A REANALYSIS OF HURRICANE ANDREW'S INTENSITY

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Hurricane Andrew, one of the United States' worst natural disasters, is upgraded to a Saffir-Simpson Hurricane Scale category 5—the highest intensity category possible

> *"The sound of the wind, that's what you never forget.*
> *The initial whisper.*
> *The growing mewing that turns into a howl.*
> *Then the cry of glass shattering.*
> *The snap of trees breaking.*
> *The grumbling of a roof peeling apart."*
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> —ANA VECIANA-SUAREZ
> September 11, 2004, *Miami Herald*
> Remembering Hurricane Andrew as 2004's Ivan threatens

The Atlantic basin hurricane database (HURDAT; Jarvinen et al. 1984) reanalysis project is an ongoing effort to extend the database back in time, and to revisit and revise, if necessary, the official tracks and intensities of tropical storms and hurricanes from 1851 to the present (Landsea et al. 2004). Wind estimates from Atlantic basin tropical cyclones are recorded in HURDAT in 6-hourly intervals as the maximum 1-min surface (10 m) wind speed (in 5-kt increments; note that 1 kt = 0.515 m s^{-1}) within the circulation of the tropical cyclone. HURDAT is utilized in a wide variety of ways, including climatic change studies, seasonal forecasting, risk assessment for emergency managers, analysis of potential losses for insurance and business interests, and the development and verification of official National Hurricane Center (NHC) and computer model predictions of track and intensity.

While the Atlantic hurricane database has widespread and varied uses, HURDAT contains many

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systematic and random errors that need to be corrected (Landsea 1993; Neumann 1994). Additionally, as our understanding of tropical cyclones has advanced, surface wind speed estimation techniques have changed over the years at NHC (e.g., Franklin et al. 2001), leading to biases in the historical database that have not been addressed. Finally, efforts led by J. Fernández-Partagas (Fernández-Partagas and Diaz 1996) to uncover previously undocumented hurricanes from the mid-1800s to early 1900s have greatly increased our knowledge of these past events. Based on Fernández-Partagas' work, an extension from 1851 to 1885 has been incorporated into HURDAT and substantial revisions have been made for the period of 1886–1910. These changes were based upon quality-controlled assessments and digitization of Fernández-Partagas' work and consideration of other original data sources and studies (Landsea et al. 2004; see the sidebar on "The Atlantic Basin Hurricane Database Reanalysis Project").

Currently, reanalysis efforts are underway for the period from the 1910s through the 1990s. Although Hurricane Andrew was originally slated to be examined sequentially under this project in 2005, in the summer of 2002 NHC requested that the re-evaluation of this storm be addressed more promptly. This decision was driven by recent findings on the surface wind structure within the eyewall of major hurricanes and by the (then) upcoming 10-yr anniversary of this significant landfalling event. Hurricane Andrew caused an enormous amount of destruction in southeastern Florida: over 25,000 homes were destroyed and more than 100,000 homes damaged, 90% percent of all mobile homes in the region of landfall were leveled, over $1 billion in damage was done to local agriculture, and total direct losses exceeded $26 billion (Rappaport 1994). More than 10 yr later, the region still feels the effects from this hurricane. For example, there has been a nearly tenfold increase in average property insurance

THE ATLANTIC BASIN HURRICANE DATABASE REANALYSIS PROJECT

The Hurricane Research Division (HRD) of NOAA's Atlantic Oceanographic and Meteorological Laboratory is engaged in an effort to extend and improve the quality of NHC's original North Atlantic best-track and intensity database, HURDAT, from 1851 to the present (online at www.aoml.noaa.gov/hrd/data_sub/re_anal.html). Employing consistent analysis methods and modern interpretations, the HRD HURDAT reanalysis project is helping to correct multiple errors and biases, determine better landfall attributes, and provide additional track and intensity data for tropical cyclones included in the database (Landsea et al. 2004). Through inspection of historical meteorological records and accounts, previously unknown tropical cyclones are also identified and considered as candidate storms to be added to the database. All recommended changes to HURDAT are subsequently submitted to NHC's Best Track Change Committee for approval.

As of early 2004, an extension of HURDAT from 1851 through 1885 was added to the database, and a reassessment was conducted for tropical cyclones already in HURDAT for the period of 1886–1910. These alterations resulted in the addition of over 262 new tropical cyclones and revisions made to another 185 of the 456 total tropical storms and hurricanes that are in the latest version of the database between 1851 and 1910. While Hurricane Andrew's changes reported here were expedited for special reasons, current work is focusing upon the reanalysis of the remainder of the twentieth century and will be included into HURDAT in sequential order. It is anticipated that alterations and additions to the database will be needed even up through the 1990s, due to changes in our understanding of the structure of tropical cyclones, better analysis tools that are available today, and the uncovering of meteorological observations not available or utilized operationally or in previous poststorm analyses.

The implications of a changing "best track" dataset are multifold. In the societal aspect, eventual benefits of an improved meteorological record of tropical storms and hurricanes include a more accurate assessment of extreme event risk for insurance interests, building code designers, and emergency managers. For tropical meteorologists, a more complete, consistent, and reliable HURDAT will provide, for example, a homogeneous record to evaluate and better predict interannual, decadal, and interdecadal variability in Atlantic basin tropical cyclone activity, as well as better standards to evaluate and validate models for track and intensity of tropical cyclones. However, a changing database does present somewhat of a "moving target" for studies that utilize HURDAT. For example, as tropical cyclone tracks and intensities are altered, official and model-based errors from past years will also change. Moreover, even the benchmarks for assessing skill in tropical cyclone track and intensity predictions [i.e., the "no skill" models of climatology and persistence (CLIPER; McAdie and Lawrence 2000) and statistical hurricane intensity forecast (SHIFOR; DeMaria and Kaplan 1999), respectively] will need to be rederived once a stable database exists after the reanalysis is complete. In the meantime, researchers in the field should be aware that the officially assessed track and intensity of storms that they are studying may be changed in the near future. While such changes may be somewhat problematic in the short term, a uniformly analyzed, improved-quality tropical storm and hurricane database will be beneficial in the long run for all users of HURDAT.

costs for hurricane wind damage in some coastal locations and limited availability of privately underwritten insurance (Chandler and Charles 2002).

Society needs reliable information as to the frequency and severity of past catastrophic events to best plan for the future. Therefore, it is crucial that accurate historical accounts of the characteristics of all tropical cyclones be obtained. This is of particular importance for significant landfalling hurricanes like Andrew. Recently, our understanding of the surface wind field in hurricanes has advanced dramatically (Franklin et al. 2003; Dunion et al. 2003). New global positioning system (GPS) dropwindsonde observations in hurricane eyewalls—first collected in the eastern North Pacific from Hurricane Guillermo in 1997—suggest that the intensities of all of the hurricanes in the aircraft reconnaissance era up through 1998 should be re-examined when the primary method for estimating surface winds was from flight-level wind adjustments.

In August 2002, NHC's Best Track Change Committee, chaired by C. J. McAdie, with members J. L. Beven II, J. M. Gross, B. R. Jarvinen, R. J. Pasch, and E. N. Rappaport, with H. Saffir serving as a noncommittee observer, met to consider proposed revisions to the official intensity of Hurricane Andrew both over the open ocean and at landfall. Complete documentation of the presentations given by E. N. Rappaport, J. L. Franklin, M. D. Powell, P. G. Black, and C. W. Landsea, e-mail exchanges on the issue, the committee's full decision, and the revised database can be found online (www.aoml.noaa.gov/hrd/hurdat/index.html). The purpose of this paper is to provide a more permanent summary of the evidence and issues considered by the committee, to record the outcome of the reanalysis, and to discuss some of the implications of these changes.

ASSESSING MAXIMUM SURFACE WINDS IN HURRICANES.

The original NHC estimates of Hurricane Andrew's intensity for most of its over-water life cycle were based primarily upon an adjustment of aircraft reconnaissance flight-level winds to the surface. In particular, Hurricane Andrew's intensity at landfall in southeastern Florida was largely determined shortly after its passage by adjusting the peak U.S. Air Force reconnaissance aircraft 700-mb flight-level winds of 162 kt to 125 kt at the surface—an adjustment factor of 77%.[1] An analysis of Andrew by Powell and Houston (1996) came to a similar conclusion—that maximum 1-min surface winds of 128 kt impacted the southeastern Florida coast. However, two recent studies by Franklin et al. (2003) and Dunion et al. (2003) provide strong evidence that the methodology originally used to assess the maximum 1-min surface wind in the poststorm analyses of Hurricane Andrew (Rappaport 1994; Mayfield et al. 1994; Powell and Houston 1996) resulted in winds too low for a substantial portion (~5 days) of the lifetime of the storm. (See the sidebar on "New understanding of eyewall structure since Hurricane Andrew" for details that have led to these changes in the methodology for determining intensity, and for discussion about the adjustment factor.)

Aircraft reconnaissance flights have been standard operating procedure since the 1940s for tropical storms and hurricanes threatening land in the Atlantic basin. In the absence of contradictory evidence, current operational practice at NHC is to estimate the surface maximum 1-min wind intensity of a hurricane at about 90% of the peak 10-s wind present at the 700-mb level (i.e. the "90% rule," Franklin et al. 2001, 2003). Such a methodology likely will remain a primary tool for assessing intensity in Atlantic basin hurricanes for at least the next few years.

ESTIMATING ANDREW'S INTENSITY.

Aircraft reconnaissance data. As Hurricane Andrew approached Florida in late August 1992, it was monitored almost continuously by U.S. Air Force reconnaissance aircraft measuring flight-level winds at 700 mb and obtaining minimum sea level pressure data. At 0810 UTC, about an hour prior to Andrew's landfall in mainland southeastern Florida, an Air Force reconnaissance aircraft at 700 mb measured a 10-s-average wind of 162 kt. Application of a 90% adjustment factor to this flight-level wind produces a surface wind estimate of 146 kt. Similarly adjusted 10-s-average flight-level winds at 0809 and 0811 UTC yield surface values of 140 and 141 kt, respectively. During the aircraft's subsequent pass through the hurricane, an additional 10-s report at 0918 UTC yields a surface value of 137 kt using the same reduction. The importance of these additional observations is that they indicate that the flight-level observation at 0810 UTC was not an isolated condition.

Analyses from the current Hurricane Wind Analysis System (H*Wind) surface wind algorithm (Dunion and Powell 2002) provide a marine exposure surface wind estimate of 153 kt, or 94% of the flight-level ob-

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[1] NHC's operational estimate of Hurricane Andrew's intensity at landfall in southeastern Florida was slightly lower—120 kt. The operational wind speed and position estimates of all Atlantic basin tropical storms and hurricane are reanalyzed soon after the event for a poststorm "best track" assessment, which may differ slightly from that given in real time.

NEW UNDERSTANDING OF EYEWALL STRUCTURE SINCE HURRICANE ANDREW

A key issue confronting both operational estimates and postanalysis assessments of hurricane intensity is the most appropriate way to adjust flight-level winds typically at 700 mb down to surface wind values. Ten-second averages of the flight-level wind in the inner core of hurricanes are assumed to represent a 1-min-averaged wind (Powell et al. 1991). Longer averaging of the flight-level winds would tend to underestimate the true maximum 1-min wind speeds because the aircraft does not remain long in the peak gradient region on a radial flight track, especially in relatively small hurricanes like Andrew. The best method for adjusting these winds to the surface had previously been unclear, because the most thorough study of flight-level winds to surface wind observations (i.e., Powell and Black 1990) contained mainly tropical storm–force maximum winds and few observations in the eyewall region.

A new understanding of the surface wind structure in hurricanes was made possible by an advance in technology, the GPS dropwindsonde (Hock and Franklin 1999), which provided the first detailed wind profile in a hurricane's eyewall from the flight level to the ocean surface. Near-surface data from individual dropwindsondes have compared favorably with concurrent observations from moored buoys and C-MAN stations (Houston et al. 2000) and collocated Stepped Frequency Microwave Radiometer data (Uhlhorn and Black 2003), although both of these studies have limited observations from the core of major hurricanes. While individual GPS dropwindsondes provide only a momentary slice of data (which is not even a vertical profile because of the inflowing and swirling flow that the drop encounters in the hurricane eyewall), a judicious partitioning and averaging of the dropwindsondes can provide useful wind mean wind conditions within the hurricane.

Franklin et al. (2003) examined several hundred over-ocean GPS dropwindsonde profiles in the hurricane eyewall and have shown that the mean ratio of surface-to-700-mb winds is about 90% in the eyewall region. Franklin et al. recommended a set of adjustment factors for the interpretation of tropical cyclone flight-level data. The results from the drop profile analyses in Franklin et al.'s (2003) study provide a way to infer winds at one level from those at another. This adjustment assumes a similar averaging time at both levels, but is not constrained to any particular averaging time. For the stronger (right hand) side of the eyewall, they found that the mean surface-to-700-mb ratio was between 86% and 90%. Thus, without additional information, estimates of the surface maximum 1-min wind intensity of a hurricane at the National Hurricane Center are assessed to be about 90%[SB1] of the peak 10-s wind observed at the 700-mb level from an aircraft.

Recent work by Dunion and Powell (2002) and Dunion et al. (2003) also supports a revised flight-level-to-surface-wind adjustment in the context of the Hurricane Research Division's H*Wind surface wind analyses of tropical cyclones. H*Wind is an analysis tool that can assimilate a variety of observations within a tropical cyclone to produce a storm-centered few-hour composite of the surface wind field (Powell 1980; Powell et al. 1996, 1998). Given sufficient observations, the analyses can be used to make estimates of the maximum 1-min winds, as well as radii of tropical storm–force or hurricane-force winds.

Using information from the GPS dropwindsondes, techniques were developed to improve H*Wind's adjustment of aircraft flight-level winds to the surface. Dunion and Powell (2002) and Dunion et al. (2003) utilized the dropwindsonde data to revise the H*Wind algorithms in a two-step process. First, analyses of the dropwindsondes show that the original H*Wind assumption that 700-mb flight-level winds were equivalent to mean boundary layer (0–500 m) winds produced an underestimation of the true boundary layer winds. Second, the dropwindsondes showed that the over-ocean surface-to-mean-boundary-layer-wind ratio reached a minimum at mean boundary layer wind speeds of 100–110 kt. This ratio was found to increase with stronger winds, in contrast to an assumed steadily decreasing ratio with stronger boundary layer winds previously utilized in H*Wind (Dunion et al. 2003; Powell et al. 2003). The combined effect of these two new changes to H*Wind produces substantially higher (10%–20%) analyzed maximum 1-min surface winds for major hurricanes, particularly when based on reductions of aircraft reconnaissance data from 700 mb. For major hurricanes, the new H*Wind methodology provides surface wind analyses with marine exposure from extrapolated flight-level wind observations that generally agree to within 5% of the Franklin et al. (2003) estimates.

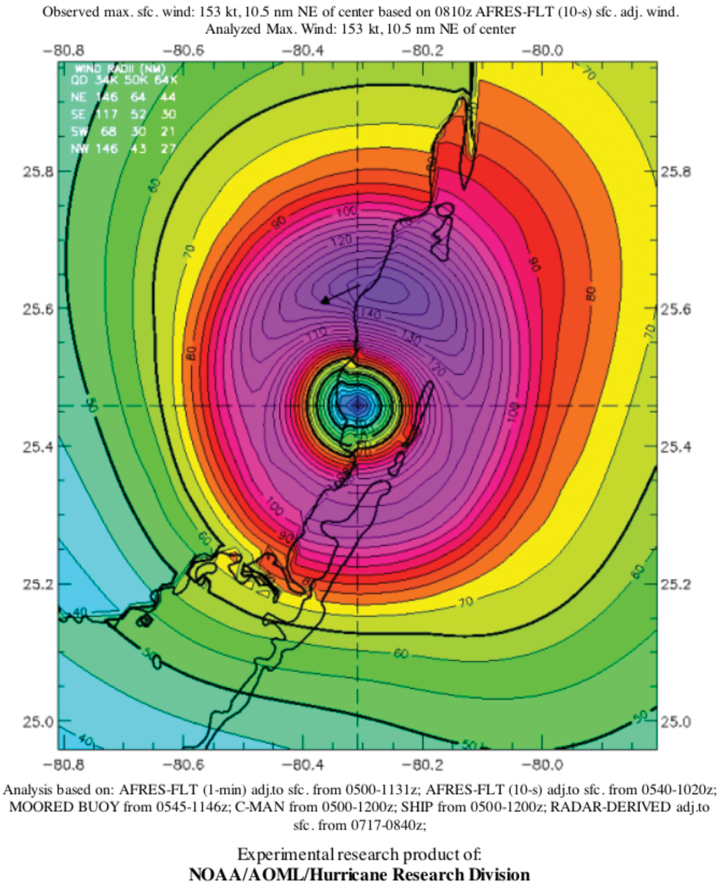
Such agreement between the two methods may not be surprising, because they are both based upon new formulations from the nearly identical sets of archived GPS dropwindsonde data. It is worth noting, however, that both methodologies had limited data available in the extreme high-wind range typical of that found in Hurricane Andrew's eyewall, though both schemes included dropwindsondes from Hurricane Mitch when it was a SSHS Category-5 system. Another consideration is that the dropwindsondes had a higher failure rate in providing winds near the surface under extreme conditions. This limitation was partially overcome by filling in the profile down to 10 m with mean conditions from hurricane eyewall dropwindsondes that did provide wind data to the ocean's surface, as long as the filled-in dropwindsonde reported winds down to no higher than 30 m (Dunion et al. 2003; Franklin et al. 2003). This technique to maximize surface wind observations was likely conservative in its surface wind estimates because of the observed tendency for the surface winds to increase relative to the boundary layer average winds in higher wind regimes.

[SB1] This factor is at the high end of the range established by the dropwindsondes (86%–90%), in part because of simple rounding of the midpoint of this range, but also to account for the likelihood that the cyclone's highest 700-mb wind speed was not sampled during the typical "figure 4" tracks routinely flown through hurricanes by reconnaissance aircraft.

servations from the 0810 UTC reconnaissance data (Fig. 1). This result is in reasonable agreement with the recommended adjustment from the Franklin et al. (2003) methodology.

Assuming that the 162-kt flight-level aircraft wind was representative of the peak 700-mb winds that were present in Andrew's circulation, a surface adjustment factor of 77% is required to diagnose Andrew at 125 kt was originally assessed. Of the 17 hurricanes examined by Franklin et al. (2003), none were observed with GPS dropwindsondes to have a mean adjustment factor this low in the eyewall. The lowest observed ratio of 83% was found in Hurricane Bonnie—a weakly convective storm with a large eye.[2] Furthermore, the adjustment factor to provide surface winds appears to increase when the boundary layer winds are very high (Dunion et al. 2003; Franklin et al. 2003) and when vertical motions are particularly vigorous (at least 1.5 m s^{-1} absolute vertical velocity between the ocean's surface to 2000 m; Franklin et al. 2003). Andrew likely satisfied both of these conditions at its landfall in southeastern Florida. Thus, there is little evidence from the dropwindsondes datasets to support Andrew having a lower-than-normal adjustment factor in the eyewall region.

Radar-derived wind vectors. Low-altitude radar feature tracking presented by P. Dodge to the committee suggested surface winds similar to those implied by applying a 90% adjustment factor to the flight-level data. Figures 2 and 3 show vectors based on feature tracking from the Miami, Florida, Weather Surveillance Radar-1957 (WSR-57) outside and within Andrew's eyewall just prior to landfall in southeastern Florida (see a loop of this radar reflectivity data online at www.aoml.noaa.gov/hrd/hurdat/andrew_cells.mpg). This technique has been demonstrated to provide lower-tropospheric wind vectors in the circulation of a hurricane that are comparable to those measured by aircraft. Tuttle and Gall (1999) reported agreement with 700-mb flight-level winds to within 10%, though the radar-derived winds have a relatively noisy signal and must be quality controlled before use. The three highest feature speeds found in the Andrew data were 171 kt at 700 m at 0739 UTC, 176 kt at 400 m at 0839 UTC, and 180 kt at 1100 m at 0730 UTC (Fig. 2), with heights based upon the radar tilt and distance from the radar site. The strongest of these velocities does not appear consistent with nearby radar feature tracks. Making the assumption that the average of the remaining two observations (174 kt) represents the maximum eyewall winds near the boundary layer top (BLT), we can adjust this wind to the surface using mean dropwindsonde profiles. Applying the Franklin et al. (2003) eyewall mean profile for the


Observed max. sfc. wind: 153 kt, 10.5 nm NE of center based on 0810z AFRES-FLT (10-s) sfc. adj. wind.
Analyzed Max. Wind: 153 kt, 10.5 nm NE of center

Analysis based on: AFRES-FLT (1-min) adj.to sfc. from 0500-1131z; AFRES-FLT (10-s) adj.to sfc. from 0540-1020z; MOORED BUOY from 0545-1146z; C-MAN from 0500-1200z; SHIP from 0500-1200z; RADAR-DERIVED adj.to sfc. from 0717-0840z;

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FIG. 1. H*Wind 1-min surface wind analysis for Hurricane Andrew at landfall in southeastern Florida around 0900 UTC 24 Aug 1992 from the revised methodology of Dunion et al. (2003) and Dunion and Powell (2002), which takes into account the vertical structure of the horizontal winds as demonstrated from recent GPS dropwindsonde data. Winds at the coast show a discontinuity due to increased roughness length as one goes from over open-ocean conditions to overland open-terrain conditions. Numbers in the upper-left corner indicate quadrant-based radii of 34-, 50-, and 64-kt surface winds.

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[2] However, hurricanes with stable boundary layers moving north of the Gulf Stream over cool waters, such as Gloria in 1985 (Powell and Black 1990) and Bob in 1991, were analyzed to have surface-to-flight-level wind ratios as low as 55% based on buoy observations.

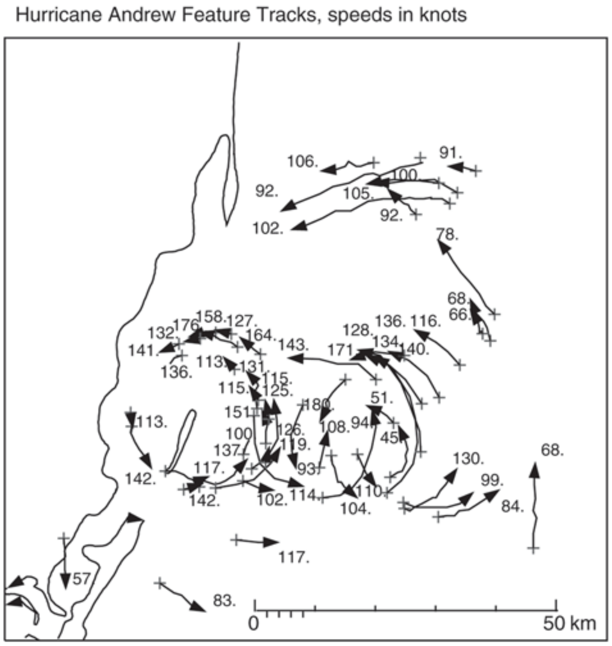

Fig. 2. Hurricane Andrew low-altitude radar feature tracks (kt) from the Miami WSR-57 radar before the radar was destroyed by the hurricane.

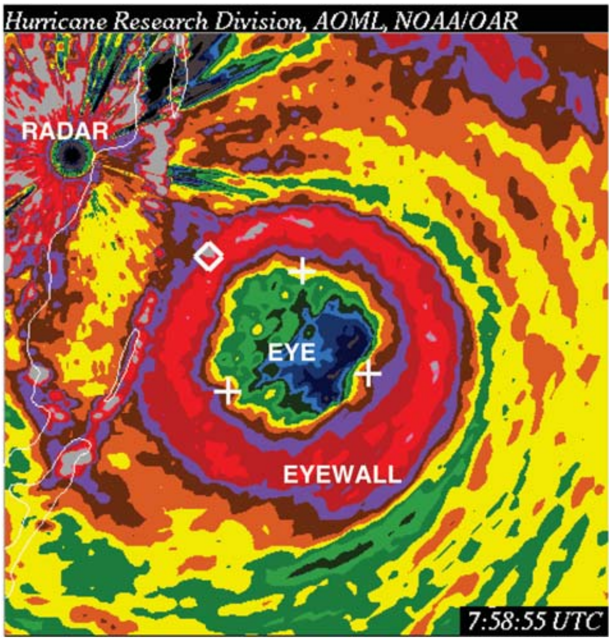

Fig. 3. WSR-57 radar reflectivity image of Hurricane Andrew at 0759 UTC. The center of the diamond indicates the position of the Fowey Rocks C-MAN station relative to the location of the eyewall. The three "plus" symbols indicate reflectivity features that were tracked between successive radar sweeps to provide low-level wind vectors. The radar reflectivity scale is red (46), purple (39), orange (33), dark green (27), black (20), and dark blue (14 dB*Z*).

strongest BLT wind speeds in their sample (135–155 kt, their Fig. 12) gives an 82% adjustment factor and a surface wind estimate of 143 kt.

The Dunion and Powell (2002) methodology was also applied to these new radar-derived wind vectors. Their analysis system suggests that these low-altitude radar feature tracks correspond to winds of 148 kt at the ocean's surface, again in close agreement with the estimates from the Franklin et al. (2003) methodology.

Surface observations. The NHC Best Track Change Committee reviewed the available surface observations from Andrew's landfall to determine whether they were consistent with the dropwindsonde-based adjustments of flight-level and radar winds discussed in the previous two sections. In particular, they focused upon two key observations: Fowey Rocks, Florida, and R. Fairbanks (an amateur weather observer located in Perrine, Florida) data (Rappaport 1994; Mayfield et al. 1994; Powell et al. 1996). The Fowey Rocks Coastal Marine Automated Network (C-MAN) weather station (elevation 44 m) reported a peak 2-min mean wind of 122 kt at its last hourly transmission before it failed after 0802 UTC. This adjusts to approximately 111 kt for a maximum 1-min surface (10 m) wind valid for over open-water exposure. At this station, the winds increased dramatically in the last hour of reporting. In particular, an 18 kt increase in the 10-min mean wind between 0749 and 0759 UTC (not shown) in conjunction with the location of the station relative to Andrew's eyewall (Fig. 3) provides strong evidence that the surface winds at that location had not yet leveled off and would likely have continued to increase to substantially higher values had it survived for at least a few more minutes. [Typically, the surface radius of maximum wind occurs at the inner edge of the eyewall or even just inside the eye when viewed by radar in the lower troposphere (Marks et al. 1992).] Based upon the position of the Fowey Rocks station, the movement of Hurricane Andrew, and an estimate of the surface radius of maximum wind for that portion of the storm, it is calculated by J. Beven that the station would likely have encountered the peak winds in the northern eyewall at about 0820 UTC, about 20 min after its final report. Assuming a linear increase of winds during this time (a conservative estimate), the peak 10-min mean station wind may have reached 145 kt. After adjusting for both station height and averaging period, this converts to approximately 148 kt for a maximum 1-min surface (10 m) wind valid for over open-water exposure.

R. Fairbanks noted a peak gust of 184 kt (corrected to 154 kt after adjusting for the overestimation bias of this type of instrument) from his home-based anemometer just before it failed. This observation was believed to be consistent with a 1-min open-terrain surface wind of about 119 kt, after employing typical gust factors (Powell et al. 1996). R. Fairbanks' observation had no wind direction associated with it and only an approximate time (0830–0900 UTC). The strongest winds experienced at the location of R. Fairbanks' home were probably not earlier than 0900 UTC, based upon Miami, Florida, radar imagery extrapolated to the time that the inner edge of the eyewall and the surface radius of maximum winds would have encountered the home (Powell et al. 1996).

As a result, C. Landsea argued that both the Fowey Rocks and R. Fairbanks instruments appeared to have failed before the strongest winds of Andrew arrived, because these observations were taken in the northwest portion of the eyewall[3] outside of the surface radius of maximum winds. The peak winds were likely closer to the storm's center in the northern portion of the eyewall (Fig. 1). Thus, neither of these observations seem to represent the maximum winds of Hurricane Andrew at landfall in southeastern Florida.

Inspection of these surface observations in comparison with surface-reduced flight-level data in Fig. 1 did not suggest a large inconsistency, though it is difficult to directly compare them for three reasons. First, the flight-level data primarily were in radial legs running north–south and east–west, which did not coincide well spatially with the Fowey Rocks and R. Fairbanks observations near the time of landfall after compositing the data with respect to the hurricane's center. Second, the Powell and Houston (1996) methodology for estimating the surface radius of the maximum wind (which was used in Fig. 1) appears to be too large [11 n mi (20 km) versus 8–9 n mi (15–17 km)] compared with the observed location of the wind center and the highest storm surge, which was thought to coincide with the peak surface winds.[4] Thus, the strongest surface winds in Fig. 1 were spread out too far radially, making direct comparisons of extrapolated flight-level winds from H*Wind analyses and in situ surface observations problematic. Finally, because of the turbulent and transient nature of the hurricane wind field, it is not straightforward to make direct comparisons between a storm-centered composite of the adjusted flight-level winds and a small number of in situ observations. It would take a systematic discrepancy over many observation points to determine that the standard 90% flight-level adjustment factor was invalid for a particular storm.

Winds at the coastline and over land. While there was unanimous agreement among the presenters and committee members that Andrew's intensity was underanalyzed during its open-water approach to southeastern Florida, there was lengthy discussion whether these strong winds were also felt along the coastline and over land. The current understanding is that the well-developed hurricane boundary layer is different over land than it is over water and that there must be a transition zone at or near the coastline between these two regimes. It was suggested (Powell et al. 2003) that the winds in the northern eyewall were weakened by increased roughness presented by shoaling and breaking waves in the shallow waters between the fringing reefs, Biscayne Bay, and the coastline before the storm made landfall. In this case, Biscayne Bay may not have represented a typical marine exposure with a small roughness length, but instead may have been more consistent with conditions experienced in an overland environment with open-exposure terrain. However, recent analyses of ocean waves within Hurricane Bonnie at landfall in North Carolina show that waves do not generally increase in height from shoaling in shallow waters, but instead show a large decrease from offshore (8–10-m mean wave heights) to the coastal locations (4–5 m) (Walsh et al. 2002).

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[3] The Fairbanks observation may instead have been in the north eyewall if it occurred around 0900 UTC, but the time of the measurement and, thus, its storm-relative location at the time of the peak measured gust are uncertain.

[4] The location of the peak storm surge caused by a hurricane can be influenced by a number of factors in addition to the radius of the maximum wind, including coastline shape, local offshore bathymetry/inland topography, astronomical tides, wave setup, inflow angle, etc. (i.e., Jelesnianski 1993). However, for the specific case of Hurricane Andrew's landfall in southeast Florida, these factors appear to be secondary in comparison to the surface radius of maximum winds (RMW) for forcing the peak storm-surge location along the coast. Sensitivity testing using the Sen, Lake, and Overland Surges from Hurricanes (SLOSH) model run with the observed Hurricane Andrew characteristics (track, central pressure, environmental pressure) and varying the RMW demonstrates the primary influence of RMW for this specific case. These runs suggest that only with a smaller RMW [8–9 n mi versus Powell and Houston's (1996) 11 n mi] does one match the observed storm-surge pattern and location of the peak surge value. (It is, however, possible that the open exposure to the ocean east of the area of the peak storm surge may have allowed for additional wave impacts, which are not explicitly modeled by SLOSH and may somewhat complicate the RMW analysis.)

While the bathymetry of the waters offshore of south Florida where Andrew hit is somewhat different from North Carolina, if such decreased wave heights did occur, it is not clear what these would imply when combined with breaking waves for changes to the roughness length relative to the open ocean.

J. Franklin presented the committee with an analysis of available GPS dropwindsondes near shore (within 10 km) and offshore (10–60 km) in the right eyewall of hurricanes making landfall in the United States. This preliminary study suggested that there could be some reduction in surface winds along the immediate coastal waters. A very limited sample of 19 dropwinsondes in the eyewalls of weak to moderate hurricanes shows an apparent 5%–10% reduction of surface wind as the coastline is approached. Using this alteration to the Franklin et al. (2003) surface wind methodology gives maximum 1-min winds at the coast of roughly 130 to 140 kt. However, given the extremely small sample of dropwindsondes (i.e., 10 near shore and 9 just offshore) and lack of any major hurricanes in this coastal analysis, such results were considered by the Best Track Change Committee to be too speculative to be applied at this time.[5] Clearly, more dropwindsonde data are needed both in the transition zone between land and water, as well as in the hurricane boundary layer over land, to properly assess the degree to which a hurricane's surface winds over open water reach the coastline.

from the WSR-57 radar in Tampa, satellite intensity estimates, storm-surge modeling runs, and surveys of wind-caused damage. These measures (discussion of these parameters can be found online at www.aoml.noaa.gov/hrd/hurdat/index.html) were mainly consistent with the revised surface wind estimates discussed in earlier sections, though they were of secondary importance to the final NHC Best Track Change Committee decision.

BEST-TRACK CHANGES. After considering the presentations regarding various recommendations for the revisions of Andrew's best-track intensities, the NHC Best Track Change Committee made alterations to the winds in HURDAT for Hurricane Andrew (Table 1 and Fig. 4) for 22–26 August. These changes were made to Hurricane Andrew's intensity data for the time while the storm was over the Atlantic Ocean just east of the Bahamas, over the Bahamas and south Florida, over the Gulf of Mexico, and at landfall in Louisiana (Fig. 5). Neither the best-track positions nor the central pressure values of Andrew were adjusted. The alterations in wind intensity were based upon the Franklin et al. (2003) methodology, which is consistent with the work of Dunion et al. (2003) and Dunion and Powell (2002) as discussed earlier. The changes to HURDAT were applied for these dates as aircraft reconnaissance observations were available throughout

Other evidence for Andrew's intensity. While the primary pieces of evidence for altering Hurricane Andrew's intensity came from revised extrapolations of flight-level winds and radar feature track data, other information on the intensity was also available and considered in the reanalysis. These were the continued central pressure drop after the measurement of the peak aircraft wind report, pressure–wind relationships, surface pressure gradients, high-altitude radar reflectivity eyewall core velocities

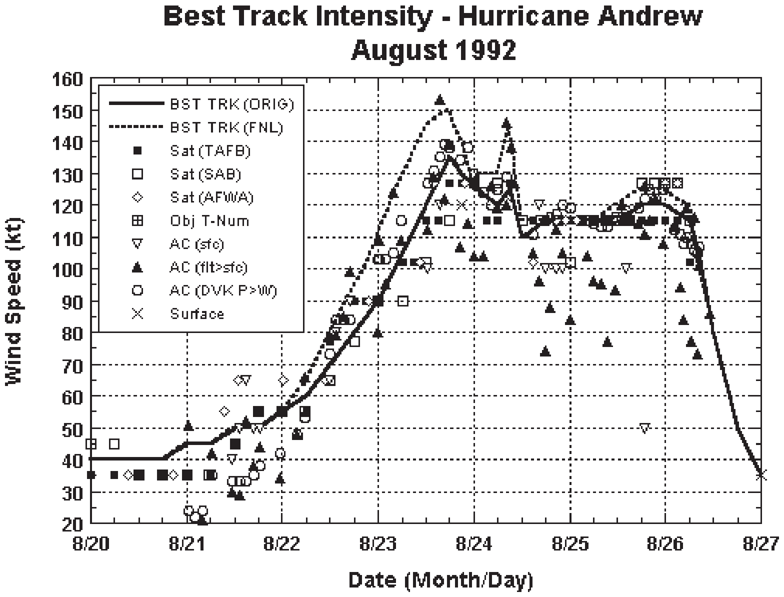

FIG. 4. Selected wind observations and original (solid)/revised (dashed) best-track maximum 1-min surface wind speed curve for Hurricane Andrew, 20–27 Aug 1992. Aircraft observations have been adjusted for elevation using 90%, 80%, and 75% reduction factors for data collected at 700 mb, at 850 mb, and near 450 m, respectively (Franklin et al. 2003).

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[5] The National Hurricane Center's operational estimates, as well as the poststorm best-track assessments, have historically made the assumption that an otherwise steady-state hurricane's maximum winds over water do survive to the coastline.

Table 1. Revisions in the 6-hourly HURDAT and at landfall in the Bahamas and the United States for Hurricane Andrew, 16–28 August 1992. Changes are listed in bold, original best rack is in parenthesis. Note that the landfall indicated for Elliott Key had not previously been described explicitly. Note also that the continental U.S. hurricane impacts for HURDAT are changed from "CFL4BFL3 LA3" (southeastern Florida as Category 4, southwestern Florida as Category 3, and Louisiana as Category 3) to "CFL5BFL4 LA3" (southeastern Florida as Category 5, southwestern Florida as Category 4, and Louisiana as Category 3).

Date/Time UTC	Latitude °N	Longitude °W	Central pressure (mb)	Maximum wind speed (kt)	Storm status
16/1800	10.8	35.5	1010	25	Tropical depression
17/0000	11.2	37.4	1009	30	“
17/0600	11.7	39.6	1008	30	“
17/1200	12.3	42.0	1006	35	Tropical storm
17/1800	13.1	44.2	1003	35	“
18/0000	13.6	46.2	1002	40	“
18/0600	14.1	48.0	1001	45	“
18/1200	14.6	49.9	1000	45	“
18/1800	15.4	51.8	1000	45	“
19/0000	16.3	53.5	1001	45	“
19/0600	17.2	55.3	1002	45	“
19/1200	18.0	56.9	1005	45	“
19/1800	18.8	58.3	1007	45	“
20/0000	19.8	59.3	1011	40	“
20/0600	20.7	60.0	1013	40	“
20/1200	21.7	60.7	1015	40	“
20/1800	22.5	61.5	1014	40	“
21/0000	23.2	62.4	1014	45	“
21/0600	23.9	63.3	1010	45	“
21/1200	24.4	64.2	1007	50	“
21/1800	24.8	64.9	1004	50	“
22/0000	25.3	65.9	1000	55	“
22/0600	25.6	67.0	994	**65** (60)	Hurricane
22/1200	25.8	68.3	981	**80** (70)	“
22/1800	25.7	69.7	969	**95** (80)	“
23/0000	25.6	71.1	961	**110** (90)	“
23/0600	25.5	72.5	947	**130** (105)	“
23/1200	25.4	74.2	933	**145** (120)	“
23/1800	25.4	75.8	922	**150** (135)	“
24/0000	25.4	77.5	930	125	“
24/0600	25.4	79.3	937	**130** (120)	“
24/1200	25.6	81.2	951	**115** (110)	“
24/1800	25.8	83.1	947	115	“
25/0000	26.2	85.0	943	115	“
25/0600	26.6	86.7	948	115	“
25/1200	27.2	88.2	946	**120** (115)	“
25/1800	27.8	89.6	941	**125** (120)	“
26/0000	28.5	90.5	937	**125**(120)	“
26/0600	29.2	91.3	955	**120** (115)	“
26/1200	30.1	91.7	973	80	“
26/1800	30.9	91.6	991	50	Tropical storm
27/0000	31.5	91.1	995	35	“
27/0600	32.1	90.5	997	30	Tropical depression
27/1200	32.8	89.6	998	30	“
27/1800	33.6	88.4	999	25	“
28/0000	34.4	86.7	1000	20	“
28/0600	35.4	84.0	1000	20	“

TABLE 1. Continued.

Date/Time UTC	Latitude °N	Longitude °W	Central pressure (mb)	Maximum wind speed (kt)	Storm status
23/1800	25.4	75.8	922	**150** (135)	Minimum pressure
24/0905	25.5	80.3	922	**145** (125)	"
23/2100	25.4	76.6	923	**140** (130)	Eleuthera landfall
24/0100	25.4	77.8	931	**130** (125)	Berry Island landfall
24/0840	25.5	80.2	926	145	Elliott Key, FL, landfall
24/0905	25.5	80.3	922	**145** (125)	Fender Point, FL, landfall [8 nmi (13km) east-northeast of Homestead, FL]
26/0830	29.6	91.5	956	**100** (105)	Pt. Chevreuil, LA

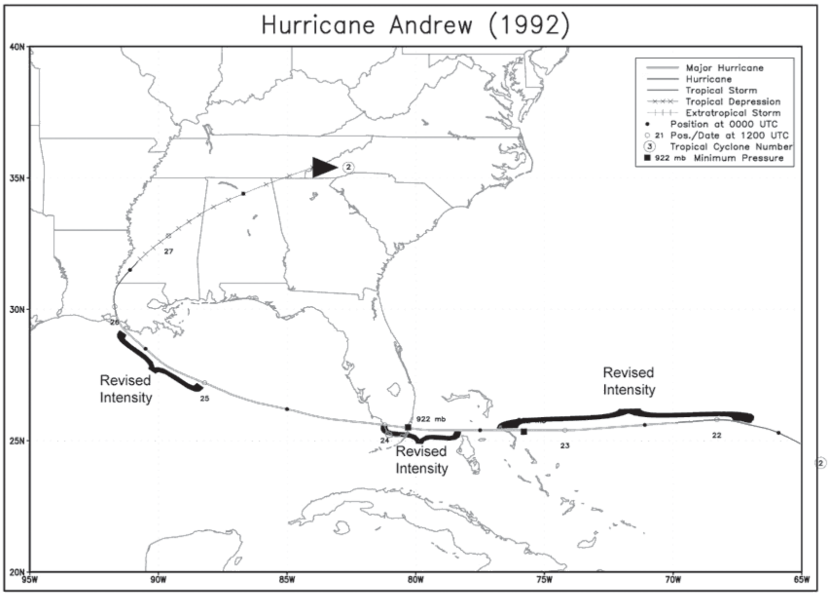

FIG. 5. A portion of the track for Hurricane Andrew with an emphasis on where changes were made in its intensity.

this period and there were limited in situ surface observations indicative of the maximum 1-min surface winds. The revisions made Andrew a Saffir–Simpson Hurricane Scale (SSHS; Saffir 1973; Simpson 1974) category-5 (i.e., maximum 1-min surface winds of at least 136 kt) hurricane at landfall in both Eleuthera Island, Bahamas, and in southeastern Florida. The maximum 1-min surface wind for Hurricane Andrew at landfall in mainland southeastern Florida near Fender Point [8 n mi (13 km) east of Homestead, Florida] at 0905 UTC 24 August was officially estimated to be 145 kt. (The original 1992 NHC best-track landfall intensity estimate was 125 kt.) The peak intensity of Andrew, originally assessed at 135 kt, was reasoned to be 150 kt at 1800 UTC 23 August just east of the northern Bahamas.

DISCUSSION OF UNCERTAINTIES.

The purpose of the reanalysis efforts is to ensure the most accurate historical hurricane record possible—one that is consistent with contemporary science. It has been suggested that the record in the case of Andrew should not have been changed, in part because of the uncertainty surrounding the maximum surface wind. However, the committee recognized that no storm's intensity can be determined with complete accuracy; the surface observations are almost never sufficiently comprehensive, and indirect measures of surface wind must always be used. Uncertainty in a wind speed estimate should not be an obstacle to revising an earlier estimate that is inconsistent with the observations, especially if it has benefited from new advances in science and understanding.

Powell et al. (1996) indicated an estimate of ±20% procedure error in assigning surface winds from flight-level aircraft reconnaissance wind data in their original methodology. For the maximum 1-min surface winds in Andrew that they analyzed, this ranges from 103 to 153 kt, reflecting the large uncertainty in the analysis methodology at that time. Franklin et al.'s (2003) examination of several hundred over-ocean hurricane eyewall dropwindsondes indicates that while the mean ratio of surface to 700-mb winds was about 90%, the standard deviation was about 19%. This value is similar to the variability suggested by Powell et al. (1996).

However, this does not mean that the uncertainty in estimating peak surface winds from flight-level data is necessarily about 20%. It is important to distinguish between the following two questions: 1) given a wind observation taken at 700 mb somewhere in the hurricane eyewall, what is the underlying concurrent wind at the surface; and 2) given a storm's maximum wind at 700 mb, what is the storm's maximum sustained wind at the surface? The 19% standard deviation is directly applicable only to the first question posed above. This variance is not appropriate for estimating the variability in the ratio of the storm's maximum surface to maximum 700-mb winds. The variance of the latter quantity is not known, but should be less than 19%, as illustrated by the following example.

Imagine a steady-state storm in which the maximum 1-min wind at the surface is 90 kt, while the maximum 1-min wind at 700 mb is 100 kt. Over time, the precise location of the maxima at both the surface and 700 mb may vary, but the peak values present at each level remain constant. By assumption, the variance of peak surface to peak 700-mb wind is zero. Even so, if the eyewall of this storm was to be sampled by GPS dropwindsondes, the dropwindsonde surface-to-700-mb-wind ratio would still have a large variance, because a) the wind distributions are not necessarily the same at the two levels, so a dropwindsonde that samples the maximum at 700 mb will not necessarily sample the surface maximum, and vice versa; and b) the dropwindsondes do not measure a 1-min wind, but measure whatever turbulence through which they happen to fall during a 0.5-s interval. These factors contribute to the high variance in adjustment-factor ratios computed from individual dropwindsondes, but it has very little to do with the relationship between peak winds from level to level. While a precise measure of the procedure error in applying the 90% rule may not be obtainable currently, mean eyewall profiles from different storms (Franklin et al. 2003) suggest that it may be near 10% (i.e., that the actual surface wind to 700-mb-flight-level ratio for Hurricane Andrew would have been between about 80% and 100%).

It is acknowledged that the reanalysis presented here of Andrew's intensity at landfall in southeastern Florida (and elsewhere in its lifetime) is not known with exact certainty, nor will it ever be. However, it is concluded here that Hurricane Andrew's intensity is very likely to be in the range of 136–155 kt for the maximum 1-min surface winds that impacted the coast at landfall in mainland southeastern Florida, with a best single estimate of 145 kt. It is quite unlikely that Andrew was a 125-kt hurricane at landfall (category 4) as was originally thought, consistent with the uncertainty discussion above. It should be noted that these category-5 conditions likely occurred on land only in a small region in south Dade County, Florida, close to the coast in Cutler Ridge. Most of the region in the country south of Kendall Drive (25.7°N) received category-4 or category-3 hurricane conditions. Peak gusts over oceanic conditions and over land were likely to be on the order of 160–170 kt, based upon typical gust factors utilized (e.g., Powell and Houston 1996). (See the sidebar on "Implications of Hurricane Andrew's reanalysis in the United States.")

While this reanalysis does not preclude revisiting Hurricane Andrew's intensity in the future if needed, it is the official estimate at this time. We are working within the bounds of the state of the science to interpret surface wind conditions in hurricanes. The violent inner core of major hurricanes has always been an area with a dearth of in situ measurements of the peak winds. Numerous uncertainties remain (e.g., how representative was the 162-kt flight-level winds of the peak winds in Andrew at 700 mb?; how much intensification to Andrew's wind field occurred after the reconnaissance plane left the north eyewall?; how are surface winds in hurricanes altered in general at the ocean–coast interface?; how may further stratifications to the dropwindsonde data provide better surface wind estimates for various right versus left asymmetries and flight-level wind speed, convective, or stability regimes?). Continued data collection and research are strongly encouraged to help clarify these important issues. However, it is realized that despite progress in scientific uncertainties, the exact wind speeds caused by Hurricane Andrew in southeastern Florida and elsewhere will never be known with complete accuracy and confidence.

SUMMARY.

- Hurricane Andrew in 1992 originally was assessed to have reached a peak intensity and Bahamian/U.S. landfall intensity of SSHS category 4, based primarily upon adjustment of flight-level winds to the surface.
- Research using GPS dropwindsondes in the late 1990s and early 2000s has demonstrated that stronger winds exist at the surface in the hurricane eyewall than originally had been believed.
- A reanalysis of Hurricane Andrew's intensity, considering this new understanding, indicates that Andrew's maximum 1-min surface winds for much of its lifetime were substantially stronger than was analyzed earlier. In particular, Hurricane Andrew is now estimated to have reached category-5 status at its landfall in both the northern Bahamas and in southeastern Florida.

IMPLICATIONS OF HURRICANE ANDREW'S REANALYSIS IN SOUTH FLORIDA

One example of a practical aspect of the outcome of Andrew's reanalysis is the potential impact on building codes and insurance rates. Previously, Hurricane Andrew was estimated to be a SSHS category-4 hurricane at landfall in south Florida (comprising Pinellas, Hillsborough, Manatee, Sarasota, Charlotte, Lee, Collier, Monroe, Miami–Dade, Broward, Palm Beach, Martin, St. Lucie, Indian River, and Brevard counties). During the twentieth century, there are relatively complete records for this region (Landsea et al. 2004). Prior to Andrew's reclassification, six category-4 and one category-5 hurricanes struck southeastern Florida: the 1919 Key West hurricane, the 1926 Great Miami hurricane, the 1928 Lake Okeechobee hurricane, the 1935 Labor Day (category 5) hurricane, the 1947 Broward hurricane, 1960's Hurricane Donna in the Florida Keys, and Hurricane Andrew (updated from Jarrell et al. 1992). This gave an average return period for "Andrew like" hurricanes (i.e., category 4 or 5) of about 15 yr for the south Florida region, though these occur rather unevenly in time during the twentieth century. However, with Andrew being reclassified as a category 5, it becomes one of two such tropical cyclones to strike the area in 100 yr. Thus, the return period is equal to or greater than 50 yr for a direct strike on the region by an Andrew-type hurricane (now upgraded to category 5).

This conclusion may be somewhat counterintuitive at first, but is more understandable if one puts Andrew into context with the other catastrophic south Florida hurricanes of the twentieth century. Previously, with Andrew considered a category-5 hurricane at landfall, it was considered as a strong as, and roughly as damaging as, the 1919, 1926, 1928, 1947, and 1960 hurricanes. But elevating Hurricane Andrew to a category 5 means that it is unlikely that these other five category-4 hurricanes could cause the same type of extreme destruction that the 1992 hurricane caused, if these systems were to hit today's southeast Florida. It is noted though that the 1926, 1928, and 1947 hurricanes were substantially larger in size than 1992's Andrew, so that they might cause more widespread, though locally less severe, damages if they were to hit today. [Moreover, it appears unlikely that any of these five remaining category-4 hurricanes that struck south Florida will be reanalyzed at a higher category based upon Dunion et al. (2003) and other preliminary assessments.] Thus, the new classification alters the assessed odds of having an Andrew-like hurricane impact from being an uncommon occurrence to a rare event.

This rough assessment agrees with specific calculations from the Hurricane Risk (HURISK) analysis program (Neumann 1987). This program synthesizes information from the entire HURDAT database to provide detailed statistics for more localized regions, including average return periods for various thresholds of wind speeds of interest. For the original and revised assessed intensities of Andrew at landfall, the return periods for various intensity hurricanes passing within 50 n mi (93 km) are quite different: 36 yr at ≥125 kt (original Andrew best-track intensity) and 82 yr at ≥145 kt (revised Andrew best-track intensity). However, the return periods for various wind speed thresholds do not themselves change significantly near Miami–Dade County, with the alteration of one data point (i.e., Andrew's estimated intensity), as one would expect from a large database of over 100 yr of tropical storms and hurricanes to impact this region.

For the public, government agencies, insurance companies, wind engineers, building code designers, and others interested in the return period of extremely devastating hurricanes, the category assigned is quite important. The implication of the above calculations is that originally an Andrew-like impact could be expected about every 35 yr in Miami–Dade County (every 15 yr for all of south Florida), while the reclassification means that an Andrew-like event is now expected to strike Miami–Dade County about once in 80 yr (every 50 yr for all of south Florida). Such information should be of use for those involved with long-range planning for the region.

- Continued research is needed to better understand the surface winds in strong hurricanes in a variety of differing environmental conditions and at the ocean–coast boundary, in particular.
- Because of this reclassification, the return period of catastrophic hurricanes like Andrew increases from about 15 to at least 50 yr for south Florida. Thus, the risk from Andrew-like hurricanes at that location is significantly less than previously had been estimated.

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