TROPICAL CYCLONE WINDS AT LANDFALL

The ASOS–C-MAN Wind Exposure Documentation Project

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A project to photographically document exposures of automatic weather stations in areas susceptible to tropical cyclones will allow correction of underestimated winds.

Hurricane Andrew taught us that nearby trees, buildings, and other obstacles to the wind can cause large differences (as much as a factor of 2) in the winds experienced at observing stations (Powell et al. 1996). During a storm event these effects add variability to the wind field, making it difficult to construct a meaningful real-time analysis. In addition, some wind features associated with terrain effects might be misinterpreted as being associated with mesoscale or convective-scale weather features. Reconstruction of landfalling hurricane wind fields typically require field visits to photographically document weather station wind exposure. The visits and analysis of the images add months to retrospective analysis efforts, and after major disasters many field investigation teams will be duplicating efforts to obtain exposure information. This paper describes a program to document wind exposures of automatic weather stations in areas susceptible to hurricanes. The documentation method and sources of information are described, followed by a description of where to obtain the information and how it is used in real time to construct a wind analysis depicting hurricane winds over open terrain.

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DOI: 10.1175/BAMS-85-6-845

In final form 24 February 2004

WIND EXPOSURE DOCUMENTATION. The modernization of the National Weather Service resulted in a replacement of human observers and traditional weather stations with an Automated Surface Observing System (ASOS). ASOS stations are the backbone of the nation's surface weather information and are typically located at airports. In addition, there are several weather stations dedicated to supporting the marine community that comprise the Coastal-Marine Automated Network (C-MAN). Although efforts are made to minimize the effect of obstructions on the exposure of automatic weather stations, (e.g., OFCM 1994), it is not always possible to optimally site weather instrumentation. Wind exposures may be poor for certain directions due to operational limitations on where equipment may be installed, as well as encroachment by vegetation and development.

Surface winds may be adjusted for the influence of surrounding flow obstacles if exposure is documented. Such documentation and the need for a standard method to measure and archive surface wind was suggested at the 1991 Interdepartmental Hurricane Conference organized by the Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM; see OFCM 1991) and discussed in Powell (1993). A resulting workshop led to the development by the American Society for Testing and Materials (ASTM) of a "Standard Practice for Characterizing Surface Wind Using a Wind Vane and Rotating Anemometer" (ASTM 1996). This standard includes instructions for documenting wind exposure at a weather station.

With photographic documentation of wind exposure, aerodynamic roughness may be estimated by applying descriptive qualifiers (Wieringa 1993; Arya 1988). Aerodynamic roughness is a length scale associated with the size of turbulent eddies near the surface (Panofsky and Dutton 1984). Ideally all wind sensors should be placed in open terrain to avoid influence from upstream obstacles to the flow. Wieringa describes open terrain (0.03-m roughness) as "level country with low vegetation and isolated obstacles with separations of at least 50 obstacle heights," for example, an airport runway. Very rough terrain (0.5-m roughness) is described as "large farms, clumps of forest, separated by open spaces of about 10 obstacle heights . . . or low-large vegetation with small inter spaces, such as orchards, young densely planted forest." Once roughness values are assigned to exposure photographs, the winds may be corrected to open terrain by using empirical techniques such as described by Simiu and Scanlan (1996) and Powell et al. (1996).

Several field visits to document surface stations in support of retrospective analysis of hurricane landfalls (e.g., Powell et al. 1996, 1998) motivated us to develop a project to document many of the automated surface weather stations in areas of the United States and territories susceptible to hurricanes.

The wind exposure documentation project is a cooperative program supported by the United States Weather Research Program (USWRP), and involving several National Oceanic and Atmospheric Administration (NOAA) agencies, including the National Weather Service (NWS), National Climatic Data Center (NCDC), National Data Buoy Center (NDBC), and the Hurricane Research Division (HRD) of the Atlantic Oceanographic and Meteorological Laboratories (AOML). Digital cameras were purchased and distributed to 36 NWS forecast offices in areas susceptible to hurricanes. Data Acquisition Program Managers (DAPMs) and their staff visited stations (Fig. 1) during normal maintenance visits to take photographs, validate anemometer height, station location, and the availability of backup power in the event of power failures. Wind exposure of ASOS weather stations was documented by photographing anemometer masts and the upstream terrain for eight wind direction sectors. In addition, the NDBC added photographic documentation to their Web site for selected C-MAN stations. Instructions for conducting the site documentation were placed on the HRD Web site (see www.aoml.noaa.gov/hrd/asos), and a Java applet was developed to assist with packaging the images and documentation and sending the information to the NCDC via FTP. NCDC then added the documentation information to their station locator Web site (see www.ncdc.noaa.gov/oa/climate/stationlocator.html).

At the time of writing, 211 ASOS stations and 30 C-MAN stations have been photographically documented (Fig. 2). In addition to providing information on wind exposure, the photos allow NCDC to document types of temperature and precipitation sensors at each station. Operational forecasters may also benefit from the wind exposure documentation as it is sometimes difficult for forecasters to be familiar with the surroundings of ASOS and C-MAN stations they work with and validate against, within their county warning areas. The ASOS exposure documentation photos and other information could be linked to the local NWS Forecast Office Web page. If a forecaster sees

Fig. 1. Documentation of Opa Locka Airport (near Miami) by DAPM Suzanne Cawn.

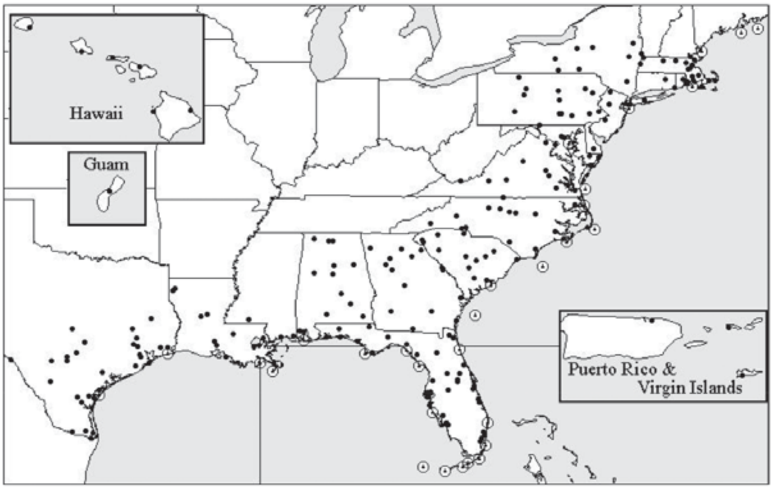

Fig. 2. Map showing locations of ASOS (filled circles) and C-MAN stations (open circles) for which exposure photographs are available.

something unusual in the observations, a mouse click could bring up the station's Web page to see if there are any obstacles affecting the wind from that direction.

CORRECTING WIND MEASUREMENTS TO STANDARD EXPOSURE.

During hurricane landfall, HRD uses estimates of roughness from each photograph to automatically correct wind observations to open terrain to better define the surface wind field. Using the Wieringa descriptors and the photographs, we developed a table of roughness lengths (see www.aoml.noaa.gov/hrd/asos/AsosRoughness.html) for each station as a function of upstream direction octant. Alternatively, a roughness estimation method developed by Lettau (1969) could be used. Note that assessment of roughness values in the field is very much an art, and estimates by experienced investigators may differ by tenths of a meter. We encourage users of the wind data from these sites to independently estimate alternative roughness values from the photographs and Wieringa descriptors. If possible, users should examine additional information (e.g., aerial imagery and topographic maps) to determine whether bodies of water or flow obstacles exist further upstream than what is shown in the Web page photographs.

The standard terrain for wind observation over land is known as "open terrain" and is associated with a roughness of 0.03 m. Open terrain is equivalent to the middle of an airport runway with unlimited upstream fetch and is consistent with the concept of "unobstructed exposure" used in the definition of the "maximum sustained wind" used in the National Hurricane Operations Plan (OFCM 2003). Unobstructed flow over the sea may be associated with roughness values typically smoother than open terrain over land, but ocean roughness depends on additional factors such as fetch, water depth, relative swell, and wind-wave directions (Anctil and Donelan et al. 1996; Donelan et al. 1993; Powell et al. 2003). For engineering applications concerning the design of buildings to resist wind loading, open terrain (Exposure C) is used in areas susceptible to hurricanes [American Society of Civil Engineers (ASCE) 2002; Vickery and Skerlj 2000]. The open-terrain wind should be considered as an upper bound to the sustained wind. Areas with uniformly rough terrain would experience weaker winds but any structures adjacent to open upstream fetches would be susceptible to wind damage.

The process of correcting a wind observation to a standard exposure has three steps.

1) Estimate the friction velocity for the given wind direction. For horizontally homogeneous, stationary flow with winds > 10 m s^{-1}, neutral atmospheric stability is assumed and the logarithmic wind law can be applied to estimate the friction velocity (u_*), given the mean wind speed (U), von Kármán constant ($k = 0.4$), height of the measurement (z), and the roughness length (Z_o):

$$u_* = \frac{Uk}{\ln\left(\frac{z}{z_o}\right)}. \quad (1)$$

For example, a mean wind measurement of 30 m s^{-1} at a height of 10 m from a wind direction sector with a 0.20-m roughness in (1) yields a friction velocity of 3.06 m s^{-1}.

2) The method described in Powell et al. (1996) and Simiu and Scanlan (1996) describes the ratio of the measured friction velocity (u_*) for the actual upstream terrain roughness (Z_o) to the friction velocity (u_{*s}) that might occur in standard open-terrain (Z_{os}) roughness (0.03 m):

$$\frac{u_{*s}}{u_*} = \left(\frac{z_{os}}{z_o}\right)^{0.0706}. \quad (2)$$

Insertion of the result of step (1) into (2) results in a u_{*s} of 2.67 m s^{-1}.

3) Given u_{*s} and Z_{os}, (1) may be solved, resulting in an open-terrain, mean wind speed of 39 m s^{-1}. If independent estimates of the roughness ranged from 0.1–0.3 m, the open-terrain wind speed estimate would range from 35–42 m s^{-1}. This exercise demonstrates that mean wind measurements associated with significant upstream terrain may underestimate the open-terrain wind by ~30%, whereas wind speed error due to inaccurately estimating the terrain roughness is ~10%. This method works best in relatively flat coastal regions; for flow associated with complex terrain (hills and valleys), local accelerations dominate the wind such that (1) and (2) are not valid. Miller and Davenport (1998) provide guidelines for such situations. It should be stressed that mean wind in (1) should be averaged on the order of at least 10 min. Continuous C-MAN measurements meet this requirement but high-resolution data are needed to compute the mean ASOS wind speed. This method prescribes that the flow is strong (> 10 m s^{-1}) for the neutral stability assumption to apply; it should not be used in stable or unstable conditions in weak flow. The method also assumes that the surface layer is in equilibrium with the upstream roughness elements. More sophisticated correction measures (e.g., Letchford et al. 2003) should be applied in locations characterized by an intervening open area (of order hundreds of meters) between the wind sensor and larger roughness elements (trees). Flow equilibrium is not completely reached under such conditions so corrections based on the rougher surface could overestimate the open-terrain wind.

During tropical cyclone episodes, HRD conducts "on the fly" corrections of automatic weather station wind observations. The corrected observations are combined with observations from other platforms using the HRD Real-Time Hurricane Wind Analysis System (H*Wind; Powell et al. 1998). H*Wind is a Java front end to an object-relational database containing all available surface wind observations surrounding a tropical cyclone. H*Wind is designed to allow a forecaster to quality control observations and conduct a real-time objective analysis of the surface wind field to provide guidance for determining the extent of tropical storm– and hurricane-force winds (see www.aoml.noaa.gov/hrd/data_sub/wind.html). Converting observations to open terrain reduces the variance of the wind field resulting in an objective analysis that better represents the mesoscale features of the storm. This type of analysis is also consistent with the wind-loading provisions in building codes, making it easier to convert maximum sustained winds to peak gusts to see if the design winds in an area were exceeded. For open-terrain winds, multiplying the sustained wind by a gust factor of 1.25–1.3 will yield an estimate of the peak 2–3-s gust within the 1-min period (Powell et al. 1996; B. Paulsen 2004, personal communication). For rough flow, the sustained wind will be weaker but the gust factor will be larger (Paulsen et al. 2003) such that peak gusts might be similar to those experienced over open terrain. For more information on gust factors in hurricanes we suggest Krayer and Marshall (1992), Vickery and Skerlj (2004), and Powell et al. (1996).

WHAT ABOUT WIND GUSTS?

Efforts over the past several years by university teams from Texas Tech, Clemson, and University of Florida, as well as post-landfall investigations by NOAA's Hurricane Research Division, the National Institute for Standards and Technology, and others are shedding light on hurricane wind gusts. The wind gust may be estimated by multiplying the mean wind over a given time period by an appropriate gust factor. For open-terrain conditions over level, relatively flat land, the peak 2-s wind gust that might be expected is about 1.3 times the peak 1-min sustained wind and 1.55 times the 10-min mean wind. In general, the rougher the terrain, the lower the sustained wind and the larger the gust factor. The data collected by anemometer towers thus far suggest that the physical mechanisms for wind gusts in hurricanes are primarily turbulent and convective mixing. Evidence of more extreme gusts, with peak 2-s gusts > 2.0 times the mean wind, are very rare in eyewall anemometer records. Photographs of debris patterns and hurricane damage to forests provide evidence of extreme gusts associated with transient wind features such as the miniswirls and microbursts but so far none have been documented with accompanying anemometer records. NOAA buoy and C-MAN data suggest that marine gust factors are smaller, on the order of 1.13 for the peak 5-s wind over a 1-min period, and 1.25 for the peak 5-s wind over a 10-min period. Open ocean GPS sonde data from hurricane eyewalls are consistent with the latter value, but the sondes may not be capable of resolving short-period gusts.

Several photographs from the NCDC and the NDBC Web sites are shown in Fig. 3 as examples of exposure conditions at some of the automatic weather station sites in hurricane-affected areas. Roughness is estimated for each exposure and identified in the figure caption. Assuming that hurricane wind condi-

a)

b)

c)

d)

e)

Fig. 3. Photo documentation of selected ASOS and C-MAN stations with estimates of exposure effects on an open-terrain, hurricane-force mean wind speed of 33.0 m s^{-1}. Digital photos for ASOS stations were field annotated with station ID and compass heading. (a) Rough terrain (~0.4 m roughness) exposure at Chatham, MA (CQX), looking north; estimated wind speed measurement for this exposure, 22.0 m s^{-1}. (b) Open-terrain exposure (~0.03-m roughness) from Panama City, FL (PFN), looking northeast; estimated wind speed measurement for this exposure, 33.0 m s^{-1}. (c) Moderately rough terrain exposure (~0.3-m roughness) from Panama City, FL (PFN), looking southwest; estimated wind speed measurement for this exposure, 23.4 m s^{-1}. (d) Rough exposure (~0.4-m roughness) from Settlement Point, Grand Bahamas C-MAN station (SPGF1), looking south from anemometer; estimated wind speed measurement for this exposure, 22.0 m s^{-1}. (e) Rough exposure (~0.6-m roughness) from Wakefield, VA (AKQ), looking south; estimated wind speed measurement for this exposure, 19.7 m s^{-1}.

Fig. 4. Assessing roughness is not valid in locations where upstream fetches are influenced by complex terrain, for example, northward-looking fetch from the St. Thomas, U.S. Virgin Islands ASOS (KSTT).

tions (33.0 m s^{-1}) might be experienced nearby in locations with open exposure, we used (1) and (2) to estimate what the instruments might measure in their actual exposures. The effect of the rougher exposures is to underestimate the unobstructed flow conditions by 30%–40%, hence it is important to correct poorly exposed measurements. It is important to note that the roughness assessments and correction methods described herein are not valid for upstream fetches influenced by complex terrain (Fig. 4), where the measurements are affected by local flow accelerations associated with hills and valleys (Miller and Davenport 1998; Powell and Houston 1998).

SUMMARY. Documentation of wind exposure, anemometer height, and station location for over 200 automatic weather stations in hurricane-susceptible areas has been accomplished through a cooperative program between NOAA's Hurricane Research Division, the National Weather Service Forecast Offices, the National Data Buoy Center, and the National Climatic Data Center. The information is available to the public through Web sites at NCDC (see www.ncdc.noaa.gov/oa/climate/stationlocator.html) and NDBC (www.ndbc.noaa.gov). There are additional automatic weather stations in hurricane areas that could be added to those displayed on the NCDC Web site by following documentation instructions (available online at www.aoml.noaa.gov/hrd/asos). A table with estimated roughness lengths for each octant of wind direction for all documented stations in hurricane-prone areas is also available on the HRD ASOS Web site. The table is used to correct wind observations to open terrain for use in real-time analyses of hurricane wind fields.

ACKNOWLEDGMENTS. The late Anne Lazar-Viront of NCDC and late Dr. Richard Marshall of the National Institute of Standards and Technology made significant contributions to the planning stages of this project. The support of Suzanne Cawn, Rainer Dombrowsky, Mac Mclaughlin, John McNulty, Steve Rinard, Al Wissman, and Lou Uccellini, all of the NWS, and Ned Guttman of NCDC is greatly appreciated. The project could not have succeeded without the dedication and professionalism of the DAPMs of the Southern, Eastern, and Pacific Regions of the NWS. This project was funded by the United States Weather Research Program Severe Weather Prediction Initiative.

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