# Vulnerability Metrics of Hurricane Forecast Accuracy

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*Abstract*

For many years, meteorologists and emergency management officials have been attempting to tune the tropical cyclone forecast evacuation process to where the people evacuated are the ones most affected by a storm. This paper attempts to display the required number of evacuees living in coastal storm surge zones and inland substandard housing. The storms that made landfall in Florida during the 2004 and 2005 seasons at category 1 hurricane strength or above are used as case studies. A "least regrets scenario" is found by comparing the forecast path issued by the NHC approximately 36 hours prior to landfall to the actual path a storm traversed. The coastal evacuee numbers are then used to calculate a vulnerability metric for a storm's affected area. The cumulative results show that even if a forecast is nearly accurate, a slight shift in the path an intensity could result in an enormous difference in the population affected.

## 1. Introduction

Evacuations of the affected population in the face of an approaching hurricane have saved thousands of lives and the heartbreak of failure to evacuate has also been graphically illustrated. The importance of having an effective evacuation plan that is inclusive of all citizens was graphically demonstrated in the tragic Louisiana landfall of Hurricane Katrina in August 2005. However, Hurricane Rita (2005) demonstrated that even a well-thought out evacuation plan can fail in the face of public panic. Even given effective evacuation strategies, the problem of determining *where* and *when* to evacuate in an individual event has plagued emergency management officials for many decades. An incorrect decision to issue an evacuation declaration can have consequences either way: failure to evacuate in the face of a landfall may cause losses of both lives and property; evacuating unnecessarily may result in lost credibility and/or economic productivity.

With the exception of Monroe County (Monroe County 2008), evacuation decisions in Florida are made predominantly on the area of likely storm surge intrusion and also includes vulnerable populations from outside the surge zone (SERT 2008). Since storm surge relates to hurricane intensity, the area – and hence population – evacuated is dependent on the forecast storm intensity and location at landfall. Thus, accurate forecasts of these storm parameters are crucial to effective protection of people and property in the face of a hurricane.

After six years of no landfalling hurricanes in Florida, seven storm landfalls in the 2004 and 2005 hurricane seasons had major impacts on the state. In this study, we focus on assessing the societal value of National Hurricane Center (NHC) landfall forecasts for these seven hurricanes. We propose a number of vulnerability indices to capture the exposure of local populations to landfall forecast errors (Section 2) and demonstrate their utility for the Florida landfalls of these seven storm cases (Section 3). Finally, we assess the effectiveness of both the NHC forecasts and our chosen metrics (Section 4).

## 2. Method

Analysis of the forecast and actual paths of the 2004 and 2005 hurricanes that made landfall in Florida, in concert with county-level storm surge zones by storm intensity, one can calculate a forecast vulnerability metric indicating the ideal evacuation scenario for a given area and storm intensity. Post-event comparison of the evacuation zone implied by the observed storm passage provides a societally-based metric of forecast accuracy.

Logically, evacuation statistics for all Florida counties for the 2004 and 2005 storms would provide the best measure of hurricane vulnerability; however, these data were unavailable for any county in Florida. As a proxy, the populations for the coastal evacuation zones for all Florida counties were calculated using either evacuation zone maps published by local county agencies (if available) or the storm surge zone maps published by SERT (the Florida State Emergency Response Team) (SERT 2008). U.S. Census Bureau population density maps (Census/Persons 2008) were then overlaid on the zone maps. The population for each evacuation/storm surge zone was calculated by area. Substandard housing (i.e. mobile homes, houseboats, trailers, etc.) numbers were also retrieved from the U.S. Census Bureau for all coastal and inland counties and included in the population analyses. The subset of total population residing in substandard housing was tracked separately in these analyses since these housing options are far more vulnerable. They were calculated from the 2006 American Community Survey Table B25033 or the 2000 Decennial Census table H33 from the U.S. Census Bureau (Census/Data 2008). Although the fraction of these residents living within a coastal evacuation or storm surge zone was unavailable, the entire substandard housing population for each coastal county was still included. The overlap between the substandard housing population and the coastal evacuation zone population is an acceptable addition to the total number of evacuees as tourists, for example, inflate the total number of evacuees anyways.

Monroe County was an exception in the process because it is not divided into evacuation zones by category. Instead, state statute requires all persons in the Florida Keys to evacuate for hurricanes of category 3 or higher (Monroe 2008). For categories 1 and 2, only nonresidents, residents of mobile homes and other substandard housing, residents of low-lying areas, women in their third trimester of pregnancy, the sick, the elderly, and the disabled are required to evacuate.

The process of analyzing each storm began by choosing a reasonable forecast time that if the evacuation order was given, it would enable people to sufficiently prepare and leave. This was chosen to be no less than 36 hours but no more than 48, depending on the storm (hurricane watches are issued approximately 36 hours before landfall). The forecast track and landfall intensity from this time was then applied to the county evacuation zone population numbers. The approximate required evacuation population was calculated for the coastal areas near landfall. The same was done for the actual track. Inland substandard housing evacuation estimates were also included for each track. From there, both tracks and evacuation numbers were compared to provide a reasonable estimate for who should have been evacuated. The final number was obtained by classifying a storm into one of three strength classes (Class A- Category 1; Class B- Category 2 or 3; Class C- Category 4 or 5) and one of five size levels from size level I at a 15 km diameter of hurricane-force winds to size level V at a 480 km diameter.

A vulnerability rating was also calculated to determine how vulnerable an affected county or group of counties is to a storm. The rating calculated for the forecast and actual storm paths were then used to obtain a forecast metric. The details of how this was calculated are summarized in Table 2.

## 3. Results

Figure 1 shows the forecast and actual paths of the 2004 and 2005 Florida hurricanes used in this analysis. Table 3 summarizes the analyzed data.

Hurricane Charley is a great example of how a slight change in track combined with rapid intensification can result in a large difference in landfall location and people affected. Figure 1A shows the 36 hour forecast and actual paths of Charley. For both paths, the first county that must evacuate is Monroe County. Because Charley passed near Monroe County below category 3 strength, the entire population of the county was not required to evacuate according to state statute. The difference between the forecast landfall in Hillsborough County and the actual landfall in Charlotte County resulted in a tremendous shift in the population affected. Because Charley was a small storm, the swath of coastal counties affected had no intersection between the forecast and actual paths, thus causing a low forecast metric score. The difference in vulnerability between the two paths is also quite tremendous mainly due to the rapid intensification of Charley. Also, according to the SERT storm surge maps, the SW FL area where Charley made landfall is much more vulnerable to flooding than the Tampa Bay area. The most ideal evacuation scenario for Charley would have been to evacuate most of the residents in the coastal zones between Pasco and Monroe Counties along the west coast of Florida because of Charley's angle of approach to the coast and ability to rapidly intensify. This would result in approximately 2.2 million coastal residents requiring evacuation. Substandard housing along the forecast path would result in 381,028 people being evacuated in a swath of counties along Charley's projected path in Florida from Tampa to near Jacksonville. For the actual path of

Charley, 356,190 people would need to be evacuated in a swath of counties from Port Charlotte to Daytona Beach. In the most ideal evacuation scenario, approximately 650,000 substandard housing residents would need to be evacuated for Charley in Florida due to the wide uncertainty of Charley's path. Combining substandard housing evacuees with coastal evacuees, approximately 2.9 million people would need to be evacuated for Charley in the most ideal evacuation scenario.

Hurricane Frances made landfall on the east coast of Florida at a much weaker intensity than forecasted by the National Hurricane Center. The forecast used for this analysis was issued approximately 45 hours prior to landfall. This forecast was used because Frances' large size and slow forward movement near the coast resulted in hurricane-force winds being felt well before the eye made landfall at 0430Z 05 September 2004. The intensity forecast at 09Z 03 September 2004 was for Frances to strengthen to 120 kts (category 4) prior to landfall, while Frances only made landfall at 95 kts (category 2). The coastal vulnerability difference was minimal as the Florida east coast near where Frances made landfall does not support large differences in storm surge. Frances' large size, however, would put a large area of Florida's east coast under evacuation orders. Since the forecast path was fairly accurate, and there was a chance that Frances could strengthen prior to landfall, the most ideal evacuation scenario would have been to evacuate based off of the forecast path. This would result in approximately 1.3 million coastal residents requiring evacuation. For substandard housing, approximately 1 million people would need to be evacuated for the inland areas across central Florida, resulting in a total of approximately 2.3 million people that need to be evacuated. Although Frances was weaker than expected, the large uncertainty in landfall intensity at the forecast time used would necessitate evacuating a larger amount of people for the worst-case category 4 scenario.

Although Hurricane Ivan did not make landfall in Florida, the damage it caused in the greater Pensacola region makes Ivan worthy of analysis. Because Ivan made landfall in Baldwin County, AL, and because the population analyses are strictly limited to Florida counties, the landfall location was adjusted to Escambia County, FL for the purposes of this study. For Ivan, the forecast track used was issued approximately 40 hours before Ivan made landfall as this gives residents along the Gulf Coast adequate time to prepare for the arrival of the storm. This forecast track was quite accurate, and the landfall intensity error was 15 kts. The main issue with Ivan was not wind damage, but storm surge. Ivan showed that even though a tropical cyclone weakens in wind strength between categories (from category 4 to 3 with Ivan), it can still carry a storm surge usually associated with the higher category. Approximately one year later, this would again be evident, on a much larger scale, with Hurricane Katrina in Mississippi and Louisiana. The vulnerability difference was somewhat significant as the forecasted intensity of 120 kts at landfall would have caused much more non-coastal damage than the actual landfall intensity of 105 kts. Since Ivan's landfall intensity was uncertain, and since the storm surge of Ivan was between 10 and 15 feet near Pensacola, the best scenario would have been to evacuate based on the forecast path and intensity resulting in an evacuation of approximately 150,000 people. For substandard housing population, 111,000 people would need to be evacuated for the coastal and inland counties between Escambia County and Bay County, resulting in a total of approximately 260,000 residents requiring evacuation in northwest Florida from Ivan.

The landfall location of Hurricane Jeanne in east central Florida was remarkably similar to Hurricane Frances earlier in September. This similarity allows for a comparison between the two storms. Jeanne, although slightly stronger than Frances at landfall (105 kts in Jeanne versus 95 kts in Frances), was also slightly smaller with regards to the radius of hurricane-force winds

(110 km in Jeanne versus 140 km in Frances). Combining the smaller size with Jeanne's approach to the coast, which was more perpendicular versus Frances which initially was moving NW towards the east central Florida coast, this results in a smaller population being affected in Hurricane Jeanne versus Hurricane Frances. With Jeanne's forecast track, chosen at approximately 36 hours prior to landfall, the biggest question was where Jeanne was going to make landfall along the east central Florida coast, if it was even going to make landfall at all. The 36 hour forecast track had Jeanne making landfall near Indian River County, then following the east coast of Florida towards the north-northwest. With the actual landfall in Martin County, the resulting affected area intersection between the two counties was small. Since Jeanne's landfall location was uncertain, the best evacuation scenario would have been to evacuate most of the east central Florida coast, resulting in approximately 500,000 evacuees. For inland substandard housing, approximately 600,000 people would need to be evacuated in a swath from the east coast of Florida to near Polk and Sumter Counties. The total number of evacuees for Jeanne in Florida would be approximately 1.1 million people. This is slightly less than half of Frances' total, reflecting the smaller area that Jeanne affected.

Hurricane Dennis provides for another comparison of two cyclones (Dennis and Ivan) that have different sizes, but similar strengths and landfall location. Ivan and Dennis, while making landfall at the same wind intensity (105 kts), were polar opposites in nearly every other way. The radius of hurricane-force winds for Ivan (170 km) was almost three times as large as Dennis (60 km). Also, the forward movement of Ivan (10 kts) was much slower than Dennis (18 kts). The faster movement of Dennis, combined with the much smaller size, allowed Dennis to be much less destructive. The storm surge for Dennis was approximately 6-7 feet which was approximately half of Ivan's surge (a larger surge reported in Apalachee Bay of up to 9 feet in some areas was most likely attributed to an oceanic trapped shelf wave that propagated along the west coast of Florida according to the NHC). The smaller size of Dennis' core also allows for a much smaller area to be affected by the storm. The analysis methodology used in this project resulted in Dennis' vulnerability to be higher than Ivan's. This can be attributed to two things: 1) Dennis' smaller size caused only one county in northwest Florida to be affected along the coast by the core in both the forecast and actual paths, and 2) The population of the northern parts of the county/counties, although not affected by the coastal strength, are included when determining the vulnerability rating of the county and area. The forecast path used for Dennis was issued approximately 36 hours before Dennis made landfall. Dennis' forecast landfall was in Escambia County with an intensity of 110 kts, while the actual landfall was in Santa Rosa County with an intensity of 105 kts. Since Dennis was so small, the best evacuation scenario would have been to evacuate coastal residents from Escambia to Walton Counties, with an approximate total of 100,000 people. This estimation covers the chance that Dennis may veer slightly from the forecast path. For inland substandard housing, approximately 80,000 people would need to be evacuated from these four counties, resulting in a total evacuated population of approximately 180,000. Compared with Ivan, this makes sense because Ivan's larger size resulted in a larger population (+80,000) necessitating evacuation.

The only hurricane in the 2004 and 2005 seasons to make landfall in Florida as a category 1 storm was Hurricane Katrina. Although much more famous for what it did in Louisiana and Mississippi, Katrina caused minor to moderate wind damage near where it made landfall along the Miami-Dade and Broward County line with an intensity of 70 kts. The forecast path used was issued approximately 30 hours prior to Katrina making landfall, which was forecasted in Palm Beach County at 65 kts. This forecast was used because this was the first forecast where the general public had an idea of what Katrina's strength at landfall would be. Since Katrina made landfall on the county line, the estimated actual path evacuation was found by analyzing a small category 1 landfall in Broward and Miami-Dade counties, though this will give an overestimate of the amount of people that need to evacuate due to Katrina's small size. The most ideal evacuation scenario would have been to evacuate the barrier islands, other very low-lying areas, and substandard housing in Miami-Dade, Broward, and Palm Beach Counties. For the coastal zones, this would result in approximately 600,000 people requiring evacuation. Katrina's post-landfall shift to the southwest caused many areas of western Miami-Dade County and the Florida Keys to be affected by the storm. Inland substandard housing would need to include the three coastal counties, Monroe, Collier, and Hendry Counties for an approximate total of 159,000 evacuees. The total population requiring evacuation for Katrina would therefore be approximately 759,000 people.

Of the seven 2004 and 2005 Florida landfalling hurricanes, Hurricane Wilma was the most powerful to hit a large metropolitan area of Florida. Although Wilma made landfall in the unpopulated mainland portion of Monroe County, the damage it inflicted on the metropolitan Miami area was extensive. A storm surge of approximately 4-9 feet occurred over the Florida Keys, with higher levels likely along the uninhabited mainland Monroe County coastline. Wind damage was extensive across most of south Florida, and was the main cause of structural damage. The forecast used to analyze Wilma was issued approximately 36 hours prior to landfall, which had Wilma making landfall in Collier County with 100 kts winds. Landfall intensity was 105 kts in the northern part of mainland Monroe County. In the most ideal evacuation scenario, coastal population from Charlotte County on the west coast to Miami-Dade on the east coast, including the Florida Keys, would need to evacuate for Wilma. This would result in a total coastal population of approximately 900,000 people requiring evacuation. Inland substandard housing population would include most of Florida south of Lake Okeechobee, resulting in an approximate total of 220,000 people. Therefore, the total population requiring evacuation for Wilma would be approximately 1,120,000 people.

## 4. Summary and Conclusions

The least regrets evacuation scenarios that were found were based on a harmonization of the storm intensity, storm size, and the county where the eye made landfall for a chosen forecast path and the actual path of each storm. Since the population data was county-level, there are clearly some caveats with this method. One must look at the results as only an approximation. Division of the counties into smaller units via the U.S. Census Bureau population density maps would provide a more accurate measure. This is particularly true for the smaller storms where Dennis, for example, was recorded as only affecting one coastal county in this analysis. By dividing the counties into smaller units, the analysis of Dennis could have included portions of the surrounding counties. This may also make the vulnerability metrics more accurate as the county-level data is coarse enough to bring the vulnerability rating of larger storms down because they require evacuating a smaller percentage of the population of counties that are far away from the center of landfall. Another factor to consider is coastal topography and how it might cause the storm surge to be greater or less than expected in smaller areas, resulting in a change in the number of people being evacuated. This analysis also does not consider housing that meets building standards but may fail in the winds of a category 4 or 5 hurricane.

Despite these caveats, the results of this analysis are useful because they are the beginning steps of determining the vulnerability of the population of the coastal counties in Florida. They also provide an estimate of the substandard housing population that would require evacuation for any storm in all counties in Florida. The path vulnerability error (PVE) and forecast score (FS) found in Table 3 show us that even if a forecast is nearly accurate, a slight shift in the path and intensity from the forecast could result in an enormous difference in the population affected. Since the population is the main concern when forecasting tropical cyclones, it is critical that in the future the meteorological community focuses on making sure that the population forecasted to be affected by a tropical cyclone is as accurate as possible.

## 5. Acknowledgements

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**Figure Captions**

Fig 1: Florida county reference map.

Fig 2: Forecast tracks (black dashed line, white cone and hatching) and actual tracks (blue solid line) for 2004 hurricanes Charley (top left), Frances (top right), Jeanne (lower left), and Ivan (lower right). Red (blue) coastal outlines indicate hurricane warnings (watches) in operation at the time that the forecast was issued. Forecasts shown were issued approximately 36 hours prior to the observed landfall time.

Fig 3: Forecast tracks (black dashed line, white cone and hatching) and actual tracks (blue solid line) for 2005 hurricanes Dennis (top left), Katrina (top right), and Wilma (below). Red (blue) coastal outlines indicate hurricane warnings (watches) in operation at the time that the forecast was issued. Forecasts shown were issued approximately 36 hours prior to the observed landfall time.

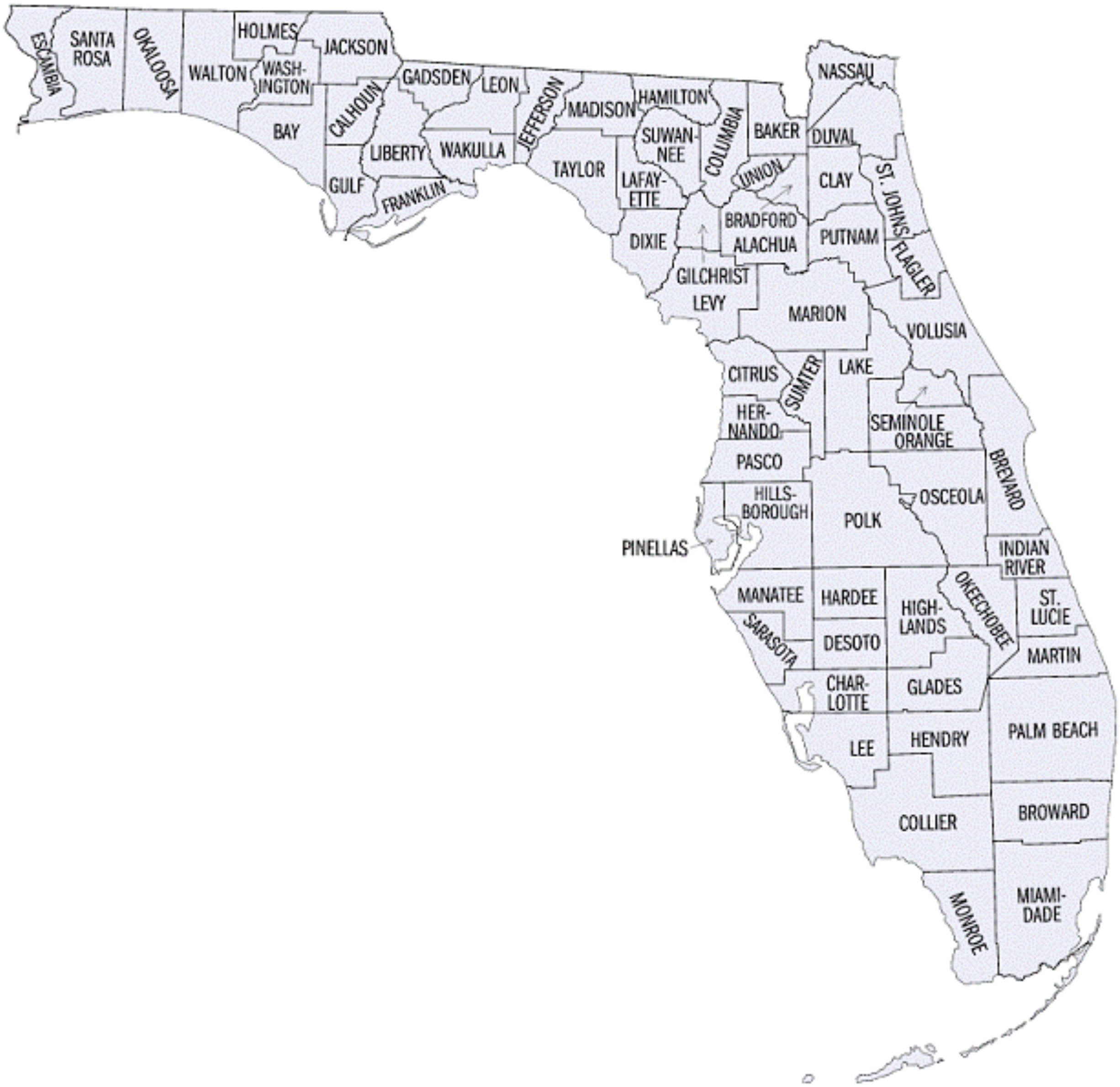
**Table Captions**

Table 1: Definitions of the vulnerability and forecast evaluation metrics introduced here.

Table 2: Summary of relevant information needed to calculate the vulnerability metrics introduced for each of the 2004 and 2005 hurricanes in this study.

Table 3: Vulnerability metrics for each of the 2004 and 2005 hurricanes analyzed here.

**Figures**

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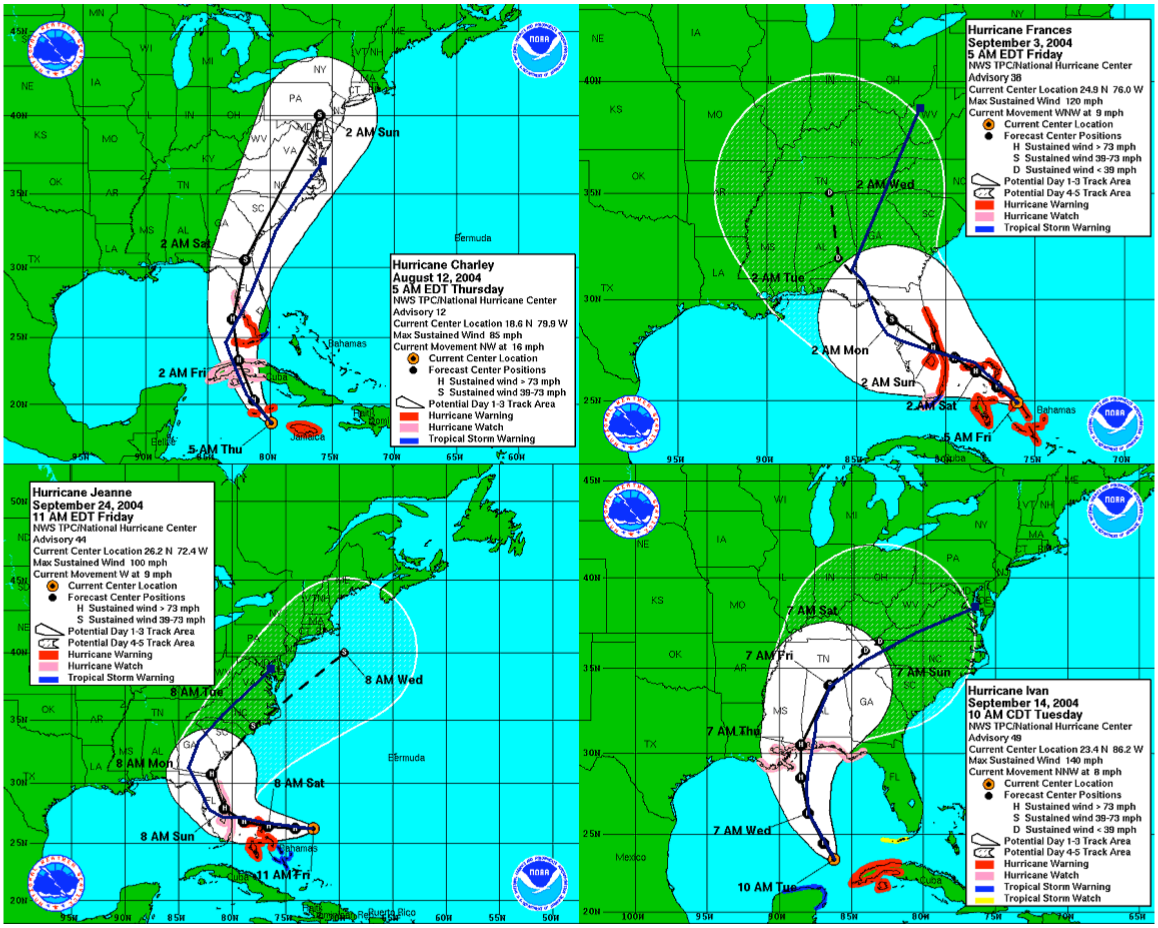


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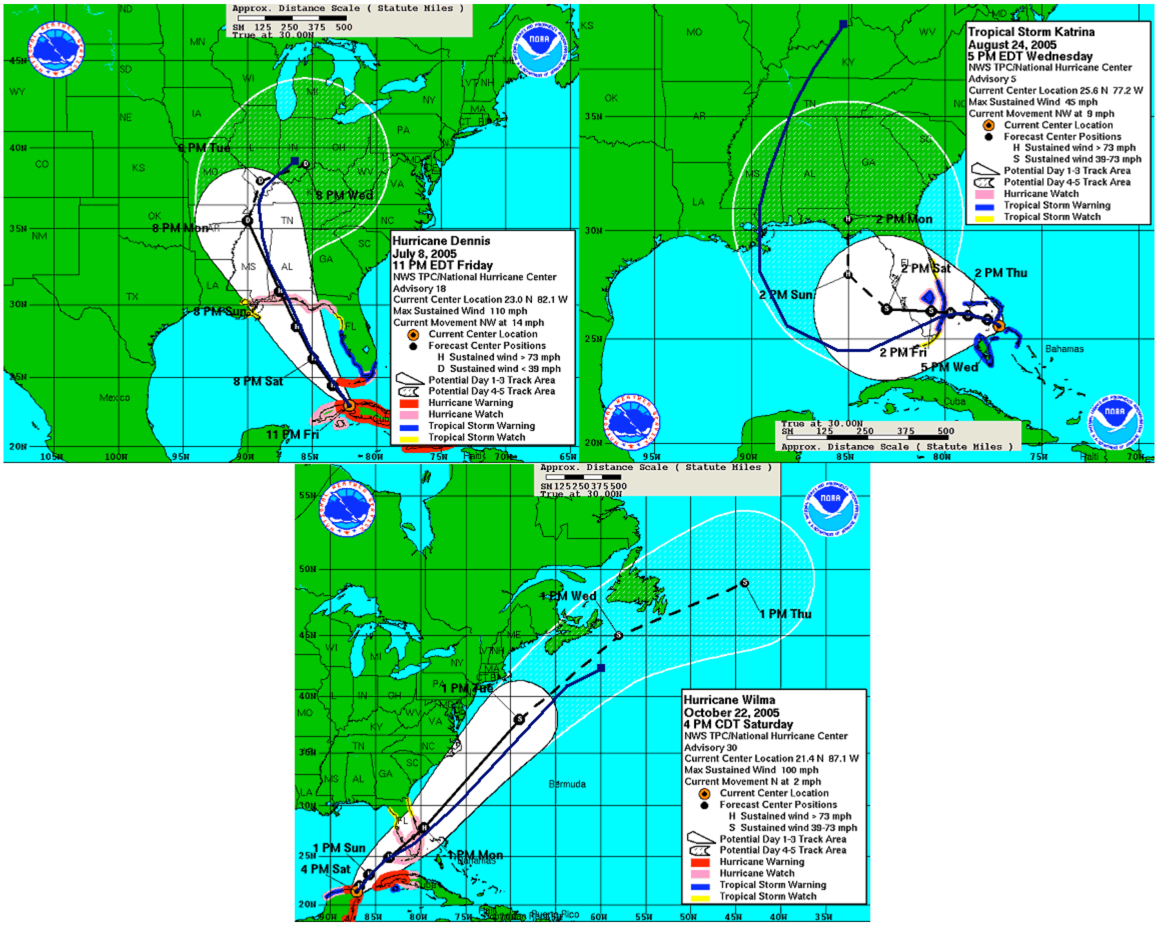


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**Tables**

| Vulnerability Metric | Symbol or Equation |
|---|---|
| Evacuated population | EP |
| Total population in affected Counties | TP |
| Forecast or actual path vulnerability (%) | $V = \frac{EP}{TP} \times 100$ |
| Path vulnerability error | $VE = \frac{V_f - V_a}{V_a}$ |
| Area intersection of forecast and actual paths, AI | $AI = \frac{\text{total \# counties in both actual and forecast paths}}{\text{\# counties in actual path only}}$ |
| Forecast vulnerability score (%), FS | $FS = (1\text{-}VE) \times AI$ |

Table 1: Definitions of the vulnerability and forecast evaluation metrics introduced here.

| **Storm Name** | **Counties Affected Intersection (A, F)** | **Landfall Error (km, h, kts)** | | | **Population Affected ($10^6$)** | |
|---|---|---|---|---|---|---|
| | | | | | Actual | Forecast |
| Charley | 0 (3, 2) | 125 | 2.5 | 35 | 1.1 | **1.5** |
| Frances | 5 (5, 7) | **30** | 0.5 | 25 | 3.6 | **6.5** |
| Ivan | 3 (3, 4) | 70 | 4 | 15 | 0.6 | 0.7 |
| Jeanne | 1 (3, 3) | 90 | 8 | 10 | 1.7 | **0.9** |
| Dennis | 0 (1, 1) | 35 | 1 | 10 | 0.1 | 0.3 |
| Katrina | 0 (2, 1) | **55** | 10 | 5 | 4.2 | **1.3** |
| Wilma | 4 (5, 5) | **50** | 0.5 | 5 | 3.4 | **1.1** |

Table 2: Summary of relevant information needed to calculate the vulnerability metrics introduced for each of the 2004 and 2005 hurricanes in this study.

| **Storm Name** | **Vulnerability (% population)** | | **Vulnerability Error** | **Fractional county intersection, AI** | **Forecast Score (%)** |
|---|---|---|---|---|---|
| | **Actual** | **Forecast** | | | |
| Charley | 75 | 14 | 0.8 | 0 | **0** |
| Frances | 11 | 19 | **0.7** | 1 | **28** |
| Ivan | 11 | 21 | 0.9 | 1 | 9 |
| Jeanne | 15 | 12 | 0.2 | 0.3 | **26** |
| Dennis | 20 | 8 | 0.6 | 0 | 0 |
| Katrina | 12 | 15 | **0.3** | 0 | **0** |
| Wilma | 19 | 27 | **0.4** | 0.8 | **46** |

Table 3: Vulnerability metrics for each of the 2004 and 2005 hurricanes analyzed here.