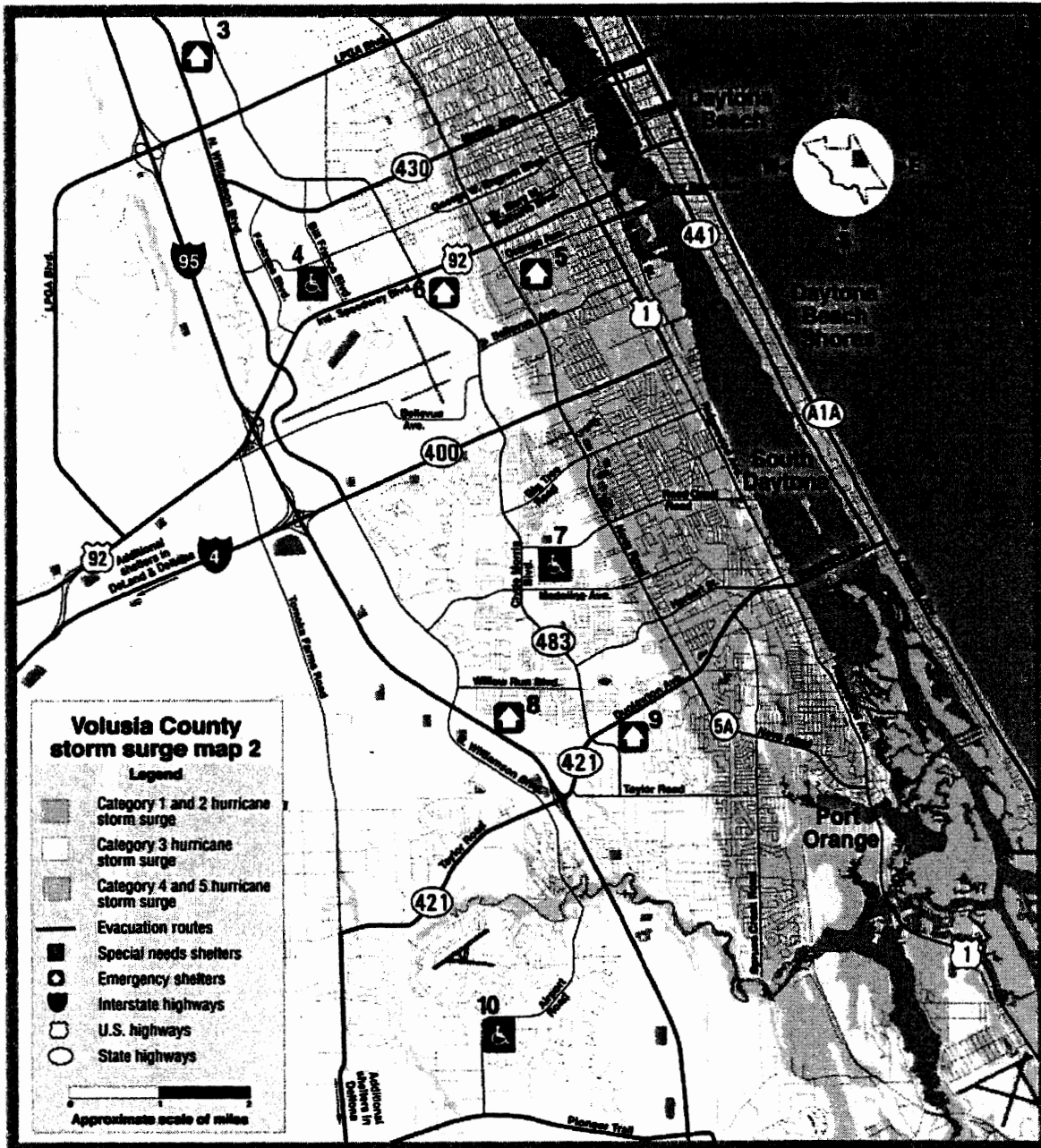


Figure 14. Sample storm surge inundation map. Credit: Volusia County, Florida; <http://www.volusia.org>

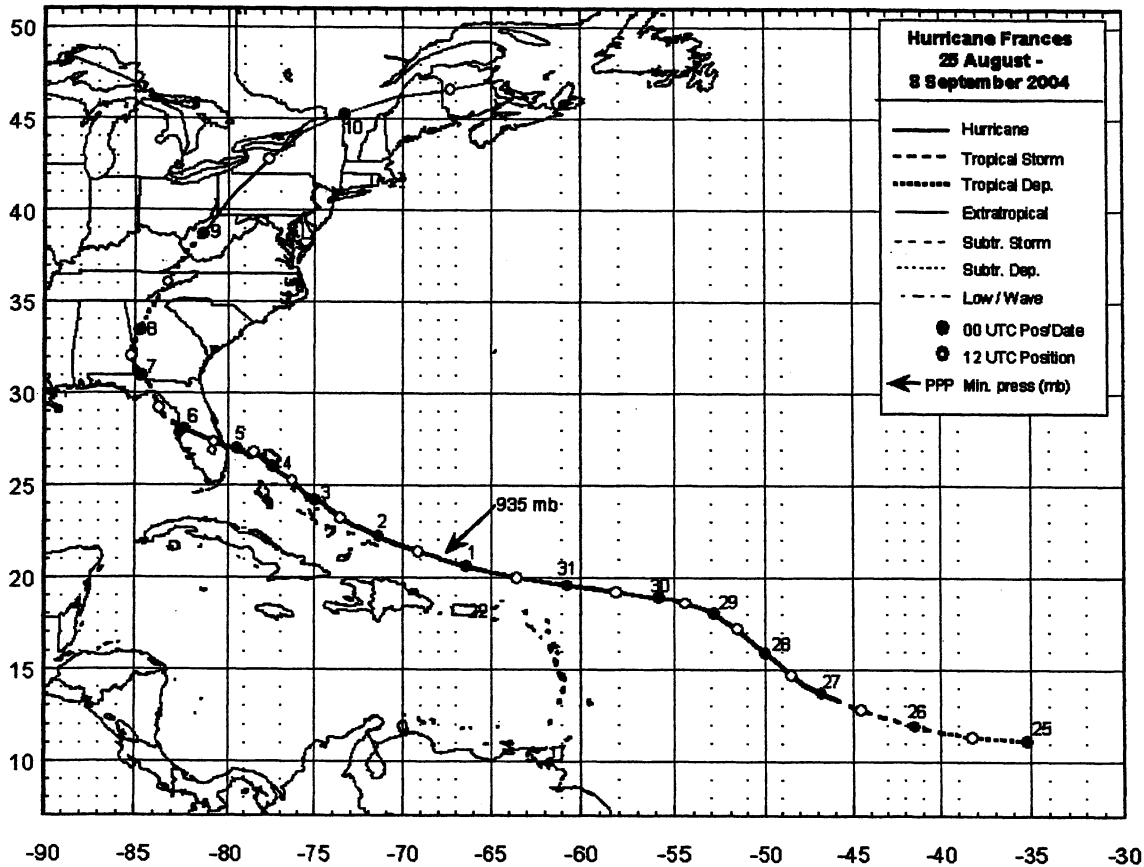


Figure 15. Like Figure 6 except for Hurricane Frances from 25 August-8 September 2004. Credit: NOAA-National Hurricane Center; <http://www.nhc.noaa.gov>

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Other Considerations

Thus far a good bit of detail on the nature of the hurricane phenomenon itself has been presented. Things such as the structure, evolution, and movement of these storms have been looked at. There are, however, two other topics that need to be addressed. Particularly when considering the issue of aircraft evacuation. The first of these is our ability to forecast the behavior of these storms (e.g., where they will go, how strong they will be, when they will cause conditions to begin to deteriorate at a given location, etc.). The second is the importance of monitoring the weather situation of the possible evacuation sites and the en-route weather to those sites.

From the previous discussions it should be clear that the center and rightward portion of the hurricane poses the greatest threat to aircraft on the ground. It is in this region of the storm where the strongest winds will be experienced, where tornado development is most likely, and where the storm surge can be experienced if located on the coast. Locations threatened by this region of a hurricane clearly need to consider the possibility of evacuating aircraft. Unfortunately, it is often the case that there can be quite a bit of uncertainty in both where the storm center will go and how intense it will be within the time frame the aviation professional needs to decide to evacuate or stay put.

Considering Ivan in 2004 as an example, conditions began to deteriorate along the Gulf Coast on the 15th of September after 00 UTC (i.e. on the evening of 14 September). This was more than 24 hours before Ivan made landfall near Gulf Shores, AL early on the 16th of September. Therefore, any aircraft evacuations would have had to occur no later than the afternoon of the 14th and the decision to move aircraft would have had to been made no later than that morning. The NHC forecast that would likely have been used to make that decision appears in Figure 16.

As it turns out, this particular storm track forecast was excellent. The "best estimate" of the forecast track (i.e., the thick black line) takes Ivan right over Gulf Shores, AL. This graphic, however,

also indicates the uncertainty in this particular forecast track at the time this forecast was made. The potential center track area (i.e., the area encircled by the thin black line showing where the storm's center could go) indicates landfall could occur anywhere from approximately New Orleans, LA eastward to Tallahassee, FL. While the highest probability of landfall, and therefore the expected worst impacts, lies along the forecast track near Gulf Shores, there was still a large degree of uncertainty in the storm track and resulting landfall location at this time. This uncertainty affects one's ability to decide on evacuation or no evacuation.

Another important consideration with regard to evacuating aircraft is en-route and destination weather. As one is monitoring the hurricane itself and where it may make landfall, one must also be looking at the weather on a larger scale; in particular the weather en-route to and at the evacuation site or sites. There are, in fact, instances when the local weather would allow one to leave a particular location to avoid a threatening hurricane but the en-route or destination weather prohibits movement.

Hurricane Charley in 2004 provides an example of this. Figure 17 contains a visible satellite image from 18 UTC on 12 August. This was one day before Charley made landfall and represents the period of time when aircraft evacuations out of central Florida would have had to occur to avoid Charley's impact. As is clear from this image, movement of general aviation aircraft northward out of Florida was almost impossible given the presence of significant weather from Florida's panhandle on up the East coast. Tropical storm Bonnie was making landfall in the panhandle about this time. IFR and thunderstorms were occurring across northern Florida. This set of circumstances was cutting off air routes out of the Florida peninsula thereby forcing general aviation aircraft in central Florida to stay in place. Once again, the issue here was not only where was the hurricane itself going to go but would the weather elsewhere allow the evacuation of aircraft to avoid this threat. The answer in this case was no.

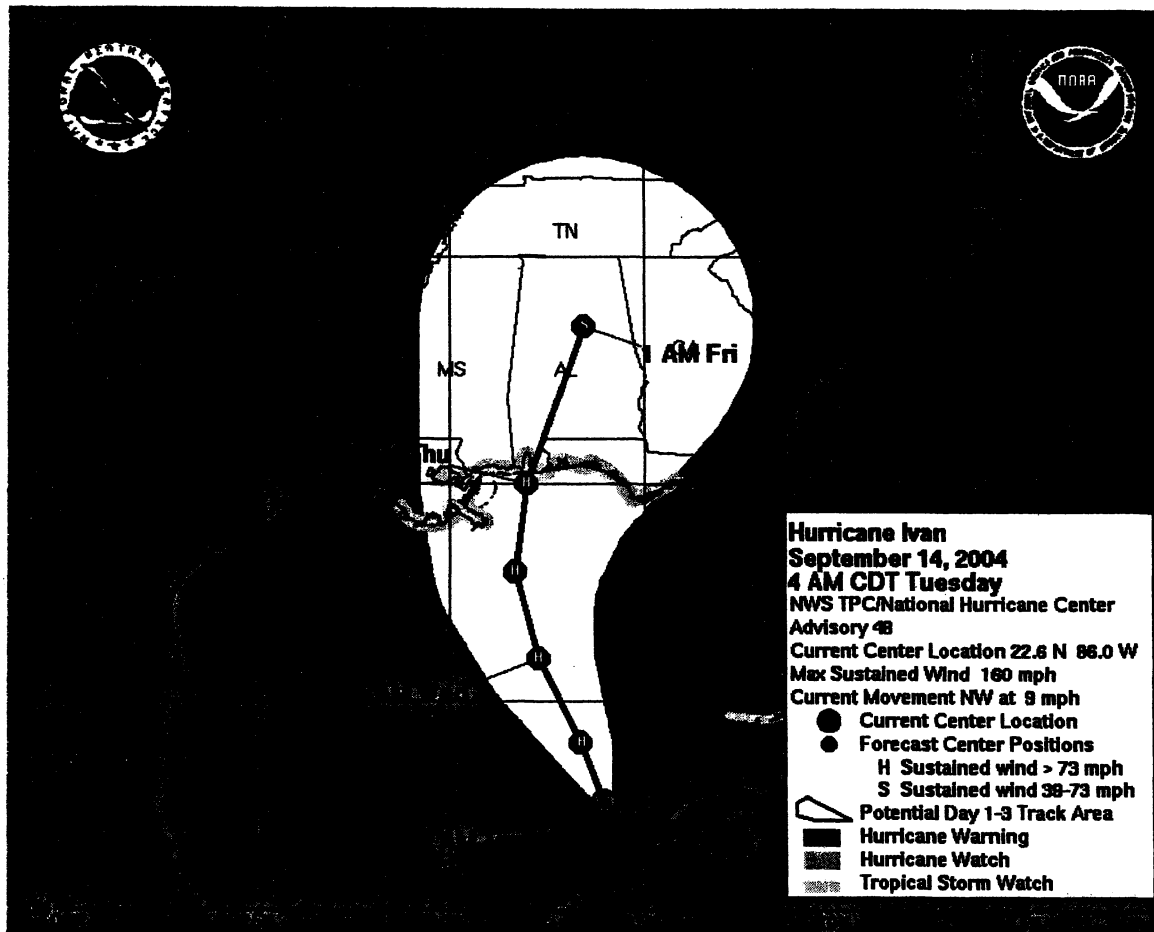


Figure 16. Forecast track for Hurricane Ivan issued at 09 UTC on 14 September. Credit: NOAA-National Hurricane Center; <http://www.nhc.noaa.gov>

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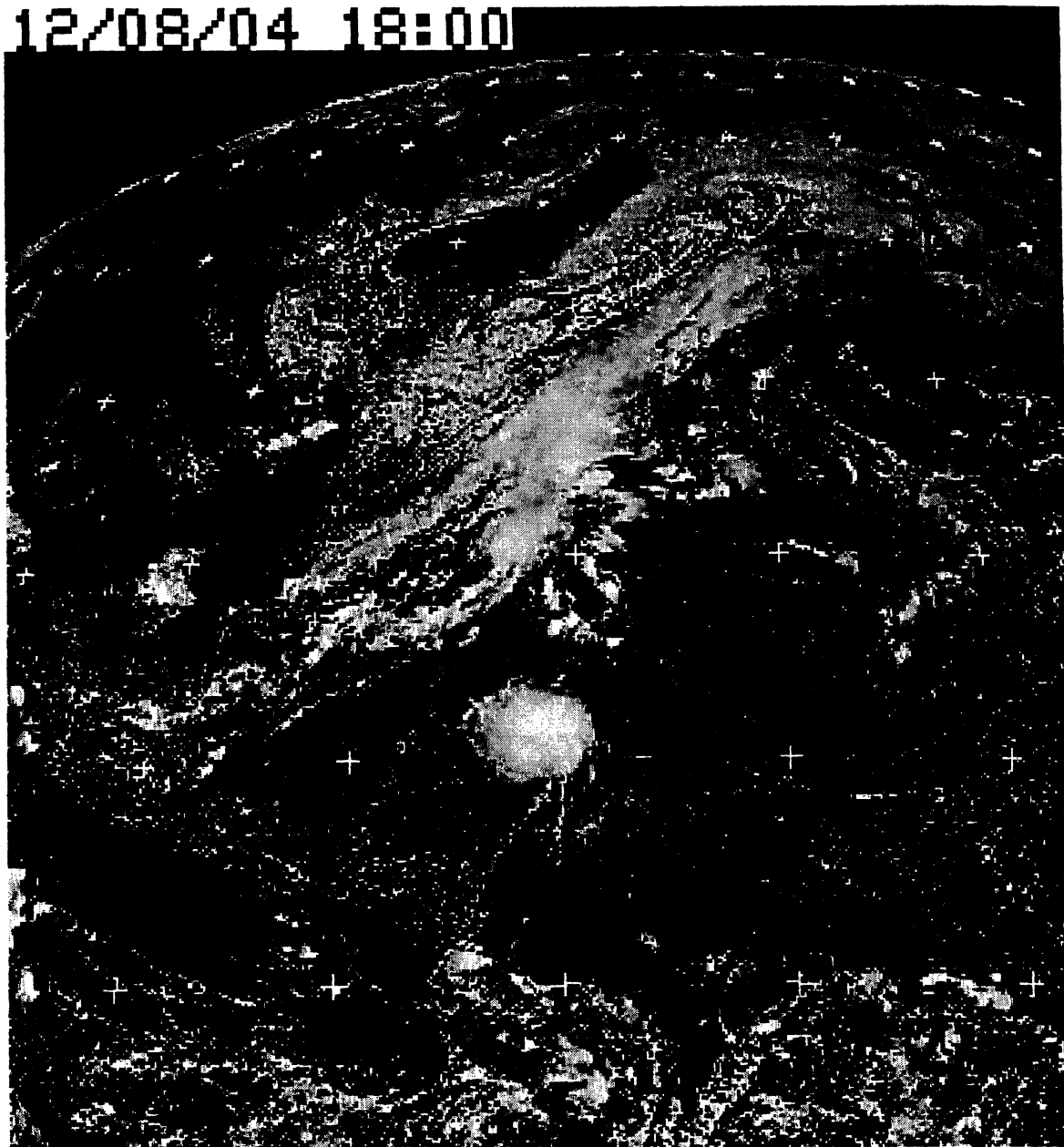


Figure 17. GOES-East visible satellite image at 18 UTC on 12 August 2004. Credit: MeteoFrance; http://www.satmos.meteo.fr/cgi-bin/qkl_sat/quicklook.pl

Summary

Hurricanes pose a significant threat to airports and aircraft located along the East and Gulf Coasts of the United States. This yearly threat exists from early summer to late fall. And while we expect some type of activity every year, we are currently in a period of increased activity that is expected to last another 20 to 30 years. Therefore, it is now more important than ever that those in the aviation field be informed about this phenomenon.

It is for this reason this paper was written. Understanding the topics covered in this paper such as storm movement, wind structure about the storm center, and uncertainty in storm track forecasts will help the decision-maker better address questions related to the protection of their resources (e.g., "What is the chance my particular location will experience hurricane impacts that require the evacuation of aircraft?"). →

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