Uncertainty in Hurricane Winds

Mark Powell[1], Peter Vickery[2], Jeff Kepert[3], and Eric Uhlhorn[4]

[1]*Atmospheric Scientist, NOAA-AOML Hurricane Research Division, Miami, Florida, USA, Mark.Powell@noaa.gov*
[2]*Senior Engineer, Applied Research Associates, Raleigh, North Carolina, USA, pvickery@ara.com*
[3]*Atmospheric Scientist, Australian Bureau of Meteorology, Melbourne, Victoria, AUS,Jeff Kepert@bom.gov.au*
[4]*Atmospheric Scientist, Cooperative Institute for Marine and Atmospheric Studies, University of Miami, Florida USA, Eric.Uhlhorn@noaa.gov*

ABSTRACT

This paper will describe the current state of the art in measuring and analyzing surface winds in tropical cyclones. Observing platforms and strategies will be reviewed, along with their advantages and limitations, and Hurricane Andrew will be revisited in light of new capabilities and findings.

KEYWORDS: Hurricane; surface wind speed; Hurricane Andrew

1. INTRODUCTION

After the devastation of Hurricane Andrew in 1992, the most thorough data collection, analysis, and wind field reconstruction effort ever conducted in a landfalling hurricane (Fig. 1, Powell et al., Powell and Houston, 1996) determined that Andrew made landfall as a Category 4 storm on the Saffir-Simpson (SS) (Editors, 1974) Scale.

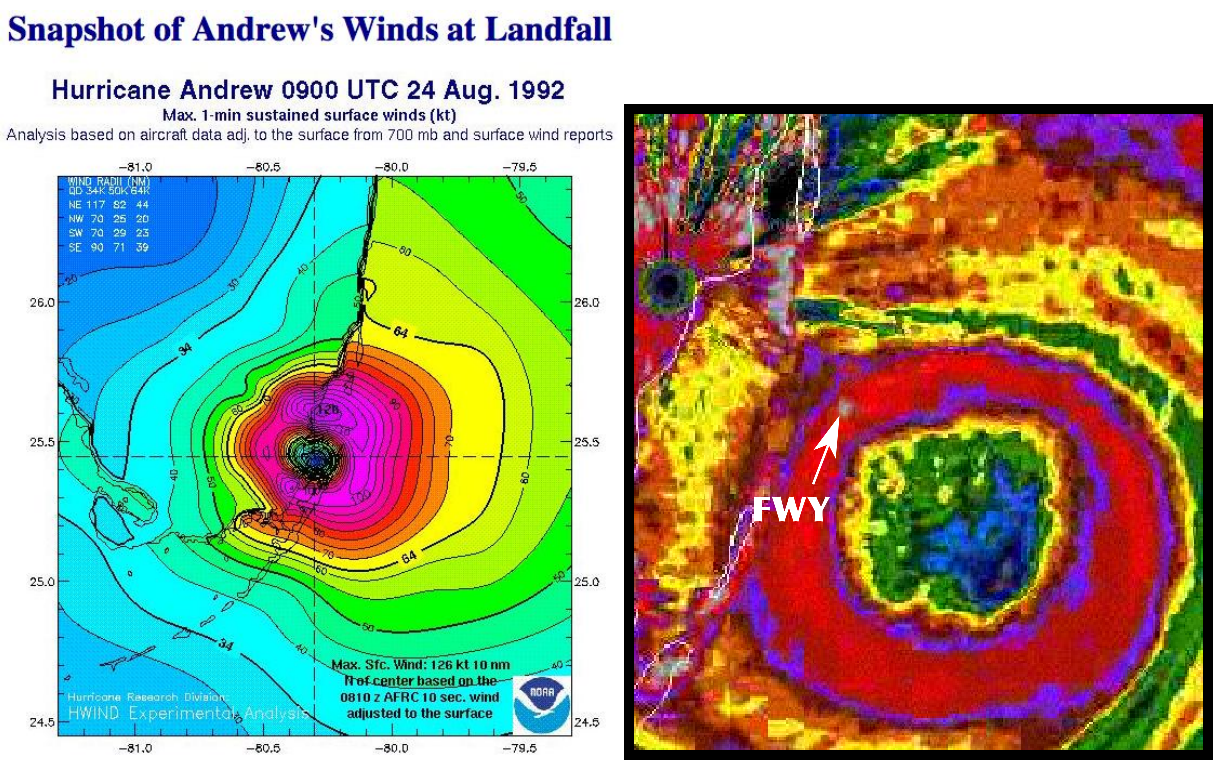

Fig. 1 L) Hurricane Andrew wind analysis as Cat 4. R) Radar reflectivity map from Miami WSR-57 radar showing location of Fowey Rocks C-MAN at time of last wind observation (0800 UTC).

In 1997, the GPS sonde (Hock and Franklin (1999) was first launched in a hurricane eyewall, and new insights began to emerge about the boundary layer structure of hurricanes (Powell et al., 1999). GPS sonde data started to affect how surface winds were estimated from reconnaissance aircraft flight-level wind measurements. The hurricane specialists of the Tropical Prediction Center (TPC, formerly known as the National Hurricane Center) are responsible for preparing the "Best Track" for a particular Atlantic basin tropical cyclone. The mission of the "Best Track" Committee (hereafter referred to as "BT", TPC 2003) is "Insure that proposed changes to the best-track files are consistent with contemporary science" with a success criteria of "accurate best-track files which withstand scientific scrutiny". The committee consists of six voting TPC meteorologists and one non-voting external member. Recently, the Best-track committee voted to reclassify Hurricane Andrew as an SS Category Five storm at landfall in South Florida (Landsea et al., 2004), based on a mean flight-level-to-surface reduction factor (90%) from an analysis of recent GPS sonde measurements (Franklin et al., 2003).

Unfortunately, this reassessment of Andrew gave little consideration to the validity of reduction factors, discounted published findings and important eyewall wind observations from Fowey Rocks, and Perrine, and did not consider additional recent observations and modeling studies that support the original assessment of Andrew as a Category Four storm.

This paper will examine the current state of the art in hurricane wind measurement and analysis. We will describe many of the available wind observing platforms, discuss their advantages, limitations, and how analysis of the information may be used to document and respond to a hurricane disaster. We provide evidence that the reassessment of Hurricane Andrew is a 20-30 % overestimate. Our discussion will show that there is considerable uncertainty in assessing storm intensity in tropical cyclones, but the situation is improving.

Since 1997, developments in wind sensing instrumentation and sampling strategies have dramatically improved our ability to measure the intensity of hurricanes as well as the extent of damaging winds. In the Atlantic tropical cyclone basin, constituting the Atlantic coast west of 60 west longitude, research and reconnaissance aircraft have been responsible for the greatest improvements, using radiometric and GPS-based remote sensing techniques. Outside the Atlantic basin, the primary observing platform remains the satellite, which is gradually improving capabilities for remotely sensing surface winds in extreme environments. The in-situ surface observing network, which should represent the ground truth for these new systems, has a mixed record; the official network in the U. S. is not reliable in extreme winds and even the coastal and buoy platforms have suffered from costly failures during critical situations. In general however, over the past few years we have experienced an unprecedented increase in the quantity and quality of observations available to document the pre-landfall wind structure of a hurricane in the Atlantic basin. The challenges facing us now include:

1) Can we improve the current coastal and inland observing network to allow high resolution documentation of extreme winds during landfall and post-landfall ?

2) Do we have sufficient data coverage to resolve wind maxima and the radial and azimuthal variation in the wind field at landfall?

3) With many platforms now measuring the same patch of ocean, how do we decide which one is correct?

4) How do we present the information so it can be used to support a wide variety of forecast, warning, emergency response, disaster assessment, and design risk applications?

5) Will new information allow us to reexamine past hurricanes in an attempt to improve the quality of the historical record?

We will qualitatively assign uncertainty based on specified instrument accuracy, estimates of the error in processing measurements to a standard framework, and experience using a variety of observing platforms to assess the wind field of hurricanes. When reporting uncertainty, we use the estimated standard deviation expressed as a wind speed or percentage. For example, a estimate of a 50 m/s wind speed with a 10% uncertainty would mean that there is a 22.5% probability that the true wind could be <45 m/s or > 55 m/s. Uncertainty should be an integral part of any wind product so the user has some idea of the variability in the estimate. However, assessing uncertainty is difficult due the dependence of measurements on multiple variables. For instance, a particular observing platform will have instrument errors that may vary with wind speed or other environmental conditions, it may have to undergo additional processing to be adjusted to a standard height and averaging time and exposure, all of which have their own errors that are not well known and also depend on environmental conditions. Finally, the measurement platform must have a sampling strategy that will minimize errors of representativeness, which in turn is related to the area coverage of the observations, and the temporal and spatial scales of the atmospheric features measured by the instrument.

2. LAND OBSERVING PLATFORMS

The primary surface observing network in the U.S. is the Automated Surface Observing System (ASOS, Fig. 2). Designed primarily for aviation use, fundamental flaws for use in extreme events include the anemometers rated to < 125 kt, lack of emergency back up power, and an outdated communication system (Powell 1993, see Masters and Blessing paper, this conference). Many of the ASOS stations in hurricane prone areas have photographic exposure documentation available on the web site of NOAA's National Climatic Data Center (Powell et al., 2004). Partial records of hurricane eyewalls have been measured in Hurricane Marilyn (1995) in St. Thomas USVI, and at Punta Gorda in Hurricane Charley of 2004. In each case power failures prevented complete documentation of the eyewall passage across the site. Accuracy of ASOS anemometers is on the order of 1 m/s or 5% for speed and +/- 5 degrees before taking into account exposure.

To help fill the gap in these situations, the Texas Tech University "WEMITE" (www.atmo.ttu.edu/WEMITE/wemite.html) and Florida Coastal Monitoring Programs (http://users.ce.ufl.edu/~fcmp/ Fig. 2) have developed portable wind measurement towers that may be assembled in advance of projected landfall locations. These programs have sampled numerous storms over the past few years and FCMP has pioneered real-time data transmission.

Fig. 2 L) ASOS station wind exposure documentation photo looking NE (Powell et al., 2004). R) FCMP tower set up at Frisco NC, the day before Hurricane Isabel made landfall in September 2003 (FCMP).

However the logistics of these deployments are arduous and to maintain safety precautions, towers have to be set up well in advance of landfall, leading to the possibility that last minute turns in the storm could cause to station to sample the storm's periphery instead of the eyewall core. To give some idea of the difficulty of intercepting landfalling hurricanes, over 15 hurricanes have been sampled over the past 6 years with the highest 1 min wind speed below 35 m/s and the maximum 3s gust speed measured thus far at ~ 50 m/s. These systems performed admirably during the busy 2004 hurricane season, helping fill the power outage void in the network of official observing stations. Uncertainty of tower measurements is <5%.

Fig. 3 L) Portable (SMART) Doppler radars with NEXRAD radar in background (NOAA/NSSL), R) Doppler on Wheels with telescoping anemometer mast (NCAR).

In the early 1990’s the National Weather Service Next Generation radars (Fig. 3, NEXRAD www.roc.noaa.gov/) began replacing the 1950’s era precipitation radars around the U. S. In the past several years, portable Doppler radars have been developed that can sample hurricanes during landfall. Doppler radars measure the velocity component of rain droplets in the direction of the transmitted beam. The main limitations of the Doppler radar is that two or more radars are generally needed to make a vector wind measurement, and ground clutter usually makes it difficult to measure winds < 100 m. NEXRAD radars measure winds at 0.5 m/s resolution and use spectral width as a measure of noise. The Ground Based Velocity Track Display (GBVTD) technique estimates a two dimensional wind fields from one ground based radar with an accuracy of 5 m/s (Lee et al., 1999). Portable Doppler radars (SMART radars and Doppler on wheels,http://www.nssl.noaa.gov/smartradars/) have added to the mix of portable networks being set up to monitor hurricane landfalls, documenting internal boundary layer development as onshore flow moves over a barrier island (Lorroso and Schroeder 2004) and well as relatively fine scale linear coherent features in the velocity and reflectivity fields (Wurman and Winslow 1998, Foster et al., 2004). The linear features have been attributed to roll vortices and even speculated to be responsible for damage but as yet there has not been enough evidence to document the process behind these features.

Observing networks are becoming more prevalent to support a variety of activities including agriculture, transportation network monitoring, water resource, and ecosystem management.   Attempts are ongoing to form networks of networks known as mesonets, with a primary example being the state of Oklahoma mesonet (http://okmesonet.ocs.ou.edu/) . The problems facing mesonets include robustness for extreme winds, redundancy, and adherence to standards for measurement and exposure. Since the mesonets represent a variety of applications, calibrations, exposures and sampling methods vary widely so they must be documented carefully and used with caution. The ASTM standard method for characterizing surface wind using a rotating anemometer (ASTM 2005) serves as a resource for helping to standardize and document the exposure of the stations. NOAA’s Forecast Systems Lab has established a nationwide mesonet (Barth et al., 2002) with observations available through the internet.

3. MARINE SURFACE OBSERVING PLATFORMS

NOAA’s National Data Buoy Center (NDBC) manages the network of oceanic moored buoys and coastal marine automated network (C-MAN) stations and buoys (Fig. 4). All stations have redundant sensors that are quality controlled and communicate observations via Geostationary satellites. The moored buoys consist of 5-m or 10 m anemometer heights and report on the hour (8.5 min average) as well as "continuous mode" in which consecutive 10 min mean winds are measured as well as the peak wind gust during each hour. The C-MAN stations also have continuous wind capability and the NDBC web site maintains exposure photos for stations closest to the coast. The NDBC platforms have a reputation as the "hurricane picket line" with the most hardened wind observing stations in the U.S., having documented eyewalls in Hurricanes Eloise, Frederic, Kate, Lili, Opal, and Ivan. Unfortunately in recent years several notable failures have occurred. The anemometer mast aboard the Fowey Rocks lighthouse folded during the eyewall of Hurricane Andrew, shortly after measuring a peak wind of 147 kts at the 39 m level. Additional failures have included buoys breaking apart from their moorings during extreme waves in Hurricane Isabel (2003) and Ivan (2004), as well as ship collisions, and erosion. Accuracies of NDBC moored buoys and C-MAN stations are on order of 1 m/s or 10% and 10 degrees for wind direction (Gilhousen 1987). There have been some indications that buoy measurements are affected by wave sheltering (Large et al 1995, Hervey 1999) but these have not been substantiated in hurricanes.

Fig. 4 L) NOAA moored buoy (6m Nomad ship hull, NOAA NDBC), R) Fowey Rocks C_MAN showing failed anemometer mast (extending horizontally to right, NDBC).

Ships of opportunity transmit wind observations to the global telecommunications system. Ship wind measurements tend to represent higher anemometer levels near 20 m and require correction for ship motion and flow distortion (Bourassa et al., 2003, Cardone et al., 1990). Ships without anemometers may report wind observations based on the descriptive characteristics of the sea state as described in the Beaufort scale. It is important to quality control ship observations by examining how a ship has compared to operational analyses and also checking a series of measurements from the ship for consistency relative to neighboring observations. Ships with anemometers and reporting Beaufort scale are believed to have uncertainties of 15% and 20%, respectively.

Drifting buoys (Drifters) represent a network supporting oceanographic research. Drifters measure wind speeds with acoustic sensors using the Wind Observation through Ambient Noise (WOTAN) method

(Vagle et al., 1990) and direction with a vane and internal compass. Mean winds are computed each hour and 4 h of data are transmitted to overflying satellites every 6 h. Drifter sensor accuracy is specified at +/- 1 m/s for winds < 20 m/s and +/- 10 degrees for wind direction. Nine drifters sampled winds in 2004 Hurricanes Frances and Jeanne. When hourly drifter data were compared to co-located Quikscat wind speeds, preliminary results show measurements were comparable (mean difference of 0.4 m/s with 1 m/s standard deviation) in winds < 15 m/s but the acoustic method overestimated higher wind speeds, probably due to increased acoustic signal from wave breaking (Morzel http://www.cora.nwra.com/~morzel/drifters.frances.html). Drifting buoys can provide valuable data in remote areas but need to be checked carefully relative to nearby conventional platforms. Uncertainty is estimated at 20% but may be reduced if they compare well with higher-quality platforms.

4. SATELLITES

The most important space-based platform for observing hurricane winds is the SeaWinds instrument aboard NASA's polar orbiting QuikScat satellite (Fig. 5, Yueh, et al, 2003), available since 1999. Sea Winds uses a Ku-band (13.4 GHz) scatterometer with two emitters, each with two different incident angles which respond to microwave scattering from capillary waves and typically provides 1-2 looks per day at a tropical cyclone with a 1800 km wide swath of measurements at either 25 or 12.5 km resolution. An ambiguity removal algorithm selects one of up to six wind vector as the most likely. QuikScat is especially helpful in identifying incipient tropical cyclones and the extent of tropical storm force (17 m/s) or gale wind speeds. The instrument measurements are sensitive to contamination from rain but many of the poor data can be identified by an algorithm that sets rain "flags". Limitations include occasional poor data on the edges of swaths and occasional poor wind directions (caused by poor choices of the available directional ambiguities), and a tendency for the signal to saturate at wind speeds above 50 m/s due to absorption of KU band microwave radiation (usually the measurement suffers from rainfall contamination well before such speeds can be measured since high winds are usually correlated with rain producing storms). Mission accuracy requirements for Quikscat are 2 m/s for wind speed and +/- 20 degrees for wind direction. Uncertainty is 10% in winds up to 35 m/s in areas without rain.

The European Space Agency satellite, ERS-2 (launched in 1995) also has a scatterometer but it operates at frequencies in the C-band (5 GHz), which receive less rain contamination but are more susceptible to signal saturation at wind speeds > 30 m/s. ERS-2 overflies a given area twice a day with a 500 km wide swath, a 50 km footprint, and a resolution of 25 km. Due to a loss of the onboard processing on the space craft, the data are now processed on land when overflying a receiving station. These data were only recently (April 2005) made available to global receiving stations by the Royal Dutch Meteorological Institute (KNMI) and availability for hurricane situations should increase (Hans Graber of the CSTARS site in Miami will be processing these data in the Caribbean and southern U. S. this hurricane season, http://www.rsmas.miami.edu/groups/cstars/). Wind speed accuracy of ERS-2 relative to NDBC moored buoys (after correcting for buoy errors) is estimated at ~0.5 m/s (Quilfen et al 2001), specified accuracy for winds above 20 m/s is 10% and +/- 20 degrees for wind direction. No detailed evaluations of ERS-2 wind speeds have been conducted in tropical cyclones, although Liu and Chan (1999) found ERS-2 useful for determining the radius of the extent of 15 m/s winds in tropical cyclones .

Geostationary (GOES) satellites have the ability to report visible images of clouds at intervals of 15-30 min. These measurements allow daytime tracking of low level cloud features, assignment of the motion vector to a particular height, and empirical adjustment of the observations to the surface Dunion et al., 2002). These observations have proven extremely important to fill in gaps in observation coverage. Typically reconnaissance aircraft fly limited radial legs in set "alpha" or figure 4 shaped patterns. In most cases the aircraft leg ends before establishing the extent of tropical storm force wind speeds. The GOES cloud drift winds help fill in this gap. Limitations include the lack of data when the storm is outside GOES range or has an extensive upper level cloud layer obscuring the surface (central dense overcast). Also, due to the experimental nature of the product, it is still not operationally generated during all hurricane situations. Recently this technique has been applied to GOES 3.9 micron near infrared channel cloud images to allow cloud tracking at nighttime. Uncertainty is 20% due to uncertainty in cloud height and surface adjustment.

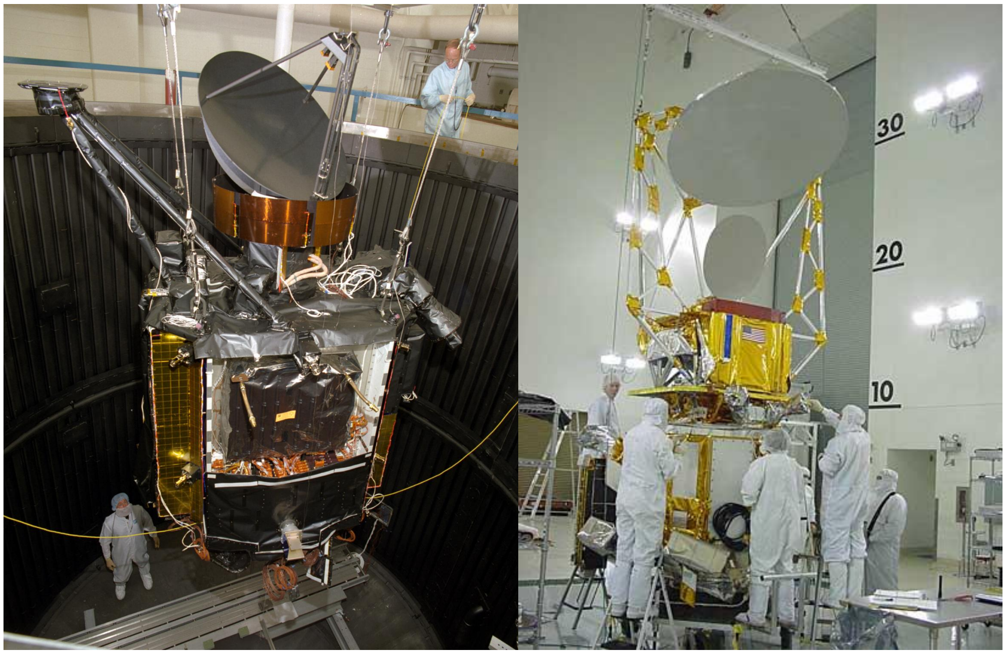

Fig. 5 L) QuikScat satellite with the SeaWinds scatterometer (Ball Aerospace&Technologies), R) Coriolis satellite with the WINDSAT polarimetric radiometer (Naval Research Lab).

The Special Sensor Microwave Imager (SSMI, Goodberlet et al., 1989) aboard three polar orbiting satellites measures emissions in seven channels at frequencies ranging from 19-85 GHz over a 1400 km swath with a 25 km footprint and spacing. Measurements are contaminated by both cloud and rain and therefore are typically only useful on the periphery of tropical cyclones. SSMI provides wind speed measurements that are sensitive to cloud and rain contamination but occasionally help to fill in gaps in data coverage beyond the aircraft. Wind speed accuracy is 2 m/s for clear skies in winds < 20 m/s. The Tropical Rainfall Measurement Mission (TRMM, Connor and Chang 2004) satellite microwave imager suffers from similar problems but has an additional channel that is less susceptible to cloud contamination. Wind speed accuracy is on order of 2 m/s in rain free areas < 20 m/s. The TRMM mission is near the end of its mission and may be up for cancellation this summer. Uncertainty in tropical cyclones is not yet established.

The Advanced Microwave Sounding Unit (AMSU, DeMuth et al., 2004) can measure upper tropospheric warm temperature anomalies in the hurricane eyewall. These measurements can be used to diagnose the pressure field and, through a non linear balance equation, the winds at the 3 km level may be estimated and then adjusted to the surface. This method is relatively new and coarse in resolution (~ 45 km horizontal) but may be useful for diagnosing intensity when no other platforms are available or in combination with other satellite platforms. GOES infrared brightness temperatures may also be used to estimate intensity through a statistical approach and are currently under development at University of Wisconsin (Kossin and Velden 2003). The uncertainty of these methods is not yet established.

Newer microwave sensors about to be released include the NASA Aqua satellite (AMSR-E), RADARSAT, ENVISAT (http://envisat.esa.int/ Horstman et al., 2004) and the Navy's WINDSAT. Each of these platforms will suffer from some contamination affects but the extent of the problem for hurricanes is not yet known. The Canadian Space Agency's RADARSAT has measured 5 cm scale surface roughness features over the sea with C-band Synthetic Aperture Radar (SAR). Swath widths are 500 km and spatial resolution is 100 m. Fine scale linear coherent features have been documented aligned with the wind direction and attributed to rolls (again without supporting evidence). Wind speed may be estimated using methods similar to those used by scatterometers (algorithms based on the normalized radar cross section). An advantage of RADARSAT is that the C-band microwave energy can penetrate clouds and rain, however, the signal can still saturate at high wind speeds. A disadvantage is that measurement of wind speed is still under development and the data are only available commercially, and not always for tropical cyclones.

The Coriolis/WINDSAT (Fig. 5, www.pxi.com/praxis_publicpages/WINDSAT.html) weather satellite uses a passive polarimetric microwave conical scanner that can measure surface wind vectors with less susceptibility to cloud and rain, at 25 km resolution over a 1025 km swath. WINDSAT is currently in calibration/validation mode and may become available during the second half of 2005. Early indications suggest a 2 m/s rms error for wind speed < 20 m/s with a 25 degree error in wind direction.

AMSR-E is the Advanced Microwave Scanning Radiometer for the Earth Observing System aboard the joint NASA/ Japan Space Development Agency AQUA satellite (http://sharaku.eorc.nasda.go.jp/AMSR/index_e.htm). AMSR-E has a swath of 1445 km and wind speed resolution at 21 and 38 km. Preliminary indications from AMSR-E data collected in Hurricanes Frances and Ivan of 2004 suggest that reasonable data can be collected outside major precipitation features (AMSR-E Data at NSIDC: AMSR-E Images of Hurricane Frances).

One of the big challenges for satellite microwave sensing is to develop techniques to reduce or eliminate rain and cloud contamination as well as extend the wind speed range for useful observing before the signal saturates. Recent experiments involving microwave sensors aboard research aircraft show great promise in helping to solve these problems.

5. RESEARCH AND RECONNAISSANCE AIRCRAFT

Through the late 1990's surface wind speeds were estimated from reconnaissance and research aircraft (Fig. 6) from visual estimates of sea state, by diagnostic boundary layer models, or empirically by applying a reduction factor (Powell 1980, Powell 1987, Powell and Black 1991). Sea State estimates (based on a visual assessment of the amount of foam coverage produced by breaking waves) were reasonable at low levels in high wind speeds but tend to be subjective and unavailable for intense storms since aircraft had to fly at higher levels (near 3 km) to maintain safety. Boundary layer models lose their basic assumptions (flight-level wind equivalent to a mean wind for the boundary layer) as soon as the aircraft ascends above 1.5 km, and also assume horizontal homogeneity, which is unlikely in the presence of curved flow with strong horizontal gradients (Kepert 2001, Kepert and Wang 2001). In the early 1990's it was recognized that the hurricane boundary layer was on the order of 500 m deep with peak winds near the top of the boundary layer followed by a gradual decrease above due to the warm core nature of the storm (causing the horizontal pressure gradient to decrease with height).

In 1997, the first hurricane eyewall launches of the new GPS dropwindsonde provided the observational details to confirm many of our beliefs on boundary layer structure. The GPS sonde (Hock and Franklin 1999) is a small cylindrical instrument package (Fig. 6) launched through a pressure tube in the aircraft skin. It falls at a speed of ~12 m/s, slowed in descent by a pyramidal shaped drogue chute. A code-less receiver collects information on GPS satellite frequencies and transmits the information back to the parent aircraft where it is processed with a full receiver into horizontal and vertical positions and wind velocities. The vertical profiles of the wind are semi-Lagrangian since the sondes move horizontally up to tens of km while falling from 1-3 km altitudes; however they certainly do not follow air parcels in a true Lagrangian sense. Based on the near surface and launch level wind speeds, empirical wind reduction factors were developed for the eyewall (90%) and outer (80%) regions of the storm (Franklin et al., 2003). These empirical reduction factors were used to reclassify Hurricane Andrew as a Category 5 storm on the SS scale (Landsea et al 2004). As will be discussed below, reduction factors based on the GPS sonde have large uncertainty. If used to estimate the peak wind in the storm, they must be referenced to the maximum wind speed at flight level rather than the flight-level wind speed at the time of launch. GPS sonde measurement uncertainties are 15% for surface values (after considering instrument, height, averaging time, and representativeness) and 10% for values estimated from boundary layer or surface layer means. Mean vertical wind profiles were constructed as a function of mean boundary layer wind speed by Powell et al 2003, resulting in profile method measurements of the surface stress, roughness, and drag coefficient at four different mean surface wind speeds. These measurements suggested an initial increase followed by a leveling off of the drag coefficient as the wind speed increased beyond 35 m/s; in sharp contrast to parameterizations used by numerical weather prediction, storm surge, and wave models. The measurements they described applied strictly to open ocean conditions; drag coefficient behavior near the coast is unknown with some speculating a similar leveling off behavior as at open sea and others suggesting that coastal shoaling and breaking wave conditions will produce higher roughness. The current ASCE wind loading standards and some preliminary results from the FCMP agree with the latter (Vickery and Skerlj 2000).

Fig. 6 L) One of two NOAA P3 hurricane research aircraft (Brad Smull). R) GPS dropsonde.

NOAA aircraft have made Doppler radar measurements in hurricane since 1982 (Marks et al., 1992, Gamache et al., 1995). Aircraft Doppler radars on research aircraft can adopt sampling strategies such as perpendicular legs, fore-aft sampling, and multiple aircraft orthogonal legs to measure the three dimensional wind field within the area comprised by the core of the hurricane (eye and eyewall). Based on comparisons of flight level observations to fore-aft scans of the airborne Doppler, uncertainty is estimated at 3 m/s but surface clutter prevents measurements below 150 m. New data assimilation and analysis techniques in development will allow rapid processing of the wind field on board the aircraft which can then be sent to forecasters on the ground via satellite communication systems.

The Stepped Frequency Microwave Radiometer (SFMR, Fig. 7) is a microwave surface wind speed sensor aboard the NOAA research aircraft (Uhlhorn and Black 2003). The SFMR measures the emission from the atmosphere and ocean surface at six separate frequencies from 4-7 GHz, as a brightness temperature T_b. The surface emission is from bubbles that form when waves break and inject air into the sea. Foam radiates as a blackbody at microwave frequencies, therefore as foam coverage increases with wind speed, the emission continues to increase. The accuracy of the brightness temperature measurement is ~ .5 K. The relationship between T_b and surface wind speed was based on PBL model estimates of surface wind from low level research aircraft flights in hurricanes, which in turn are associated with an uncertainty of ~ 2 m/s (Powell 1980) in winds up to 50 m/s. For winds > 55 m/s, the PBL model uncertainty is larger and there is some evidence of underestimation. The measurement of the attenuation of the signal due to rainfall also makes it possible to remove the rain effects so the SFMR is the lone microwave wind measurement technique that is not contaminated by rain. The theoretical saturation of

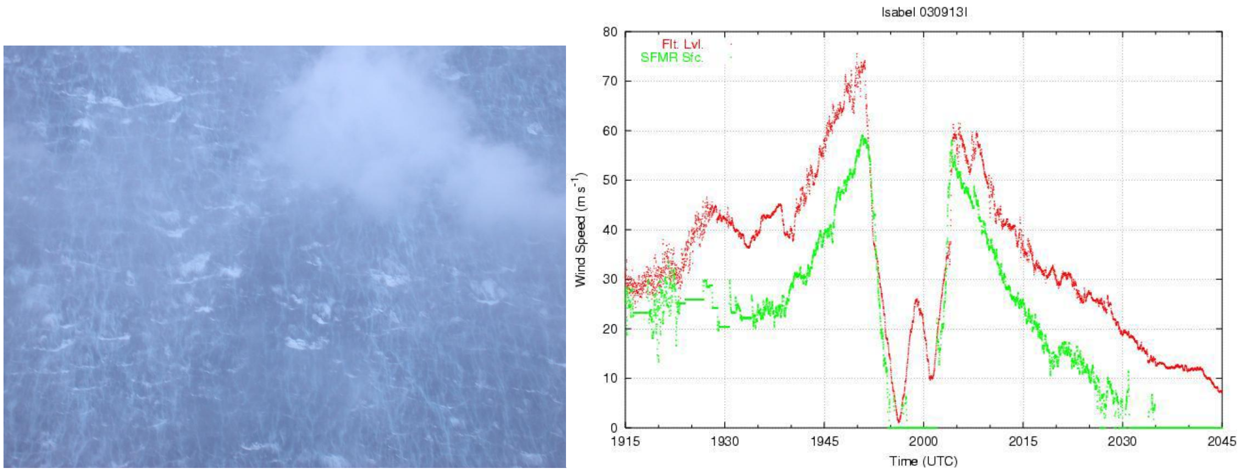

Fig. 7 L) Hurricane sea state showing foam coverage as observed from 2.2 km (Paul Chang), R) SFMR (green) and flight level (red) radial profile of wind speed in Hurricane Isabel (2003) during CBLAST experiment.

the signal should not be reached until the brightness temperature approaches the black body temperature of the sea surface. Therefore the theory of measurement suggests that the SFMR will not saturate at high wind speeds. Limitations of the SFMR include spurious values in sand bars and land areas that are awash or any location in which the sea foam is caused by mechanisms other than wind alone (e.g. current flowing against the wind, shoaling conditions in shallow water). Comparisons of the SFMR to GPS sonde MBL-estimated surface winds indicated a high bias of ~ 2 m/s and additional variability dependent on sea state. The SFMR is able to document how the surface wind relates to the wind at flight level, and in particular, the location and magnitude of the surface wind relative to the peak wind measured at flight level. The high radial resolution of the measurements (30 s running mean of 1 s samples providing a radial resolution of ~ 3 km) provides an unambiguous measure of the peak surface wind that allows improved (relative to GPS sondes) estimation of flight-level wind reduction factors. For example, Fig. 7 shows the SFMR depicting peak surface wind inward of the maximum flight level wind as well as higher reduction factors on the left side than the right (relative to the storm motion). The performance of the SFMR has lead to an initiative that will further evaluate the instrument and improve the algorithm. In the next few years it's possible that SFMR sensor technology will be implemented on the operational C-130 reconnaissance aircraft fleet operated by the 53rd Air Force Reserve squadron at Keesler Air Force Base. Uncertainty is 10% in winds up to 60 m/s and 15% in higher winds. Work is ongoing to establish the upper range of SFMR measurements.

6. H*WIND REAL-TIME OBJECTIVE WIND FIELD ANALYSIS

With realtime processing and a great deal of cooperation with contributing agency scientists, the various measurement platforms mentioned above are processed into a common standard framework for averaging time (maximum 1 min mean), exposure (marine or open), and height (10 m) Powell et al., 1996. A time-to-space conversion is employed to present the observations as a range and bearing from the storm center over a particular time "window" during which the storm intensity is assumed to be stationary. In practice, one wants to minimize the time window length (for storms undergoing rapid intensity change) while maximizing the data coverage over the analysis domain. Typically a 3-6 h time period is required to assemble sufficient observational coverage for an analysis. This storm relative manner of displaying the observations allows one observation platform to cover a relatively large area over a period of several hours, helping to fill data voids. If multiple observing platforms are sampling the storm, scientists can faced with a large number of observations over an analysis domain, including many that may appear in the same relative patch of ocean. Measurements do not always agree so it's important to conduct quality control (QC) to remove unrepresentative observations. QC is a subjective process that relies on the experience of the scientist who must make decisions based on how a particular observing platform is faring relative to its neighbors, given the particular storm situation and past performance. In practice, the analyst develops confidence with particular platforms in given situations, for example the GPS sonde surface wind estimated from the mean of the samples over the lowest 150 m (GPS_WL150) shows a more stable measurement than the sonde sample closest to 10 m. In comparison to various satellite measurements nearby, there may be indications that rain contamination was affecting the satellite measurement, and that the variability in estimating a surface wind from the flight level wind may be too high to allow a confident measure of the surface wind. In this example the GPS sonde WL150 measurement would be considered the "anchor" observation and help guide which nearby platforms are representative.

The NOAA Hurricane Research Division (HRD) Real Time Hurricane Wind Analysis System, known as H*Wind, (Powell et al 1998) includes a graphical, interactive method for conducting QC (Fig. 8). Once the poor quality observations are "flagged" they can be removed from further consideration and the surviving observations may be submitted for objective analysis. The objective analysis acts as a mechanical interpolator filling in regions with no data based on surrounding measurements that have survived the QC process and weighting factors that are assigned to each observing platform. The analysis is further constrained to preserve the speed and radial location of the peak observed wind by enhancing the spline fitting amplitudes so the maximum is not "smoothed out".

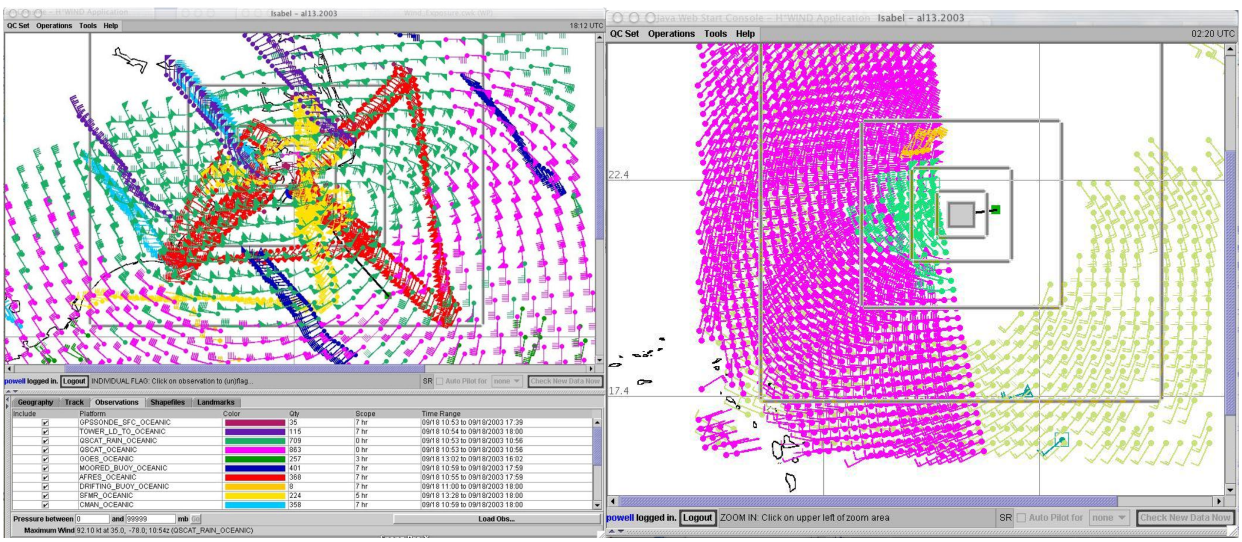

Fig. 8 H*Wind QC interface data distribution for Hurricane Isabel (2003) L) at landfall with both research and operational aircraft reconnaissance , R) in open ocean without aircraft reconnaissance. Wind barbs depict direction and wind speed for color-coded observing platforms listed in table.

Real-time wind analysis "snapshot" products are designed to serve are experimental wind field guidance on the current hurricane intensity and wind radii (outermost extent of tropical storm , 50 kt, and hurricane force winds in each storm quadrant (NE, SE, SW, NW). An H*Wind analysis snapshot provides header information on the various platforms that contribute the the analysis, information on the maximum surface wind and its location, the radial extent of tropical storm force, 50 kt, and hurricane force winds in each storm quadrant, and additional information on the central pressure, radius of maximum wind, and storm motion. Analysis image files, gridded files, and GIS shape files are available from the HRD web site (http://www.aoml.noaa.gov/hrd).

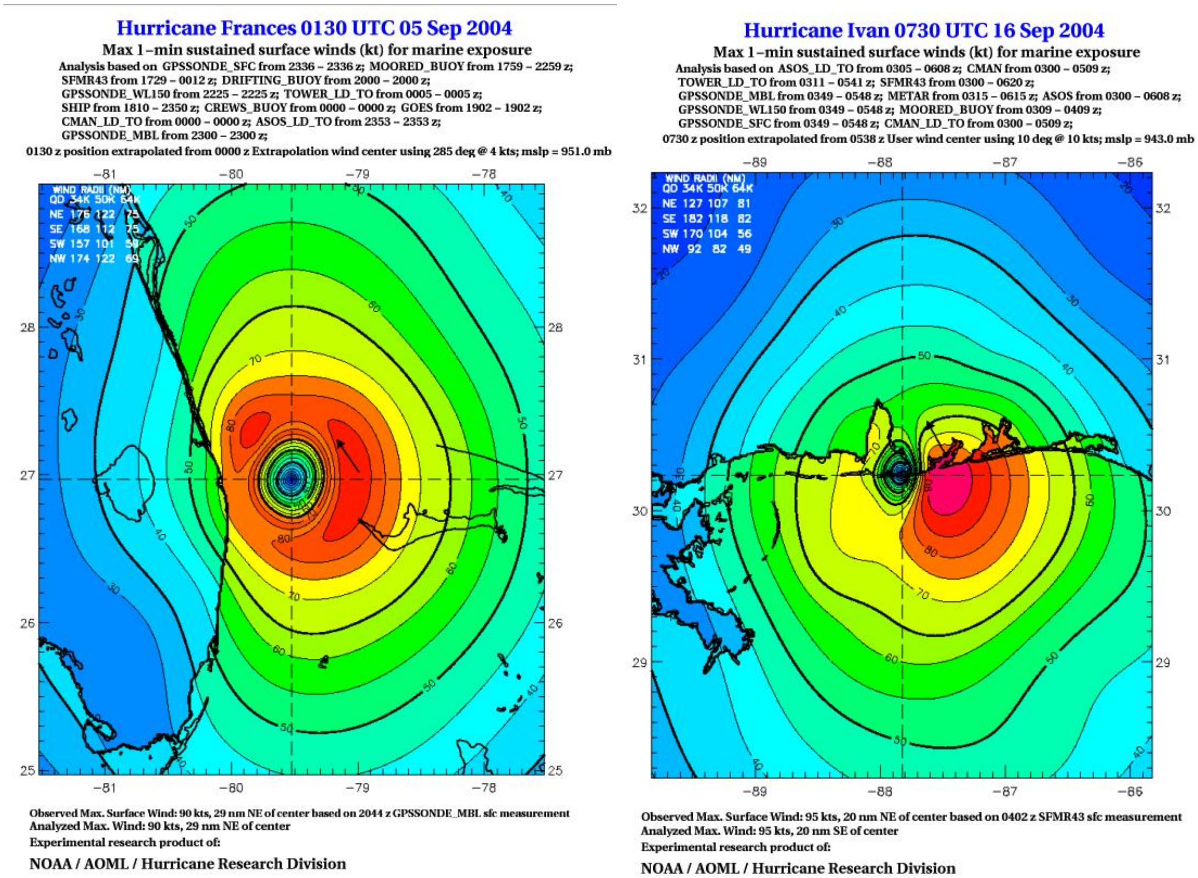

Fig. 9 Realtime wind analysis conducted for L) Hurricane Frances (2004), R) Hurricane Ivan (2004).

Experimental real-time analyses are conducted at 6 h intervals (0130, 0730, 1330, 1930 UTC) to document the intensity, extent of damaging winds, and the changes in the wind field. During hurricane warning episodes, analyses are conducted at intervening 3 h intervals (0430, 1030, 1630, 2230 UTC). To be useful as experimental guidance products, analyses must be available about 1.5 h before the release of official advisories by the National Hurricane Center. Wind analysis snapshot products are mapped to storm locations at a time near the end of the observation time window. Typically 4-6 h of observations are necessary to provide enough observational coverage to conduct an analysis. For example, a 1930 UTC wind analysis would comprise all observation available from 1530-1915 UTC, and the analysis is then mapped to an estimated 1930 UTC storm center position extrapolated from the last available reconnaissance aircraft center fix (e.g. from an 1800 UTC fix) based on the current motion of the storm. Since H*Wind is a research effort and not operational, realtime analyses are not available 24-7, although we attempt to provide analyses in realtime during regular working hours and warning episodes.

H*Wind is designed as a global tropical cyclone wind observing system. Locations of all active tropical cyclones are depicted and available observations are plotted. As satellite observing platforms improve their ability to measure high winds, it is conceivable that H*Wind analyses could be conducted globally within the next few years. With a suitable wind model, global automated blended analyses could begin even sooner. JAVA versions of H*Wind are under development for testing by global tropical cyclone forecast offices.

Advantages of H*Wind include an objective, observation-based measure of the magnitude and extent of damaging winds in a hurricanes using a common framework. An H*Wind analysis is only as good as the data that go into it. If an observing system did not sample the wind in a particular location, H*Wind will not assume that the winds could have been greater in that area. If large areas are missing observations, voids will have to be filled by background fields from earlier analyses, or, in the case of tropical cyclone basins without reconnaissance aircraft (Fig. 8 R shows a data coverage that would be similar for tropical cyclone regions without reconnaissance aircraft coverage), a wind model could be blended with available observations.

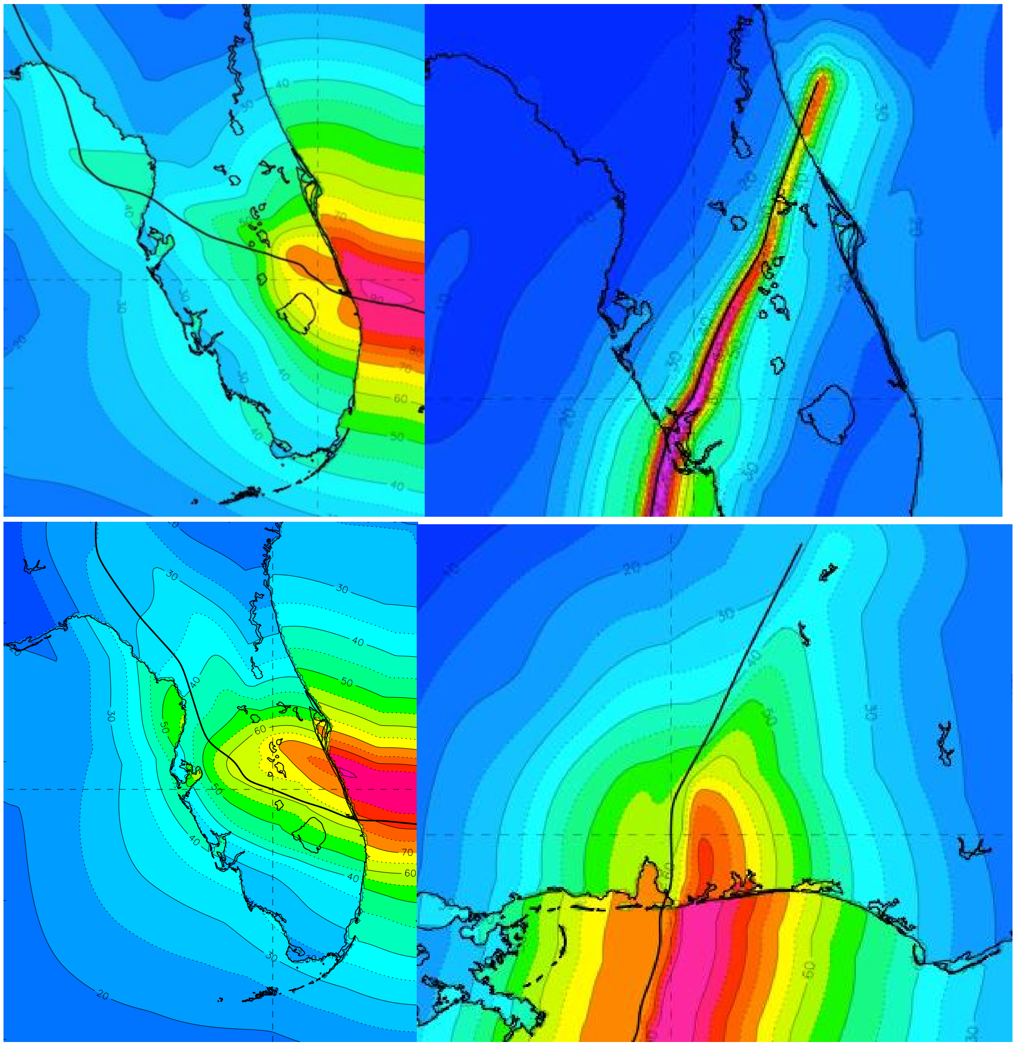

Fig. 10 H*Wind swath products for 2004 Hurricanes Frances (top left), Charley (top right), Jeanne (bottom left), and Ivan (bottom right). Wind speeds are in knots.

A retrospective analysis can improve on the quality of real-time analyses by including all data before and after the analysis center time (e.g. use all data from 1630- 2230 UTC for a retrospective 1930 UTC analysis). The H*Wind analyses are not an operational NOAA product and are therefore considered experimental but are being used to support research and a wide variety of applications including wave and storm surge modeling, disaster assessment, and analysis of record.

One particular application that looks promising is collaboration with the Department of Homeland Security Federal Emergency Management Agency (DHS-FEMA) to provide an inland projection of peak winds (Fig. 10) using the official forecast and the H*Wind analysis within a few hours of landfall. After landfall the failure of ASOS stations and the lack of aircraft observations (for safety precautions, aircraft do not typically fly reconnaissance patterns over land) leaves few platforms available for realtime analysis so we decay the landfall wind field using HRD's inland wind decay model (Kaplan and DeMaria 1995). The resulting wind swath map is gridded and made available on our web site in shape file format.

In addition, the peak winds are evaluated at each census tract point and provided to DHS-FEMA for use as input to their Multi Hazard damage assessment model (HAZUS). Comparisons of HAZUS loss estimates compared to the Property Claims Services organization insurance claims suggest an excellent agreement during the 2004 hurricane season.

7. WIND UNCERTAINTY

The uncertainty of the H*Wind analysis depends on the errors of the observing platforms contributing to the analysis, errors in how the observations are processed to the common analysis framework, and representativeness errors associated with how well a diverse set of measurements collected over a time period constitute the current state of the wind field.

Since H*Wind is constrained to match the peak observed wind measurement in the eyewall, the representativeness error comes down to whether that measurement may have been exceeded in some other unsampled part of the eyewall. The only way to minimize that error is to enhance data coverage as much as possible in the eyewall region. Since hurricane wind speed gradients are much stronger in the radial than the azimuthal directions, most reconnaissance aircraft flight patterns focus on the radial resolution. Small but intense storms have relatively steep radial wind speed profiles necessitating increased radial resolution to minimize sampling error. Azimuthal resolution should increase with the motion of the storm, and should attempt to sample regions with high radar reflectivity associated with possible convectively enhanced wind gusts. Therefore, given two storms of the same intensity, a small, fast moving storm will be more susceptible to sampling error than a slow moving large storm. A guideline for representative sampling would be a radial resolution of 0.1 Rmax (radius of maximum wind speed in km) and an azimuthal (deg) resolution of $360/ 0.8C_t$ (C_t is translation speed in m/s). An ideal reconnaissance aircraft pattern in a storm like Andrew would comprise eight radial passes of one km resolution separated by 45 degrees over a 3-6 h period; such a pattern would probably sacrifice sampling the outer extent of tropical storm force winds in order to more accurately sample the inner core intensity of the hurricane. Aircraft sampling in Andrew was close to 1 km radial (using peak 10 sec values each minute), and 90 degrees azimuthal. If only four orthogonal passes are available and the left-right storm motion asymmetry is twice the translation speed, the error of missing the azimuth corresponding to the maximum wind speed would be ~ 1/8 to 1/4 the storm motion (~ 1.25-2.5 m/s in Hurricane Andrew).

In a study of Hurricane Andrew (Powell et al., 1996) errors were estimated for adjustment of marine platforms to 10 m (3%), and adjustment for averaging time using a gust factor (6%). For land platforms the errors were 7% for height adjustment, 5% for exposure adjustment and 6% for the gust factor. Recent gust factor research (Vickery and Skerlj 2005) confirming similar gust factors for tropical cyclones and other high wind events may help reduce uncertainty. Consequence errors for not standardizing observations could be 15-30% for each process. Measurement platforms discussed previously list 10 -20% instrument accuracies in high winds. Assuming these errors are equivalent to standard deviations, they can be added to estimate the associated variance for a given wind estimate. Hence a peak wind of 50 m/s from a could have an error of +/- 5-20%, depending on the platform. Estimates for reducing the wind speed from the 3 km level to the surface using a reduction factor or a boundary layer model have large uncertainty with reduction factor standard deviations on the order of 19% before adding additional error for averaging time/gust factor, and sampling. If the reduction factor is based on the peak flight level wind or if the aircraft is flying < 1500 m, uncertainty is smaller. In most cases, the 3 km level is well above the level of maximum wind speed (500m) and is subject to a weakening of peak wind speed with height due to a relaxation of the pressure gradient associated with the storm's warm core. If the aircraft is at 1500 m or below, there is a good correlation of the flight level wind speed with the mean boundary layer wind speed (Powell et al., 2003). Boundary layer model estimates of the surface wind speed compare well with GPS sonde surface wind speeds for wind speeds < 55 m/s, but show a low bias thereafter (Powell et al., 1999).

Observing platforms with the smallest errors are those that already measure within the standard framework, therefore eliminating the need for height, averaging time, and exposure adjustments. Based on experiences conducting real-time and retrospective H*Wind analyses during the 2003-2004 hurricane seasons observing platforms with the least uncertainty for estimating the peak wind in a hurricane are 1) Coastal 10 m towers, 2) C-MAN stations (with marine exposure, the closer to 10 m the better), 3) SFMR, 4) GPS sonde, and 5) Moored buoys.

For example, the FCMP towers measure the highest 1 min and 3 s wind speeds, and turbulent intensity every 15 min at 10 m, and the WEMITE towers provide similar measurements, although not yet available in realtime. This information greatly reduces uncertainty, since no height adjustment or gust factor are required to estimate the maximum 1 min wind at 10 m, and upstream roughness is computed from the measured turbulent intensity. In addition, careful and repeated calibrations reduce the tower uncertainty to < 5% primarily due to instrument error < +/-0.5 m/s (for RM Young Wind Monitor instruments; F. Masters, J. Schroeder; personal communication). C-MAN stations or moored buoys at 10 m in marine exposure only require a gust factor to estimate the maximum 1 min wind speed (6%) and accounting for instrument error (10%) for a total uncertainty (in 50 m/s winds) of 12%.

Remote sensing platforms measure winds over a "footprint" of the ocean. H*Wind uses footprint information to compute the maximum 1 min wind speed from remote sensing platforms. To estimate a time scale for the measurement, the footprint can be divided by the measured wind speed. For Quikscat with a 25 km footprint, a 30 m/s wind speed would representa time scale of ~ 800 s so a gust factor is required to compute the maximum 1 min wind over the ~ 14 min time period. A refined time scale estimate would need to be sensitive to differences between the streamwise and transverse scales of the turbulence relative to how the instrument scans the surface. For the SFMR, based on an aircraft motion of ~ 110 m/s and a height of 3 km, the footprint is ~ 6 km, measured at high radial resolution, resulting in a time scale of about 2 min or less in winds over 50 m/s, so the SFMR is already equivalent to a 1 min wind speed. Provided the SFMR is not over regions where mechanisms other than wind are causing sea surface foam coverage (shoaling waves, land, current opposing the wind), its fine radial resolution provides a superior estimate of the peak surface wind in the storm with uncertainty of 10% primarily due to the emissivity-wind relationship. The SFMR is still under validation and is expected to improve as algorithms are enhanced and the range of the instrument is established.

The GPS dropsonde samples at a 0.5 sec rate as it falls and has a height error of +/- 2 m and an instrument accuracy of ~ 2 m/s. Typically only a few GPS sonde drops are made during a reconnaissance flight. The sondes are launched with a strategy to attempt to target the radius of maximum wind at the surface (based on the radial flight-level wind speed profile). However, with so few sondes available on a given flight there is insufficient radial resolution to resolve the maximum wind. A sonde measurement time scale is difficult to assign because the sonde measurement is representative of whatever feature it happens to fall through. A surface measurement attributed to 10 m may be anywhere from 8-12 m and could represent a gust, lull, or mean wind speed. In addition, a forward (upward) centered differencing scheme introduces a high bias of ~ 0.5 m/s at the surface. An alternative and more stable measure of the mean surface wind is estimated from the mean surface to 500 m layer average (MBL) or the average of the lowest 150 m layer sampled by the sonde (WL150). In moderate wind speeds Houston et al reported GPS sonde winds to compare to within 3.5 m/s of nearby (within 20 km) conventional buoy and C-MAN stations (Houston et al., 2000), and found the best comparisons when the MBL-estimated sonde wind was assumed to represent a 5 min average. Therefore, in H*Wind, a 1.06 gust factor is applied to estimate the maximum 1 min wind speed over a 5 min time period. In H*Wind each method for GPS sonde surface wind estimation is available to compare to neighboring observations to help determine which is most representative.

In general, GPS sonde wind speeds determined from the MBL method compare to within 2.5 m/s of the SFMR. It is important to recognize that there is no absolute "ground truth" when evaluating various observing platforms in extreme winds. Each platform has its unique characteristics and limitations. The coastal tower might be the most accurate platform but will be difficult to place with sufficient resolution to sample the peak wind speed. The GPS dropsonde provides a high quality measurement but has insufficient radial resolution to sample the peak wind speed. The SFMR has the required radial resolution but has uncertainty in the emissivity-wind speed relationship.

TABLE 1. Uncertainties of Hurricane Surface Wind Observing Platforms

Platform	Height (m)	Averaging time	Measurement Method	Instrument Uncertainty	Combined Uncertainty
FCMP, WEMITE Tower	5, 10	1-900 s	prop anemometer	1 m/s	5%
SFMR	10	6 km/WS	foam emissivity brightness temp.	0.5K	2 m/s , 10% WS > 55m/s
C-MAN	10-40	10 min	prop anemometer	1 m/s or 10%	12%
Moored Buoy	5, 10	10 min	prop anemometer	1 m/s or 10%	12%
GPS	8-12	0.5 with 5s filter	motion via GPS	3 m/s	15%
GPS from WL150	10	5 min	motion via GPS	3 m/s	10%
GPS from MBL	10	5 min	motion via GPS	3 m/s	10%
Max Recon (GPS based)	10	5 min	GPS/Max Recon	13%	15%
Max Recon (sfmr-based)	10	2 min	SFMR/Max Recon	7%	7%
QSCAT	10	25 km/WS	Ku Backscatter	2 m/s until hvy. rain	10% until hvy. rain
GOES Cloud Drift	10	5 min	cloud motion-> Sfc wind	2.6 m/s	15% for WS<25 m/s
ASOS	7, 10	2 min	cup anemometer	1 m/s or 5%	10% if record survives
Ship	~ 20	10-30	anem or Beaufort	10%	20%
Recon 0.9	10	5 min	GPS/Recon	19%	20%

H*Wind allows us to combine these and other diverse observations to attempt to provide sufficient data coverage to resolve the radial and azimuthal features of the wind field. A qualitative assessment of uncertainty for various observing platforms used in H*Wind is contained in Table 1. Combined uncertainty includes instrument, exposure, averaging time, height adjustment, and representativeness errors. Platform inter-comparisons in close time and space proximity will help to identify biases and variability in a variety of atmospheric and oceanic conditions. By keeping track of these differences relative to platform, analysis, and forecast, we can assess how well an analysis or forecast reproduces the observations.

Additional methods to consider to assess analysis uncertainty include Monte Carlo simulations and Bootstrap resampling. In the Monte Carlo simulations the observations are perturbed with noise relevant to the variance properties of the observing platform and then objectively analyzed. After hundreds of analyses are conducted the resulting variance will provide an estimate of the uncertainty. In the Bootstrap approach, observation platform errors are not required; If we have N observations, we sample N times from the observation database, with replacement, and then prepare the analysis, and repeat the process hundreds of times to compute the variance across the analyses.

8. HURRICANE ANDREW REVISITED

Hurricane Andrew was recently reclassified to a Category 5 storm on the SS scale. The basis for the reclassification was a "new understanding" that the surface wind in the eyewall is 90% (with 19% standard deviation) of the wind at flight level (Landsea et al., 2004, Franklin et al., 2003). GPS sonde winds fail (due to insufficient GPS satellites for the wind calculation) near the surface in stronger wind conditions (e.g. only 69 out of 175 eyewall drops with 700 mb flight level winds > 50 m/s also reported surface winds). Franklin et al., 2003 replaced missing low level observations with a mean profile representative of sondes that sampled low levels. While this approach avoided a problem associated with a limited number of data in extreme conditions, it created another problem in that the sondes that sampled the lowest levels were representative of much weaker conditions.

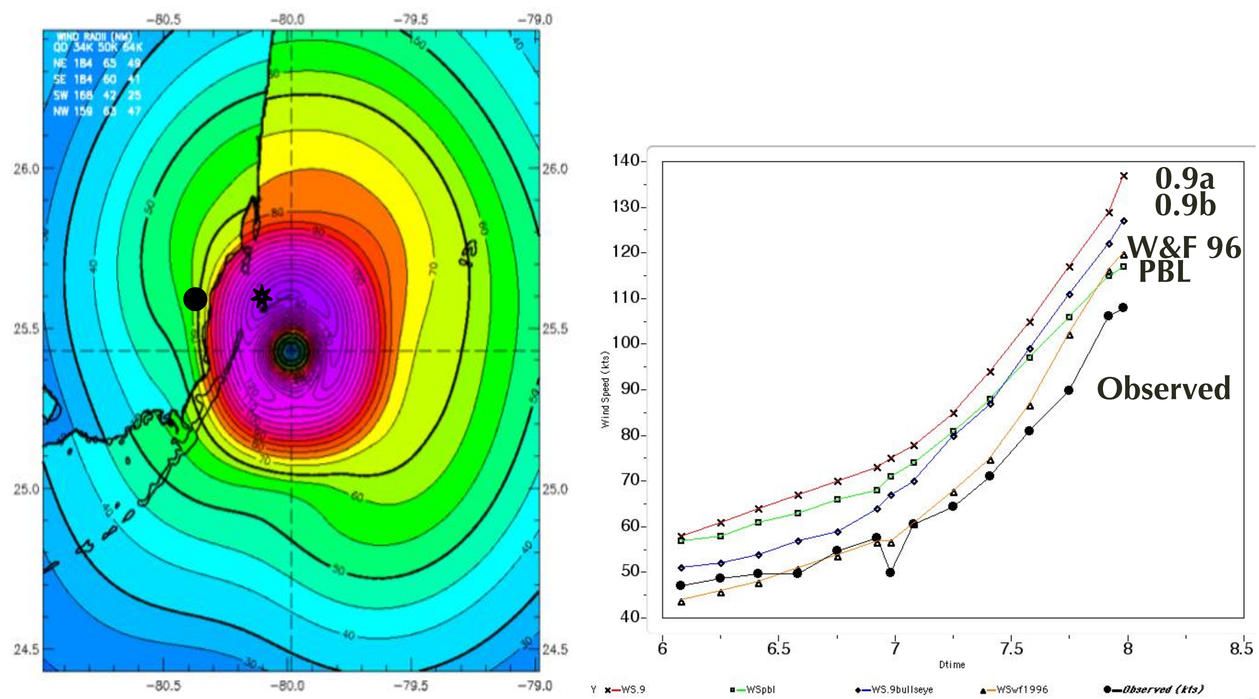

Figure 11. L) Surface wind analysis (kts) for 0759 UTC 24 August 1992 using the 0.9 rule. Fowey Rocks C-MAN location is noted by star, Perrine noted by circle. R) Fowey Rocks observed wind record (kts) compared to moving different wind fields past the platform location.

Anemometers in Andrew's eyewall failed to sample complete records but provide a valuable opportunity to validate the ".9 rule" for adjusting flight-level winds to the surface in the eyewall at the locations of the peak measurements. At 0759 UTC, 24 August 1992, the Fowey Rocks C-MAN station measured a maximum sustained surface wind of 108 kts (Powell et al., 1996). The data transmission system failed soon afterwards, followed by the instrument mast (Personal communication, Doug Scally 2002). An objective analysis of the North-South and East-West legs of the 700 mb (3 km) flight-level observations from 0410-0830 UTC adjusted using the 0.9 rule (Fig. 10 .9a, .9b) shows a peak wind of 146 kts but winds are ~140 kts at Fowey Rocks (star), over 30 kts higher than observed. Even the estimates of Powell et al 1996 (W&F 96 and PBL) are about 10 kts higher than observed.

The highest surface wind measurement in Andrew, 119 kts (Powell et al., 1996) came from a Perrine homeowner, using a 10 m mast attached mounted near the side of his house. The mast failed at the time of this measurement with the mast falling from east to west (Rappaport 1994) consistent with an east or east northeast wind direction in the northern part of the eyewall. As discussed in Powell et al., 1996, the most likely time of this observation was ~ 0900 UTC. Shifting the objective analysis in Fig. 11 to the storm location at 0900 UTC shows ~ 142 kts in Perrine, over 20 kts higher than observed. These comparisons indicate that the "0.9" method used to adjust the 700 mb flight-level winds to the surface overestimated winds in these locations by ~29% and 19%, respectively. Conversely, estimating the flight level winds by dividing the Fowey Rocks and Perrine measurements by 0.9 significantly underestimates flight level winds at similar radii.

GPS sonde wind profiles in hurricane eyewalls, together with comparisons of SFMR surface winds to maximum flight-level measurements provide data to support empirical reduction factors for estimating surface winds from flight level winds alone. To estimate peak winds in the eyewall, the peak flight level wind (rather than the flight level wind at the time of launch) must be compared to the highest GPS sonde or SFMR measurement on a particular radial flight leg. Over 500 GPS sonde profiles from 1997-2003 were compared to the maximum flight-level wind speeds on the same radial flight leg. Unfortunately, none of the storms in the GPS sonde database, including Mitch when a Cat 5, show 700 mb winds as high as Andrew (~82 m/s min ob). Earlier storms showing 700 mb winds similar to Andrew include Inez (Hawkins 1969), Allen in 1980 (on Aug 8th after an eyewall contraction, Jorgensen 1984), Gloria 1985 at peak intensity (peak tangential winds at 550 mb although the distribution of convection in Gloria was asymmetric due to shear of the environmental flow (Franklin et al., 1993)), Gilbert of 1988 near peak intensity (Dodge at al.,1991), and Hugo in 1989 (Black and Marks 1991). Characteristics of such Intense hurricanes include a contracting eyewall process and winds at 700 mb that are as strong as winds at 500 m. This is in contrast to the usual situation where the winds at 700 mb are of the order of 10 - 30% lighter than those at 500 m. A vertically well-mixed eyewall would contribute to smaller values of the surface wind reduction factor.

When examined (Fig. 12) relative to maximum flight level winds > 50 m/s (rather than the flight level wind at the time of GPS sonde launch) the mean reduction factor based on the GPS sonde is 0.76 with a 13% standard deviation. For the SFMR, the mean reduction factor is 0.81 with a 7% standard deviation. Restricting the data to peak flight level winds above 70 m/s (Andrew's peak flight level wind was 83 m/s) yields much fewer data and similar ratios. Andrew's relatively fast motion (10 m/s) and limited azimuthal resolution in reconnaissance sampling (four azimuths) adds ~ 1.25 m/s of sampling representativeness uncertainty. If we use the reduction factors suggested by these data, Hurricane Andrew's maximum surface wind speed range may be reevaluated. A gust factor (1.06) should be applied to the GPS sonde adjustment resulting in a 67 m/s maximum sustained wind with a 14 % combined uncertainty. For the SFMR, the estimate of Andrews maximum sustained surface wind speed is also 67 m/s with a combined uncertainty of 7%. These values are close to the original estimates of Powell et al., 1996 and are more relevant to assessing the peak surface wind speed than the methods described by Landsea et al., 2004.

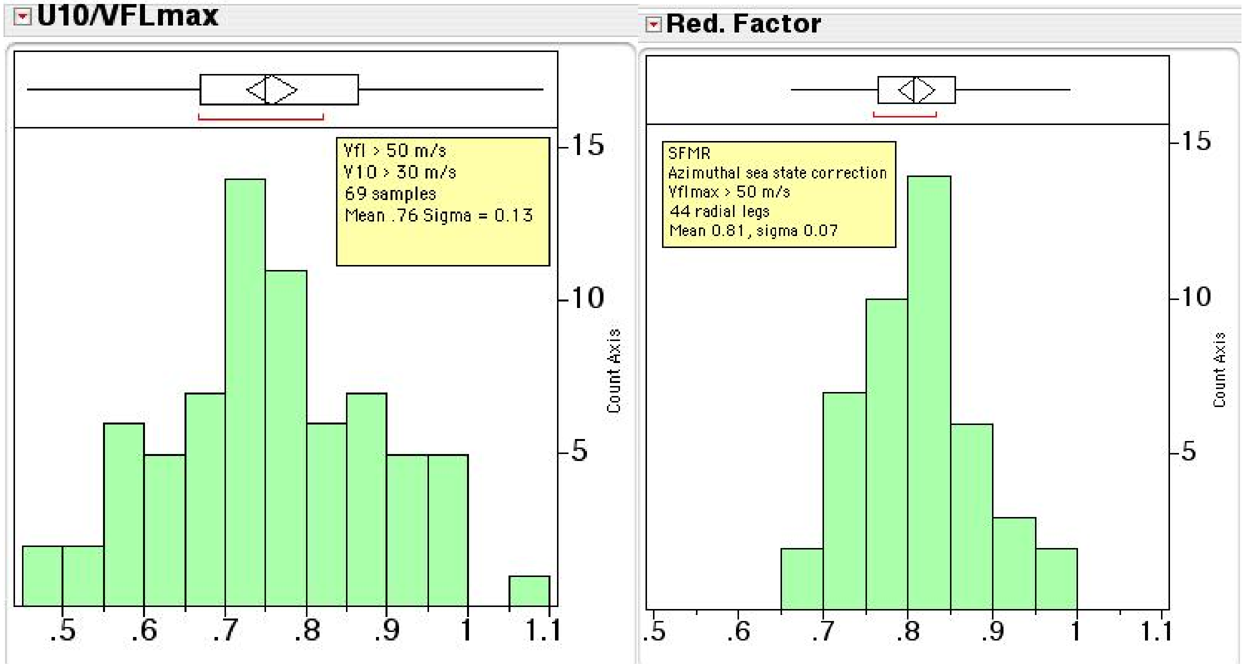

Fig. 12 Ratio of surface wind speed to the max flight level wind speed on the same radial leg of the flight pattern, for max flight level winds > 50 m/s. L) GPS sonde (69 radial flight legs) R) SFMR (44 radial flight legs).

Another factor to investigate is whether the reduction factor varies with azimuth. Franklin et al., 2003 noted that reduction factors were 4% higher on the left side of the eyewall than the right (looking in the direction of storm motion) but this variation was not incorporated in the the Landsea et al 2004 "reanalysis" of Hurricane Andrew. An examination of SFMR reduction factors (Fig. 13) shows a similar azimuthal relationship. A simulation of Andrew using Kepert's tropical cyclone boundary layer model (Kepert 2000, 2001, Kepert et al,. 2001) also suggests an azimuthal variation (Fig. 13) in reduction factor consistent with the highest values on the left side of the storm. If azimuthal variation were taken into account our wind estimate for Andrew would decrease since the peak flight level winds in Andrew were measured on the North (right) side of the storm.

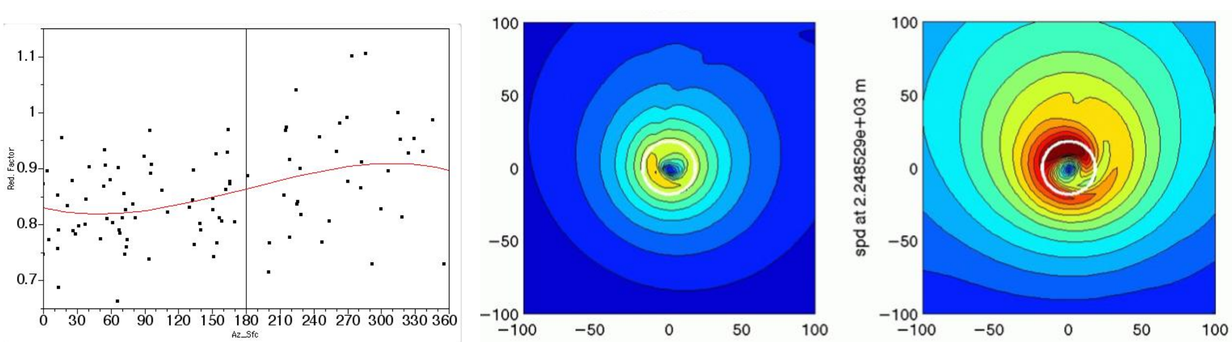

Fig. 13 L) Azimuthal variation of SFMR reduction factor (0 is front), Middle) Kepert model simulation of Andrew surface wind field, R) Kepert model 3 km level wind field.

One plausible reason for the overestimate of the 90% rule may have to do with the exposures of the GPS sonde surface wind measurements upon which it is based. As discussed in Powell et al (2003), nearly all the sondes were launched well offshore from coastal waters. The aerodynamic roughness of the sea in such conditions was shown to initially increase with wind speed until hurricane force and then decrease with further increases in wind speed. If open water roughness lengths were assumed for Fowey Rocks, the estimated winds at 10 m would increase from 108 to 120 kts (still 20 kts less than the 90% rule). The winds at Perrine would increase from 119 to ~150 kts if converted from open terrain to an open ocean roughness of 0.1 mm, about 8 kts greater than the 90% rule. These roughness length adjustments suggest that the 90% rule might be more appropriate in open ocean conditions than on the coast at landfall.

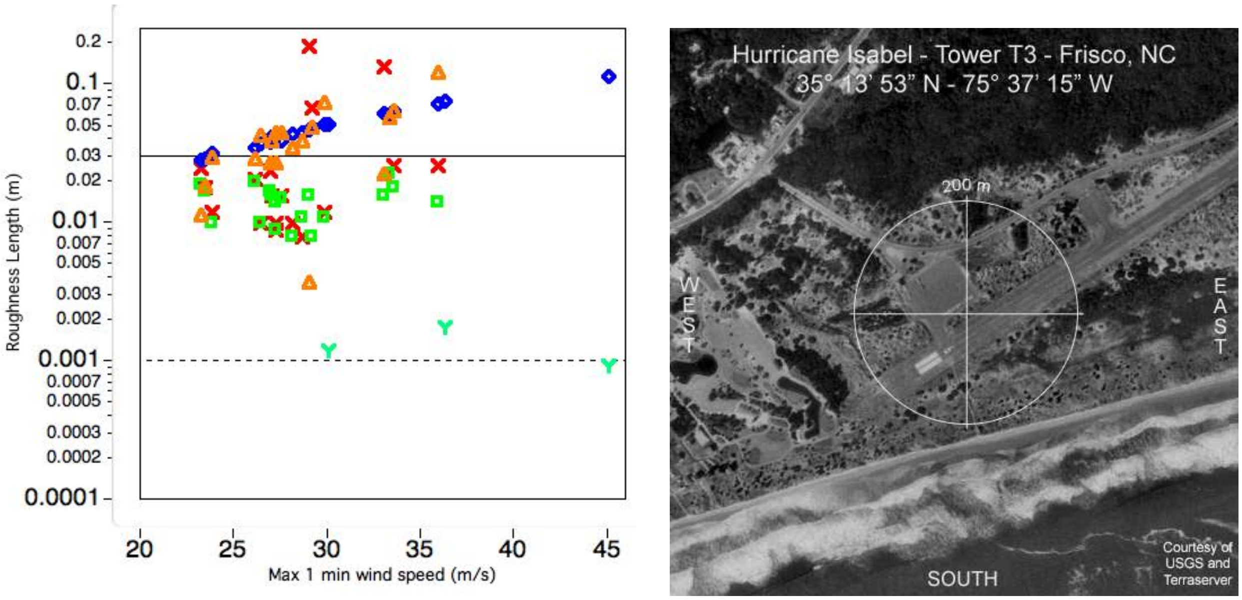

Figure 14. R) Dependence of coastal roughness on maximum 1 min sustained wind speed for onshore flow within 200 m of the shoreline (R). Measurements from Cape Hatteras in the eyewall of Hurricane Isabel, courtesy of the State of Florida Coastal Monitoring Program. Isabel measurements [29], from 5 m (squares), 10 m (x), profile method (triangles), Large and Pond's drag coefficient relationship (diamonds), and open ocean measurements (Y) from other hurricanes by Powell et al., 2003.

Unfortunately there are still too few GPS sonde wind profiles to construct mean wind speed vertical profiles near the coast. Additional surface layer turbulence associated with coastal wave breaking and shoaling conditions could be expected to contribute to larger roughness on the coast, but this has not yet been established. University teams have begun to collect detailed wind measurements from instrumented towers deployed ahead of hurricanes. A particularly interesting set of measurements was collected by Reinhold and Gurley (2003) as part of the FCMP (Fig. 14). Coastal roughness measurements within 200 m of the shore were recently obtained during the landfall of Hurricane Isabel at Cape Hatteras by the State of Florida Coastal Monitoring Program (Reinhold and Gurley)]. These unique measurements (Fig. 14) in onshore flow document roughness values generally more than an order of magnitude larger than open ocean roughness in similar wind speeds. Further measurements are needed to see if this behavior persists for winds greater than SS category one conditions, but these data suggest that coastal roughness is similar to open terrain conditions over land and much rougher (with weaker winds) than open ocean conditions. If this is validated by additional measurements in more extreme wind speeds, flight level reduction factors near the coast would need to be decreased. The GPS sonde- and SFMR-based reduction factors discussed above compared well with the original Andrew assessment of Powell et al., 1996 but that assessment was about 10% higher at the Fowey Rocks location, also suggesting that the reduction factors may need to be lower near the coast.

9. CONCLUSIONS

Uncertainty of wind measurements in hurricanes has been qualitatively assessed for a variety of observing platforms. Beside instrument accuracy, additional factors affecting uncertainty include corrections for height, averaging time, and exposure, as well as sufficient resolution to provide a representative estimate of the peak wind. Uncertainty of 5-14 % can be reached based on measurements from portable towers, SFMR, GPS sonde, C-MAN stations and moored buoys, or using revised reduction factors as discussed above.

In response to the challenges listed in section 1:

1) Hurricane wind observing platforms still suffer power and anemometer failures but over the last few years the WEMITE and FCMP programs have helped to document wind conditions in the absence of official reporting stations. In a time with increased need for vigilance and security, our national offshore, coastal, and inland observing network must be improved to be capable of withstanding and monitoring extreme events. A process has begun to attempt to improve the capabilities of the ASOS network, but C-MAN and moored buoys must also improve performance in extreme winds.

2) An unprecedented number of marine wind observations are available to help monitor wind conditions in hurricanes approaching land. Chief among these are the aircraft-based SFMR and GPS sonde, supplemented by NASA's QuikScat satellite and conventional moored buoys and C-MAN stations. Space-based microwave remote sensing continue to improve and it is probable that these platforms could begin to measure extreme winds after a few more years. For periods of 3-6 hours, storm-relative data coverage from current (figure 4) aircraft reconnaissance patterns are sufficient to resolve the peak wind in typical hurricanes moving at average speeds of 5 m/s. For faster moving hurricanes, reconnaissance patterns should evolve to provide increased azimuthal resolution. For small hurricanes, patterns should be enhanced to provide increased radial resolution of 0.5-1 km. These patterns would sacrifice outer wind field monitoring at the expense of more information on the structure of > 25 m/s winds. The extent of tropical storm force winds is less sensitive to rain contamination of remote sensors and could be resolved with further satellite and conventional observing platform coverage.

3) The process of assessing observation quality still depends on analyst experience in evaluating how various platforms perform relative to each other in a variety of environmental conditions. Advanced statistical methods used in data assimilation for mesoscale numerical weather prediction models may provide the promise of automated QC and objective analysis. Mesoscale models are beginning to simulate realistic hurricane features and hindcasts. The next generation numerical hurricane prediction models (such as the H-WRF) will be mesoscale and will require detailed evaluations against observed fields to assess model performance.

4) A variety of new wind products have been developed as experimental research products. Some of these will become operational for realtime disaster assessment and response, as well as guidance in the forecast and warning system, and input to storm surge and wave forecast models.

5) New information from GPS sondes and the SFMR were used to re-evaluate Hurricane Andrew's maximum sustained surface wind speed at landfall in South Florida. Reduction factors based on these data resulted in a maximum sustained surface wind speed 67 m/s, very similar to the original assessment of 66 m/s by Powell et al., 1996 with an uncertainty range of 7% (SFMR-based reduction factor) to 14%, (GPS sonde-based reduction factor) compared to the 75 m/s estimate (Landsea et al., 2004) that represented an uncertainty of 19%. Consideration of left-right asymmetries and the possibility of increased aerodynamic roughness near the coast would further decrease the winds 4-10%. While a SS category five storm is within the outer limit of the uncertainty, the observations and revised reduction factors point towards a SS Category four hurricane. The Coupled Boundary Layer Air Sea Transfer (CBLAST) experiment collected many additional high wind measurements from SFMR and GPS sondes during 2003 and 2004. We will examine these data to refine our investigation. The danger in any wind speed assessment based on limited

information is that subsequent research findings will disprove the evaluation. We believe that our reassessment of Hurricane Andrew has re-established the original wind speed estimate as a Category four storm. Any reexamination of significant "storm of the centery" historical hurricanes needs to carefully evaluate all existing surface observations compared to any new method, following well established methods to consider height, averaging time, and exposure effects. Furthermore, such reexaminations should be conducted in an open forum by an independent group of scientists and engineers from a variety of academic, federal, and private sector organizations representing expertise in micro- and tropical meteorology, physical oceanography, atmospheric turbulence, and civil, coastal, and structural engineering.

REFERENCES

Barth, M.F., P.A. Miller, and A.E. MacDonald, 2002: MADIS: Providing Value-Added Observations to the Meteorological Community. FSL Forum, June, 2002.

Black, P. G., and F. D. Marks, 1991: The structure of an eyewall mesovortex in Hurricane Hugo (1989). 19th AMS Conference on Hurricanes and Tropical Meteorology, May 6-10, Miami, 579-582.

Bourassa, M. A., D. M. Legler, J. J. O'Brien, and S. R. Smith, 2003: SeaWinds Validation with Research Vessels, J. Geophys. Res., 108, DOI 10.1029/2001JC001081.

Cardone, V. J., J. Greenwood, and M. Cane, 1990: On trends in historical marine wind data, J. Climate, 3, 113-127.

Connor, L. N, Paul S. Chang, 2004 Determination of ocean surface wind speeds from the TRMM Microwave Imager. In Review, IEEE Transactions on Geoscience and Remote Sensing

Demuth, J. L., M. DeMaria, J. Knaff, and T. H. Vonder Harr, 2004: Evaluation of Advanced Microwave Sounding Unit Tropical-Cyclone Intensity and Size Estimation Algorithms, J. Appl. Meteor., 43, 282-296.

Dodge, P., R. W. Burpee, and F. D. Marks, 1991: Airborne Doppler radar analyses of the core of Hurricane Gilbert. 19th AMS Conference on Hurricanes and Tropical Meteorology, May 6-10, Miami, 551-552.

Dunion, J. P., C. W. Landsea, S. H. Houston, and M. D. Powell, 2003: A reanalysis of the surface winds for Hurricane Donnna of 1960. Mon. Wea. Rev., 131, 1992–2001.

Dunion, J.P., S.H. Houston, C.S. Velden, and M.D. Powell, 2002: Application of surface-adjusted GOES low-level cloud-drift winds in the environment of Atlantic tropical cyclones. Part II: Integration into surface wind analyses. Mon. Wea. Rev., 130, 1347-1355.

Editors, 1974: The hurricane disaster potential scale. Weatherwise, 27, 169, 186.

Foster, R., and coauthors, 2004: Observational and theoretical evidence for roll vortices in the hurricane boundary layer. 13th AMS Conference on Interactions of the sea and atmosphere, Portland, ME.

Franklin, J. L., S. J. Lord, S. Feuer, and F. D. Marks, Jr., 1993: The kinematic structure of Hurricane Gloria (1985) determined from dropwindsonde and Doppler radar data. Mon. Wea. Rev., 121, 2433-2451.

Franklin, J. L., M. L. Black, and K. Valde, 2003: GPS dropwindsonde wind profiles in hurricanes and their operational implications. Wea. Forecasting, 18, 32– 44.

Gamache, J.F., F.D. Marks, and F. Roux, 1995: Comparison of three airborne Doppler sampling techniques with airborne in situ wind observations in Hurricane Gustav (1990). J. Atmos. and Ocean. Tech., 12, 171-181.

Gilhousen, D.B., 1987: A field evaluation of NDBC moored buoy winds. J. Atmos. Oceanic Technol., 4, 94-104.

Goodberlet, M. A., C. T. Swift, and J. C. Wilkerson, 1989: Remote sensing of ocean surface winds with the Special Sensor Microwave/Imager, J. Geophys. Res., 94, 14,547- 14,555.

Hawkins, H.F. and S. M. Imbembo, 1976: The structure of a small, intense, hurricane-- Inez 1966. *Mon. Wea. Rev*., **104**, 418-442.

Hervey, R., 1999: Are moored buoy winds too low in high seas? Preprints Third Conf. on Coastal Atmos. and Oceanic Prediction and Processes, New Orleans, LA, Amer. Meteor. Soc.

Hock, T. R., and J. L. Franklin, 1999: The NCAR GPS dropwindsonde. Bull. Amer. Meteor. Soc., 80, 407–420.

Horstman J., W. Koch, and S. Lehner, Ocean Wind Fields Retrieved from the Advanced Synthetic Aperture Radar Aboard ENVISAT, Ocean Dynamics, in press 2004.

Houston, S. H., P. P. Dodge, M. D. Powell, M. L. Black, G. M. Barnes, and P. S. Chu, 2000: Surface winds in hurricanes from GPS-sondes: Comparisons with observations. Preprints, 24th Conf. on Hurricanes and Tropical Meteorology, Ft. Lauderdale, FL, Amer. Meteor. Soc., 339.

Jorgensen, D. P., 1984: Mesoscale and convective scale characteristics of mature hurricanes. II: Inner core structure of Hurricane Allen (1980), *J. Atmos. Sci*., **41**, 1287-1311.

Kaplan, J. and M. DeMaria, 1995: A simple empirical model for predicting the decay of tropical cyclone winds after landfall. J. App. Meteor., 34

Kepert, J.D., 2001: The dynamics of boundary layer jets within the tropical cyclone core. Part I: Linear theory. J. Atmos. Sci., 58, 2469-2484.

Kepert, J.D. and Y. Wang, 2001: The dynamics of boundary layer jets within the tropical cyclone core. Part II: Nonlinear enhancement. J. Atmos. Sci., 58, 2485-2501.

Kepert, J.D., 2002: The impact of landfall on tropical cyclone boundary layer winds. Extended abstracts, 25 th Conference on Hurricanes and Tropical Meteorology, Amer. Meteor. Soc., San Diego, California, 29 April - 3 May, 2002, 335-336.

Kossin, J. P., and C. S. Velden, 2003: Tropical cyclone intensity estimates using geostationary satellite infrared imagery. Proc. 57th Interdepartmental Hurricane Conference, Miami, FL,

Landsea and coauthors, 2004: A reanalysis of Hurricane Andrew's uncertainty. Bull. Amer. Meteorological Society, 85, 1699-1712.

Large, W. G., Morzel, J., Crawford, G. B. Accounting for surface wave distortion of the marine wind profile in low-level ocean storms wind measurements. J. Phys. Oceanogr 1995 vol. 25, page 2959

Lee, W.-C., B. J.-D. Jou, P.-L. Chang, and S.-M, Deng, 1999: Tropical cyclone kinematic structure retrieved from single Doppler radar observations. Part I. Interpretation of Doppler velocity patterns and the GBVTD technique. Mon. Wea. Rev., 127, 2419-2439.

Liu, K. S. , and J. C. L. Chan, 1999: Size of tropical cyclones as inferred from ERS-1 and ERS-2 data. Mon. Wea. Rev., 127, 2992-3001.

Lororso, S., and J. L. Schroeder, 2004, Hurricane boundary layer rolls observed during the landfall of Hurricane Isabel, 26th AMS Conference on Hurricanes and Tropical Meteorology, Miami.

Marks, F.D., R.A. Houze, and J.F. Gamache, 1992: Dual-Aircraft investigation of the inner core of Hurricane Norbert: Part I: Kinematic structure. J. Atmos. Sci., 49, 919-942.

Powell, M. D., 1980: Evaluations of diagnostic marine boundary layer models applied to hurricanes. Mon. Wea. Rev., 108, 757–766.

Powell, M. D., 1987: Changes in the low-level kinematic and thermodynamic structure of Hurricane Alicia (1983) at landfall. Mon. Weather Rev., 115 (1), 75-99.

Powell, M. D., and P. G. Black, 1990: The relationship of hurricane reconnaissance flight-level measurements to winds measured by NOAA's oceanic platforms. J. Wind Eng. Ind. Aerodyn., 36, 381–392.

Powell, M. D., P. P. Dodge, and M. L. Black, 1991: The landfall of Hurricane Hugo in the Carolinas: Surface wind distribution. Wea. Forecasting, 6, 379–399.

Powell, M. D., 1993: Wind measurement and archival under the automated surface observing system (ASOS): User concerns and opportunity for improvement. Bull. Amer. Met. Soc., 74(4), 615-623.

Powell, M. D., S. H. Houston, and T. A. Reinhold, 1996: Hurricane Andrew's landfall in South Florida. Part I: Standardizing measurements for documentation of surface wind fields. Wea. Forecasting, 11, 304–328.

Powell, M. D., and S. H. Houston, 1996: Hurricane Andrew's landfall in South Florida. Part II: Surface wind fields and potential real-time applications. Wea. Forecasting, 11, 329–349.

Powell, M. D., S. H. Houston, L. R. Amat, and N. Morisseau-Leroy, 1998: The HRD real-time surface wind analysis system. J. Wind Eng. Indust. Aerodyn., 77–78, 53–64.

Powell, M. D.,T. A. Reinhold, and R. D. Marshall, 1999: GPS sonde insights on boundary layer wind structure in hurricanes. Wind Engineering intothe 21st Century, Larsen, Larose, and Livesey (eds), Balkema, Rotterdam, ISBN 90 5809 059 0

Powell, M. D, P. J. Vickery, and T. A. Reinhold, 2003: Reduced drag-coefficient for high wind speeds in tropical cyclones. Nature, 422, 279–283.

Powell, M.D., D. Bowman, D. Gilhousen, S. Murillo, N. Carrasco, and R. St. Fleur, 2004: Tropical Cyclone Winds at Landfall: The ASOS-CMAN Wind Exposure Documentation Project. Bull. Amer. Met. Soc., 85, 845-851.

Quilfen, Y., B. Chapron, and D. Vandemark, 2001: The ERS Scatterometer Wind Measurement Accuracy: Evidence of Seasonal and Regional Biases, J. Atmos. and Ocean. Tech., 18, 1684-1697.

Rappaport, E. N., 1994: Hurricane Andrew. Weather, 49, 51–61.

Ulhorn, E. W., and P. G. Black, 2003: Verification of remotely sensed sea surface winds in hurricanes. J. Atmos. Oceanic Technol., 20, 99–116.

Vagle, S., W.G. Large, and D.M. Farmer, 1990: An evaluation of the WOTAN technique of inferring oceanic winds from underwater ambient sound, J. Atmos. Ocean. Tech., 7, 576-595.

Vickery, P. J. & Skerlj, P. F. Elimination of exposure D along the hurricane coastline in ASCE 7. J. Structural Engrg., 126, 545-549 (2000).

Vickery, P. J. and P. F. Skerlj, 2005: Hurricane gust factors revisited. In press, Journal of Structural Engineering.

TPC, 2003: Best track Committee Charter.

Yueh, S. H., B. Stiles, and W. T. Liu, 2003: QuikSCAT Wind Retrievals for Tropical Cyclones, IEEE Trans. Geoscience and remopte sensing, 41, 2616-2628.

Wurman and Winslow, Intense Sub-Kilometer-Scale Boundary Layer Rolls Observed in Hurricane Fran, Science 1998 280: 555-557