An Analysis of Hurricane Irma's Maximum Winds in South Florida

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Hurricane Irma struck South Florida on 10 September 2017 and caused significant wind damage to structures and trees as well as widespread power loss. Irma caused more than personal inconvenience to many South Floridians, and its aftermath left people asking how they can be better prepared for the next hurricane. From a wind impact perspective, it is important to spatially quantify the wind magnitude so that residents and business owners of South Florida can have a better understanding of the maximum wind speeds experienced in their neighborhood during Irma.

Hurricane Irma's winds have been analyzed across the National Weather Service Miami County Warning Area, which includes the Florida Peninsula from Lake Okeechobee southward and adjacent coastal waters of the Gulf of Mexico and Atlantic Ocean. All available data from surface-based weather stations and anemometers are incorporated. WSR-88D Doppler velocity data were also analyzed and used to fill in the gaps for locations where observations are sparse. These data were further augmented with results of ground wind damage surveys. Detailed, color-contoured maps of sustained winds and gusts have been created in addition to a list of observations. For the purposes of consistency on the color-contoured map, all sustained wind observations are converted to a 10 meter, one minute average using standard conversion metrics. The results indicate that sustained hurricane force winds up to Category 2 strength on the Saffir-Simpson Hurricane Wind Scale with higher gusts occurred in southern portions of coastal Collier County, including portions of the Naples area. In the east coast metropolitan areas of Miami, Fort Lauderdale, and West Palm Beach, most areas received sustained strong tropical storm force winds between 48-63 kt (55-73 mph) with hurricane force gusts of 70-87 kt (80-100 mph).

BACKGROUND AND METHODOLOGY

Surface Observations

Observed winds from surface based platforms include data from Automated Surface Observing Sites (ASOS), WeatherBug, WxFlow, National Data Buoy Center (NDBC), National Ocean Service (NOS), Remote Automated Weather Stations (RAWS), Florida Automated Weather Network (FAWN), Citizen Weather Observing Program (CWOP), South Florida Water Management District (SFWMD), Soil Climate Analysis Network (SCAN), WeatherStem, Integrated Coral Observing Network (ICON), personal weather stations and an anemometer from a spotter. In addition to the observations that Weather Forecast Office (WFO) Miami compiled for the Post-Storm Report (PSH), observations from WFO Miami's Local Storm Reports (LSRs) during Irma and the National Hurricane Center (NHC) Tropical Cyclone Report (TCR) on Irma were used. First, for each anemometer site, the maximum sustained wind during Irma, the averaging time and the height of the anemometer were obtained. We then determined which of the anemometers continuously recorded throughout the storm and which ones stopped reporting prior to the time of the likely peak winds. After that, all observations were converted to 1-min, 10m winds. One caveat is that some of the observation sites only report wind observations hourly, some report every 15 minutes, some report every 5 minutes and some more frequently. Some of the anemometer sites continuously record data and report the maximum wind averaged over a given time period, whereas sites that report every hour or every 15 minutes do not necessarily record every minute of data. For these observations, it is possible that the maximum wind could have been missed, even if the instrument did not stop reporting prior to the peak of the storm. Furthermore, there were some maximum wind values from anemometers that were low outliers compared to surrounding observations, and some sites were already known to have a low bias due to poor exposure of the instrument. Overall, there are more than 120 locations that reported wind observations from anemometers in and near South Florida that were considered for inclusion in this study. However, only about 75 of these were used after eliminating the sites that had low maximum values because either the anemometer failed prior to the peak of the storm or were low outliers due to poor exposure. Of the 75 that were used, about one-third of them may not have recorded the highest wind due to a non-continuous sampling interval.

Wind observations with averaging periods ranging from 2-min to 15-min are converted to 1-min values using factors nearly identical to Table 1.1 from Harper et al. (2010). The factors used for this analysis are listed in Table 1. For simplicity, we do not differentiate between marine exposure and land exposure when converting the winds to 1-min values. If we had accounted for and applied the Harper et al. (2010) technique for marine and land exposure it would have only made a difference of 1 to 2 kt, on average.

Time-average of observation	Factor used to convert to 1-min
2-min	1.03
5-min	1.06
10-min	1.12
15-min	1.13

Table 1. Multiplication factors used to convert various time-averaged winds to a 1-min wind.

For converting winds at elevated anemometers down to 10m, the chart from Franklin et al. (2000) is used (Chris Landsea, personal communication). This chart is shown below (Figure 1). For example, to convert a 40m wind to a 10m wind, a factor of 0.90 is used. This methodology is used for all anemometers above 10m in Florida during Irma, regardless of whether the observation occurred in the eyewall or in the outer bands. Additionally, there are numerous observations with anemometers at 2m, 6m and 8m, especially from Texas Tech's portable network. There is no published or agreed-upon material for how to adjust these winds to the 10m level. However Hsu et al. (1994) derived the factor in the Power Wind Profile Power Law. In order to adjust winds from below 10m up to 10m, we first use the Power Wind Profile Power Law

$$u = u_r\left(\frac{z}{z_r}\right)^{\propto}$$

where u = wind at 10m, u_r = wind at some reference level z_r, z = 10m and α = 0.143, as derived in Hsu et al. for near neutral stability conditions. The stability in tropical cyclone environments is fairly close to neutral, so we use the factor of 0.143 as in the Hsu et al. study. When this equation is applied, it's equivalent to multiplying the following factors to arrive at a 10m wind: 1.03 for 8m, 1.08 for 6m and 1.26 for 2m. There are some locations where we compare wind data to validate or calibrate these factors. A comparison is made to determine if these factors are

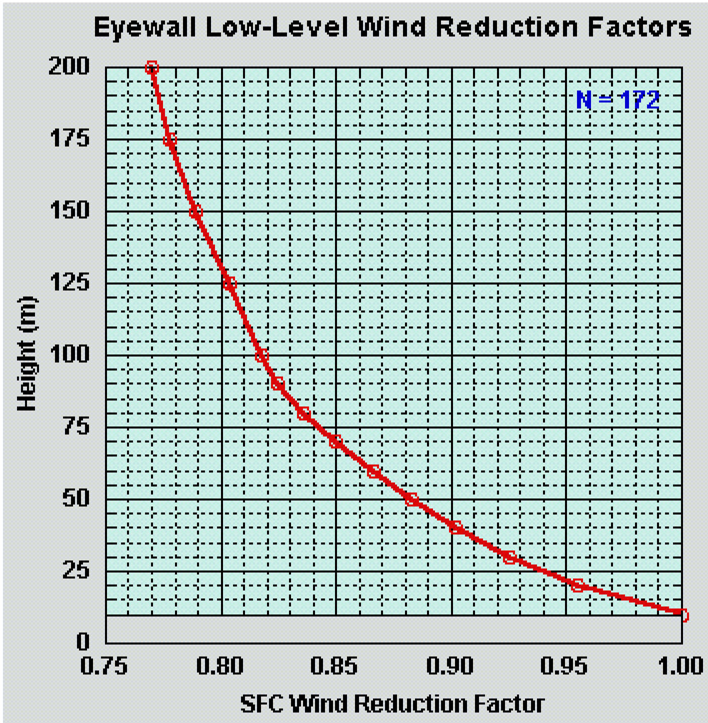

Figure 1. Conversion factor used to adjust elevated anemometer winds to 10m. Figure from Franklin et al. (2000).

reasonable using a cluster of four maximum wind observations all located in the immediate area between Hollywood Beach and Fort Lauderdale Beach, one of which is a 2m observation. The other three observations are either at 10m or higher. After adjusting those to 10m, all three of those observations have the exact same maximum wind value of 58 kt. The one anemometer at 2m, in the same vicinity, recorded a maximum wind of 50 kt at 2m. The number 58 is 16 percent higher than 50. Therefore, it is determined that 1.26 is too large of a factor to use to convert a 2m wind to a 10m wind. Instead, we use 1.16 for 2m, 1.047 for 5m and 1.02 for 8m. The values used are about 62% of the values obtained using the Power Wind Profile Power Law. This more conservative approach ends up yielding wind values that are much more realistic and well representative of the observed damage. To further support using this lower factor, we analyze the strongest wind observation recorded in Miami-Dade County (0214A) located about five miles southwest of Florida City. The anemometer at this site is at 2m AGL. The highest 1-min wind recorded there was 66 kt. Using a factor of 1.26 would have yielded a 10m wind of 83 kt (Category 2). Instead, applying the factor of 1.16 yields 77 kt, which is a much more reasonable value. In the final analysis, we place a value of 75 kt at that point because the last step in the methodology is a subjective final adjustment, where deemed necessary to best fit the data and the damage.

Radar Data

Velocity data from the WSR-88D radar from Miami, FL (KAMX) was used in this study. Using the methodology from Franklin et al. (2003) to reduce winds from a given altitude down to the 10m level in a hurricane environment, there were two main ways the radar data is used for this study. First, in locations with good coverage of reliable surface observations for which the anemometer did not fail, the radar data was compared with the time of the maximum wind reported by the anemometer. Second, for areas in South Florida where surface based wind observations are sparse, radar data was used to fill in those data gaps.

First, the radar data was compared to all reliable surface wind observations. It is important to note that locations near the line of zero Doppler velocity (zero isodop) near the time of maximum winds could not be compared. There are 32 sites across South Florida with reliable maximum wind observations that were compared to the radar data for the purpose of calibrating how well the radar data matches up with the max wind obs. To determine the wind value that is then reduced to 10m, numerous radar velocity pixels in the vicinity were averaged. Generally, the pixels within five or ten miles or so of the site were averaged. Also, pixels at radar times within about five or ten minutes of the peak wind observation were averaged. This spatial and temporal methodology corresponds well with sustained winds, as opposed to gusts (Stacy Stewart and Richard Pasch, personal communications). To determine the estimated 10m wind from the radar data, typically, one of the lower available tilts was used. No radar data above 10,000 ft was used. The value chosen based on the aforementioned spatial and time average was then reduced to 10m. Based on Franklin et al. (2003) and personal communications with NHC hurricane specialist Richard Pasch, the conversion factors used to reduce the value aloft to 10m are listed in Table 2. In Table 2, "convection" is defined by areas where the lowest tilt (0.5 degree) reflectivity is equal to or greater than 30 dBZ.

Height (ft)	Eyewall	Outer convection	Outer non-convection
10,000	0.90	0.85	0.80
5,000	0.80	0.80	0.75
2,500	0.75	0.75	0.75
1,000	0.80	0.80	0.80
500	0.80	0.80	0.80

Table 2. Reduction factors used to convert radar velocities to 10m. Convection refers to instances for which the lowest tilt reflectivity is equal to or greater than 30 dBZ. Non-convection areas in the outer portion of a tropical cyclone contain lowest tilt reflectivity values of less than 30 dBZ.

Once the 32 values were reduced to 10m, they were compared to the maximum 10m, 1-min value from the anemometers. The radar values are, on average, 7 kt or 12% higher than the anemometer values. The standard deviation in the difference values between the anemometer and radar values is 5 kt, with a range from -3 to +17 kt.

For areas of South Florida that lack surface observations, the time of the strongest Doppler velocity winds was found using the radar data. Numerous points across South Florida were chosen. The wind was averaged near that area/time spatially/temporally as previously described, and then reduced to 10m. The wind value was then further subtracted by 7 kt since we found in the previous step that the radar data is 7 kt too high compared to the reliable anemometer data.

When determining the final values used for the map (Figure 4), the anemometer data was weighted heavily in areas with good coverage of reliable maximum winds from anemometers. In areas where the anemometer data is somewhat questionable, a combination of the radar data and anemometer data was employed. In areas that completely lack anemometer data, the radar data was used, reduced to 10m and then subtracted by 7 kt. The final step in the methodology was to subjectively make any final adjustments to the wind data to better fit the observed damage as well as nearby observations.

DATA, RESULTS AND DISCUSSION

Radar data

Reflectivity and velocity data are available from 9 through 11 September and were viewed using GR-2 Analyst. Figures 2 and 3 show the 0.5 degree reflectivity and velocity data, respectively, at 1736 UTC on 10 September. In the velocity image, the enhanced wind in Irma's north eyewall is

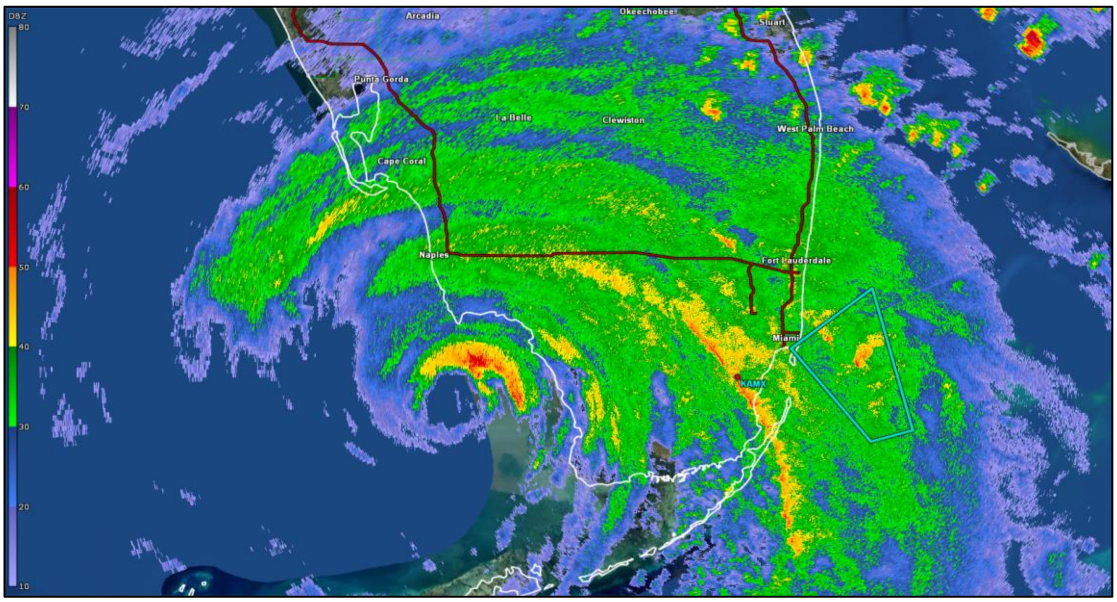

Figure 2. 0.5 degree reflectivity from the KAMX Miami WSR-88D radar at 1736 UTC on 9/10/2017.

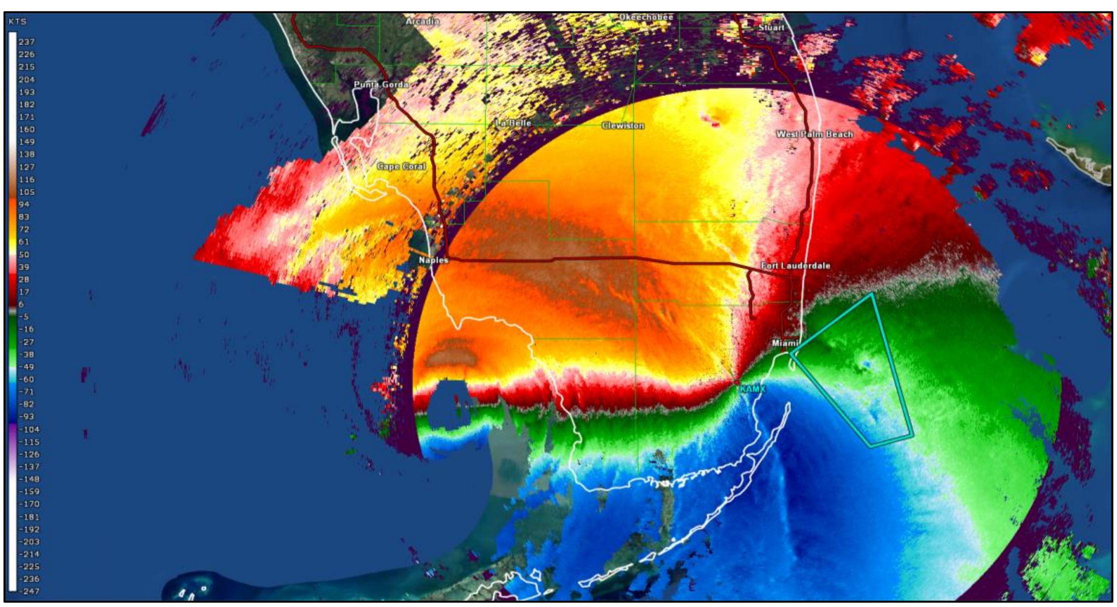

Figure 3. 0.5 degree velocity from the KAMX Miami WSR-88D radar at 1736 UTC on 9/10/2017.

clearly evident. There is a secondary maximum over inland Collier County, where sustained Category 1 winds were occurring at 10m at the time.

<u>Final Analysis of Maximum Sustained Winds</u>

After analyzing the anemometer data and radar data, a map of maximum sustained winds was plotted (Figure 4). It should be noted that short duration gusts are not included in this study and are likely 20-25 kt higher, on average, than the 1-min averaged wind. Figure 4 was created using ArcMap and interpolating the data. The values from the dataset were plotted as point values, then interpolated using the Natural Neighbor method. This method works by finding the closest subset of input samples to each point, and weights them based on proportionate areas to interpolate a value (Sibson 1981). There are a total of 151 points of maximum sustained wind speed used to construct the map in Figure 4. The values were then put in basins by wind speed for display purposes. The colors are binned based on Saffir-Simpson Hurricane Wind Scale category. However, there is such a large area of the map where winds peaked at Category 1, that we split the Category 1 winds into two bins. Areas where the winds peaked at tropical storm strength are also separated into two bins – one for 57-63 kt (shown in green), and the other for 45-56 kt (shown in blue in Figure 4). Although sustained winds in the blue area were analyzed to have not exceeded 56 kt, all locations in South Florida experienced sustained winds of at least 45 kt (52 mph) during Irma according to the analysis. It is possible that all locations received sustained winds over 48 kt (55 mph).

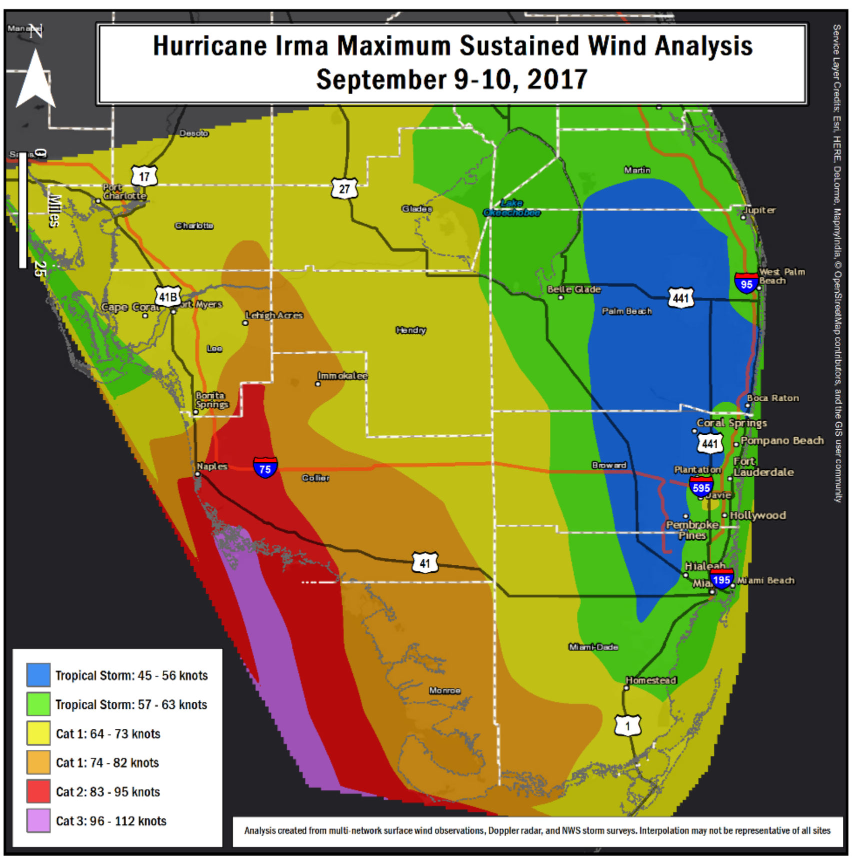

Figure 4. Maximum sustained (1-minute averaged) winds experienced in Hurricane Irma according to the analysis performed for this study.

In Figure 4, there are some areas with high confidence in the analysis and other areas where we have low confidence in the analysis. One low confidence area is a large chunk of central Palm Beach County where surface observations are lacking and radar data quality is lacking in that area due to its distance from KAMX and its proximity to the zero velocity line at all times when the strongest winds were likely occurring. The other low confidence area is along the northern Gulf Coast of Collier County between Naples and the Lee County border. Irma's central core was inland and deteriorating quickly as it passed nearest this area, so it is possible that only low-end Category 1 sustained winds occurred along the coast of northern Collier County. For areas outside of the Miami-South Florida CWA, from Martin County northward, and from Lee County Northward, our analysis contains very few points. The aim of this study is to produce accurate results for all land areas in the Miami-South Florida National Weather Service CWA and for Lake Okeechobee. Counties in the South Florida CWA include: Miami-Dade, Broward, Palm Beach, Glades, Hendry, Collier and Mainland Monroe. Residents outside of this area should not use this map to deduce the wind magnitude in their county. It should also be mentioned that the data may not be very accurate on the extreme western edge of the map over the Gulf of Mexico. A county-by-county discussion of maximum sustained winds follows.

<u>County by County Discussion of Maximum Sustained Winds</u>

Collier County: In Collier County, there were at least eight anemometers that recorded sustained winds of hurricane force after converting the max wind to 10m, 1-min (one Cat 3, one Cat 2, and six Cat 1 observations). A spotter on Marco Island reported 97 kt winds. A Texas Tech instrument located a couple of miles NE of Marco Island Airport on the inland side of US-41 recorded a 1-min, 2m wind of 74 kt, which converts to 86 kt at 10m using the factor of 1.16 from this study. Therefore, Category 2 winds were analyzed at this location. This location was in the northeastern eyewall, only about 5 to 10 miles inland from where landfall occurred. A WeatherBug station near Naples International Airport recorded winds of 81 kt with a gust to 123 kt. This location was either in the western half of the eye or the western eyewall. Therefore Category 2 winds could have easily been located near or just east of this location.

Sustained Category 3 winds of 96-100 kt were likely confined to a very small area of the eye that touched Marco Island and the immediate coastline of Collier County to the east of Marco Island, including Goodland and Cape Romano. Sustained Category 2 winds (83-95 kt) likely extended farther inland into west-central Collier County in the eastern eye wall, including the Golden Gate Estates and Orangetree areas. All of the greater Naples area received hurricane force sustained winds. More than half of the Naples population may have only received Category 1 winds, with Category 2 winds likely affecting much of southern and eastern portions of Naples. Winds to Category 2 strength likely accompanied the northeastern eye wall (in a small area) until Irma reached the Collier/Lee county line. While Irma was moving through northern Collier County, damage reports indicate that the strongest winds occurred inland from the coast with weaker winds along the Gulf Coast, and this is supported by observations from anemometers and radar data. Confidence is high that Immokalee experienced high-end Category 1 sustained winds, similar to the winds experienced in Naples (high Category 1 to low Category 2). Along the northern coast of Collier County, to the north of Naples, sustained winds likely peaked at Category 1 strength.

Miami-Dade County: The majority of the population experienced sustained winds of strong tropical storm force, with a few notable exceptions. In Miami-Dade County and adjacent Biscayne Bay, there were four anemometers that recorded sustained Category 1 hurricane force winds. None of these were directly in the metro (populated) area of Miami-Dade.

An anemometer set up by Texas Tech five miles southwest of Florida City recorded a maximum 1-min wind of 66 kt at 2m. This converts to 77 kt at 10m using our conversion factor of 1.16 to adjust from 2m up to 10m. Government Cut (located near Fisher Island, less than one mile from the southern tip of South Beach) recorded a maximum wind of 64 kt (65 kt after converting to 10m and 1-min). Fowey Rocks (a station well out over the water where central Biscayne Bay meets the Atlantic Ocean) recorded a maximum wind of 73 kt (elevated). After reducing this to 10m and converting to 1-min, it yields a maximum wind of 67 kt. Station 3AS3W over the middle of the Everglades north of US-41 and east of the Collier County border recorded a 15-min averaged wind of 59 kt at 8m. This converts to a 10m, 1-min wind of 67 kt. Turkey Point Nuclear Plant recorded a maximum wind of 62 kt (63 kt after converting to 10m and 1-min). This is 1 kt below hurricane force.

Based on the aforementioned wind observations as well as radar data, damage surveys and careful analyses by the authors, most of the populated areas of Miami-Dade County experienced sustained winds of strong tropical storm force (50-63 kt). However, there were a few areas that likely experienced sustained winds of Category 1 hurricane strength. Sustained winds may have reached hurricane force (around 65 kt) in portions of Key Biscayne. Although not explicitly shown in Figure 4, it is possible that sustained winds briefly reached 65 kt within a mile of Biscayne Bay (east of Bayshore Drive and east of Old Cutler Road) from Coconut Grove to Pinecrest to Palmetto Bay. However, more likely, sustained winds in that area peaked around 60-63 kt (just below hurricane force). Sustained winds likely reached the lower limits of Category 1 strength in portions of Homestead, especially southern and western portions of Homestead, including Florida City and southern portions of the Redland. In coastal Miami-Dade County from Downtown Miami northward, including Miami Beach, North Miami Beach, Little Haiti, North Miami and Aventura, sustained winds likely peaked in the 57-63 kt range. Sustained winds likely only reached the 48-56 kt range for the western and northern parts of the metro area (west of the Palmetto Expressway to Krome Avenue) including West Kendall, Doral and Miami Lakes.

Broward County: In Broward County, the lone hurricane force sustained wind of 70 kt was recorded on the roof of the Seminole Hardrock Casino Headquarters building (about 60 ft), and the value reduces to 66 kt after converting to 10m. Category 1 winds are analyzed to have occurred within a mile or so of that location in Figure 4. Between Ft. Lauderdale Beach and Hollywood Beach, there were four anemometers. All four recorded a maximum wind of 61 kt (70 mph) (after converting to 10m and 1-min). In the coastal and central areas of metro Broward County, sustained winds peaked in the 57-63 kt range (just below hurricane force). Sustained winds were lower in western areas such as Weston, Tamarac and Coral Springs, where the winds likely peaked in the 45-56 kt range. The gusts in Broward were mostly in the 70-90 kt range.

Glades and Hendry Counties, Lake Okeechobee: A sustained Category 1 wind of 67 kt was recorded at Airglades Airport in northeastern Hendry County. The four anemometers over Lake Okeechobee peaked between 56-59 kt (after converting to 10m, 1-min). These sites report at 15-

min intervals. Radar data suggests winds on the Lake were borderline strong tropical storm or low end Category 1. Winds of 57-63 kt were analyzed for most of Lake Okeechobee, but southwestern portions of the lake likely experienced low-end Category 1 hurricane force sustained winds. Sustained winds of Category 1 strength likely occurred over most of Glades and Hendry Counties, with highest winds in the LaBelle and Felda areas. Wind in northeastern Glades County likely peaked at slightly below hurricane force.

Palm Beach County: Sustained winds peaked in the 48-56 kt range over southern coastal areas and most of central Palm Beach County. Stronger winds – in the 57-63 kt range – were observed along the immediate coastline north of West Palm Beach to Jupiter.

Mainland Monroe County: All of Mainland Monroe County likely received sustained winds that peaked in the Category 1 range (64-82 kt).

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