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Hurricane Katrina Winds Measured by a Buoy-Mounted Sonic Anemometer

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ABSTRACT

The eye of Hurricane Katrina passed within 49 n mi of an oceanographic observing system buoy in the Mississippi Bight that is part of the Central Gulf of Mexico Ocean Observing System. Although a mechanical anemometer failed on the buoy during the hurricane, a two-axis sonic anemometer survived and provided a complete record of the hurricane's passage. This is the first reported case of a sonic anemometer surviving a hurricane and reporting validated data, and it demonstrates that this type of anemometer is a viable alternative to the mechanical anemometers traditionally used in marine applications. The buoy pitch and roll record during the storm show the importance of compensating the anemometer records for winds oblique to the horizontal plane of the anemometers. This is made apparent in the comparison between the two wind records from the anemometers during the hurricane.

1. Introduction

On 14 December 2004, the University of Southern Mississippi (USM) had a 3-m discus buoy deployed in the Mississippi Bight at 30°02′32.710″N, 88°38′50.235″W (Fig. 1) near the 20-m isobath. Originally funded for research to extend the range that Real-Time-Kinematic (RTK) GPS could be used in the marine environment (Howden et al. 2004), the buoy (USM3m01) has also served as an initial observing element in the Central Gulf of Mexico Ocean Observing System (CenGOOS; www.cengoos.org). CenGOOS is part of the Gulf of Mexico Ocean Observing System Regional Association (GCOOS-RA), which is part of the Integrated Ocean Observing System (see, e.g., Malone 2003). The buoy was outfitted with a survey-grade GPS receiver and a suite of instruments to monitor the local meteorological conditions and the oceanographic parameters that affect sea level. The instrument suite is shown in Table 1. The design, fabrication, and integration of the buoy system were done by the Geochemical and Environmental Group (GERG) at Texas A&M University that operates the Texas Automated Buoy System (TABS; Guinasso et al. 2001). To ensure redundant measurements of vector winds and to test the operation of the newer acoustic anemometer designs, both an R. M. Young 5106 and a two-axis Gill Wind-

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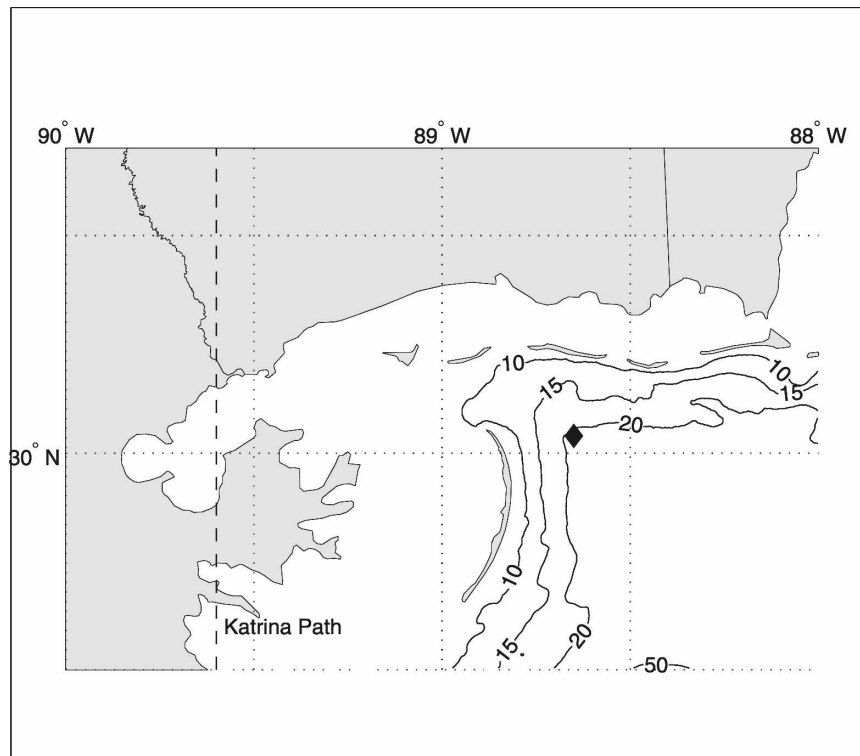E-mail: stephan.howden@usm.edu

FIG. 1. Buoy USM3m01 is shown with the diamond. The dashed line is the path of the center of the eye of Hurricane Katrina.

Sonic anemometer were installed on the buoy. Table 2 lists the specifications for the anemometers.

Mechanical anemometers—such as the R. M. Young 5106—have been the standard for marine applications. The NOAA/National Data Buoy Center (NDBC) has primarily used this type of anemometer for measuring winds. However, mechanical anemometers can be vulnerable to mechanical failure at wind speeds above 60

TABLE 1. Instrument suite on buoy USM3m01. The barometric pressure and humidity sensors failed before Hurricane Katrina.

Instrument grouping	Description	Manufacturer	Model
Meteorological package	Anemometer	R. M. Young	5106
	Compass for anemometer	R. M. Young	32500
	Anemometer	Gill	WindSonic
	Barometer	Vaisala	PTB210
	Temperature/humidity	Rotronic	MP101
Oceanography package	Doppler current meter	Aanderaa	973900R
	Conductivity/temperature	SeaBird	SBE37SMP
	ADCP	RD Instruments	WH600–1
	Nitrate sensor	Satlantic	MBARI ISUS
	Fluorometer	Wetlabs	FLNTUS
Motion sensors	GPS receiver	Novatel	OEM4-G2
	3-axis magnetometer	Honeywell	HMR3300
	Pressure sensor (on SBE37)	SeaBird (Druck)	37
	3-axis IMU	Crossbow	IMU400-CC
Communications	Wireless network card	LinkSYS	
	GlobalStar satellite modem	Motorola	GSP-1620
	Surface acoustic modem	Linkquest	UWM2000
	Service ARGOS transmitter	Seimac	Wildcat PTT

TABLE 2. Specifications, sampling rate, and averaging period of the anemometers.

Manufacturer	Gill Instruments Limited	R. M. Young
Model	WindSonic	5106
Type	Sonic	Helicoid propellor
Communications	RS-232	
Sampling rate	4 Hz	2 Hz
Compass	Honeywell HMR3300	R.M. Young 32500
Wind speed		
Range	0–60 m s^{-1}	0–100 m s^{-1}
Accuracy	±3% @ 20 m s^{-1}	±0.3 m s^{-1}
Resolution	0.01 m s^{-1}	0.1 m s^{-1}
Distance constant	N/A	2.7 m
Wind direction		
Range	0°–359°	0°–359°
Accuracy	±3° @ 20 m s^{-1}	0.9°
Resolution	1°	0.5°
Averaging period	10 min	10 min
Damping ratio	N/A	0.25
Delay distance	N/A	1.3 m

mph (26.8 m s^{-1}; Thoren 2001). The result can be a loss of valuable data when major storms such as hurricanes pass over the buoys, though the track record for these anemometers is good except for buoy capsizing events. At higher latitudes, icing can become a problem with unheated R. M. Young 5106 anemometers, and thus the sonic anemometers may be a good alternative.

On 29 August 2005 the center of the eye of Hurricane Katrina passed approximately 49 n mi to the west of USM3m01 (Fig. 1). During the storm, the R. M. Young anemometer failed at winds of about 20 m s^{-1}, but the Gill WindSonic continued to operate and provided a data record that was used to help reconstruct the hurricane's wind field (Powell et al. 2006). The data were posted on the NDBC Web site in real time until the power failed at the Stennis Space Center in Mississippi. The buoy continued to collect data, which were later retrieved by TABS servers. The rest of this paper describes the anemometer setup, compares the performance of the two anemometers during the deployment and through the storm (until the failure of the R. M. Young), presents the WindSonic data through the entire storm, and presents the poststorm calibration of the WindSonic. Ancillary measurements from the buoy are used to show the importance of correcting winds for buoy tilt during strong events. A more comprehensive article of Hurricane Katrina is in preparation.

Anemometer setup

Prior to installation of the anemometers, the instruments were calibrated in a wind tunnel at NDBC, located at the Stennis Space Center. The detailed calibration results are shown in the appendix. The Gill WindSonic anemometer read low by an average of 3%. The wind direction was off by less than 0.5° from average. The R. M. Young had a speed error of less than 0.5% on average and a direction error of less than 0.3°. The results of these tests showed that both instruments are capable of accuracies within WMO (1996) guidelines (wind speed accurate to 0.5 m s^{-1} for speeds <5 m s^{-1} and accurate to less than 10% of greater wind speeds, and wind direction accurate to 5°), though clearly the R. M. Young gave more accurate readings.

Both anemometers were mounted on masts at a height of 5 m [a standard height for moored buoys; WMO (1996)] above the nominal buoy water line (Fig. 2). Both anemometer masts are nearly equidistant from the center of the buoy hull, with the mast for the R. M. Young mounted at an angle of 150° from buoy north and the mast for the WindSonic mounted at an angle of 270° from buoy north. Winds flowing from 120° relative to buoy north flow past the R. M. Young before reaching the WindSonic, and winds flowing from 210° relative to buoy north flow past the WindSonic before reaching the R. M. Young.

The R. M. Young is essentially a wind vane with a propeller. Wind speed is measured via the helicoid propeller, and a compass (R. M. Young 32500) measures wind direction as the unit turns into the wind. The ultrasonic WindSonic anemometer (manufactured by Gill Instruments Limited) measures two orthogonal components of the wind acoustically. This sensor was aligned with the "north" line of the buoy by means of a laser plumb bob and a laser level. The orientation of the buoy north is monitored by the Honeywell HMR3300 magnetometer that was similarly aligned with buoy north. The compass for the R. M. Young was digitally aligned with the HMR3300 magnetometer by matching the bearing output of the R. M. Young to the output of the Honeywell. Both the R. M. Young compass and the Honeywell magnetometer used for the WindSonic anemometer were calibrated, in place on the buoy, during the burn test in October 2004.

The Honeywell HMR3300 is a three-axis tilt compensated solid-state compass system that makes use of a two-axis accelerometer at up to a 60° tilt angle. The compass is capable of data rates up to 8 Hz. The compass is interfaced to an RS232 line driver that makes interfacing to the USM buoy system easy. The compass has an autocalibration routine that allows calibration of both heading and tilt while installed in the buoy. The HMR330 compass has a feature that enables the user to zero the tilt values before compass calibration. The unit was used both to compute wind heading and to perform

Fig. 2. Buoy during burn-in test at GERG. The Gill WindSonic is on the mast to the left
and the R. M. Young is on the mast to the right.

a wind correction for buoy tilt for the Gill data. Table 3 lists specifications of the HMR3300. Because a low wind bias due to buoy tilt has been thought to be unnecessary for significant wave heights below 11 m (Gilhousen 1987), GERG followed the NDBC practice of not correcting the R. M. Young records for tilt.

The wind sampling was set for 10-min vector wind averages and 5-s gusts computed every half hour. Both anemometers were sampled during the same 10-min intervals. For the R. M. Young, the raw data were taken at 2 Hz, while the WindSonic samples were taken at 4 Hz. Because the HMR3300 takes data at 8 Hz, it was subsampled at 4 Hz for the Gill data. The sampling

scheme follows WMO (1996) guidelines for sampling data at standard times.

2. Results

Anemometer comparison

Figure 3 shows a scatterplot of 10-min-averaged winds for the two anemometers from buoy deployment until the failure of the R. M. Young on 29 August 2005. It should be noted that the winds shown in this manuscript are the measured winds at a 5-m elevation and have not been raised to the standard 10-m elevation.

TABLE 3. Manufacturer specifications and buoy sampling setup for Honeywell solid-state compass.

Manufacturer	Honeywell International SSEC
Type	Solid-state 3-axis tilt compensated compass
Model	HMR3300
Data rate	8 Hz subsampled to 4 Hz
Directional accuracy ($\pm 0°–30°$)	3.0°
Directional resolution	0.1°
Tilt range	$\pm 60°$
Tilt accuracy	
Tilts of 0°–60°	0.4°
Tilts of 30°–60°	1.0°
Tilt resolution	0.1°

The mean wind speed is 5.38 ± 0.04 m s^{-1} for the WindSonic and 5.27 ± 0.04 m s^{-1} for the R. M. Young. The standard deviations are 2.80 and 2.83 m s^{-1}, respectively. The regression line has a slope of 1.01 and an intercept of -0.18 m s^{-1} with an r^2 of essentially 1. The lower R. M. Young values for the higher winds occurred during an April storm, Hurricane Dennis in July, and Hurricane Katrina until the R. M. Young anemometer had a catastrophic failure. Figure 4 shows a time series of wind direction difference. The bias, or mean, is 6.3° and the standard deviation is 5.5°.

Figure 5 shows time series of wind speeds and gusts from both anemometers over the period of 28–31 August 2005. The two records track well until 29 August 2005. Although the R. M. Young begins to read a successively weaker airspeed than the Gill throughout 29 August 2005, it does capture the higher-frequency wind speed features before failure. It is important to note the half-hourly sampling of data of 10-min-duration results in 20-min data gaps during which higher gusts may have been missed. A more robust set of procedures for increasing the sampling rate during extreme events is being developed to prevent such occurrences in the future.

The ratio of gusts to 10-min-averaged winds (or the gust factor) for the WindSonic anemometer record averages 1.31, with a standard error of 0.01, for the period when the winds were greater than or equal to 20 m s^{-1}. This compares well with gust factors determined from previous hurricane studies. For example, Powell et al. (1991) found a mean gust factor of 1.3 for 5–8-s gusts and 8.5-min mean winds at a 10-m elevation from buoy measurements during Hurricane Hugo.

The cause of the discrepancy between the high wind speeds retrieved by the R. M. Young and the Wind-Sonic is predominantly because of corrections applied to the WindSonic winds for buoy pitch and roll, as is
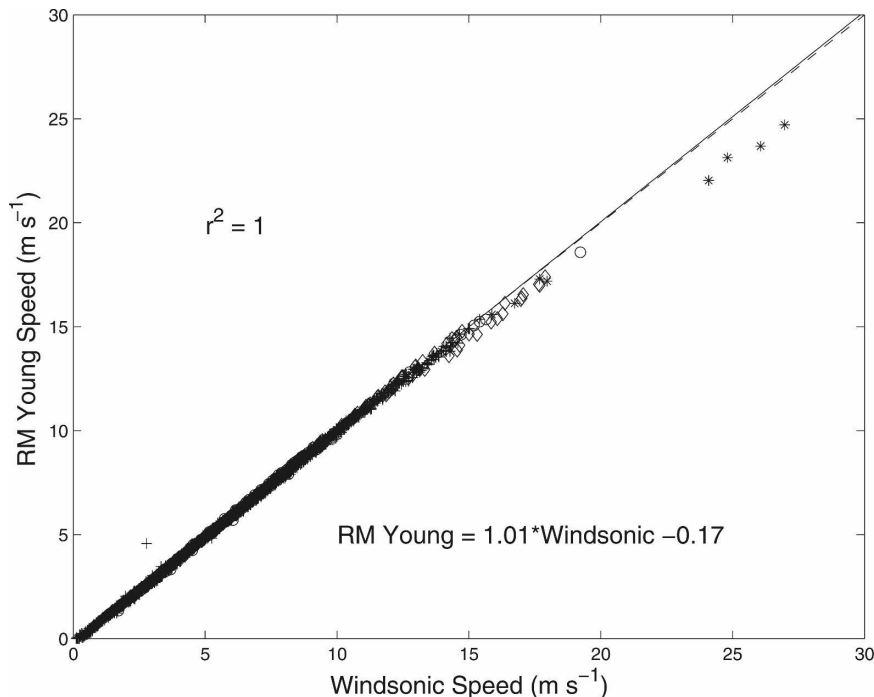

FIG. 3. Scatterplot of half-hourly, 10-min vector-averaged wind speeds from the two anemometers. Diamonds are data surrounding the period when Hurricane Dennis made landfall, asterisks are data during Hurricane Katrina, circles are data during an April 2006 event, and pluses are all other data.
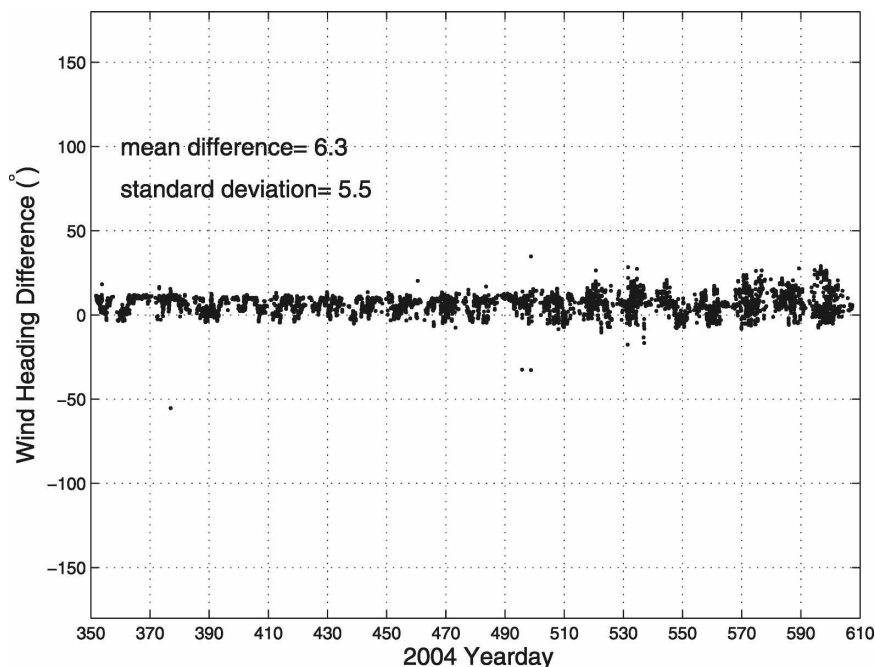
FIG. 4. Heading difference of anemometers.

apparent by looking at the wind speed difference along with buoy pitch and roll (Figs. 6a,b). These corrections are only for the tilt of the anemometer axes relative to the horizontal and are not for the apparent wind caused by the buoy motion itself. The latter are assumed to be reduced by the 10-min averaging.

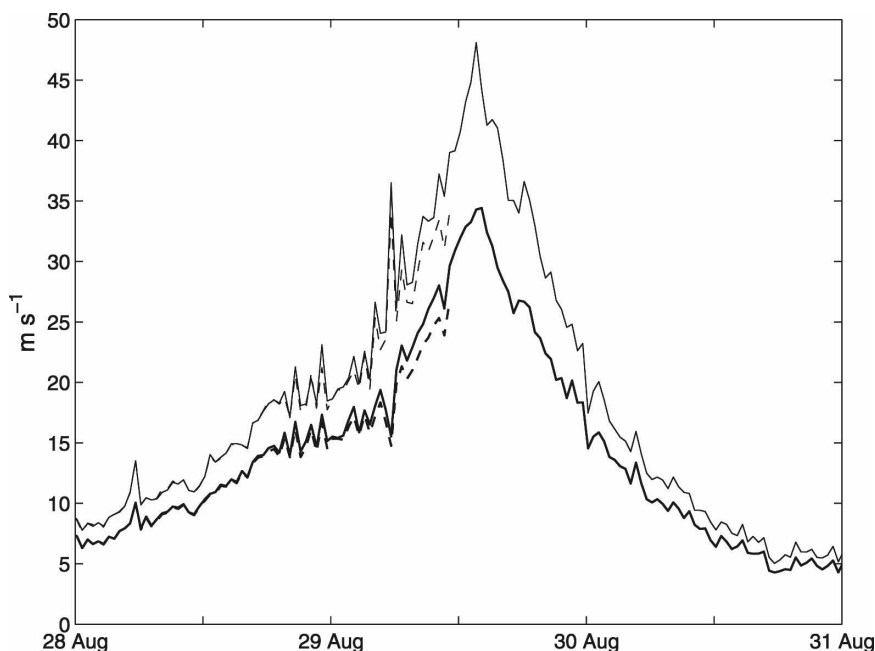Figures 6c,d show currents relative to the buoy and significant wave height (SWH), as determined using the

FIG.5. Time series of half-hourly, 10-min vector-averaged winds (bold) and half-hourly, 10-min gusts. Solid (dashed) line is the Gill WindSonic (R. M. Young 5106) data. Times are UTC.
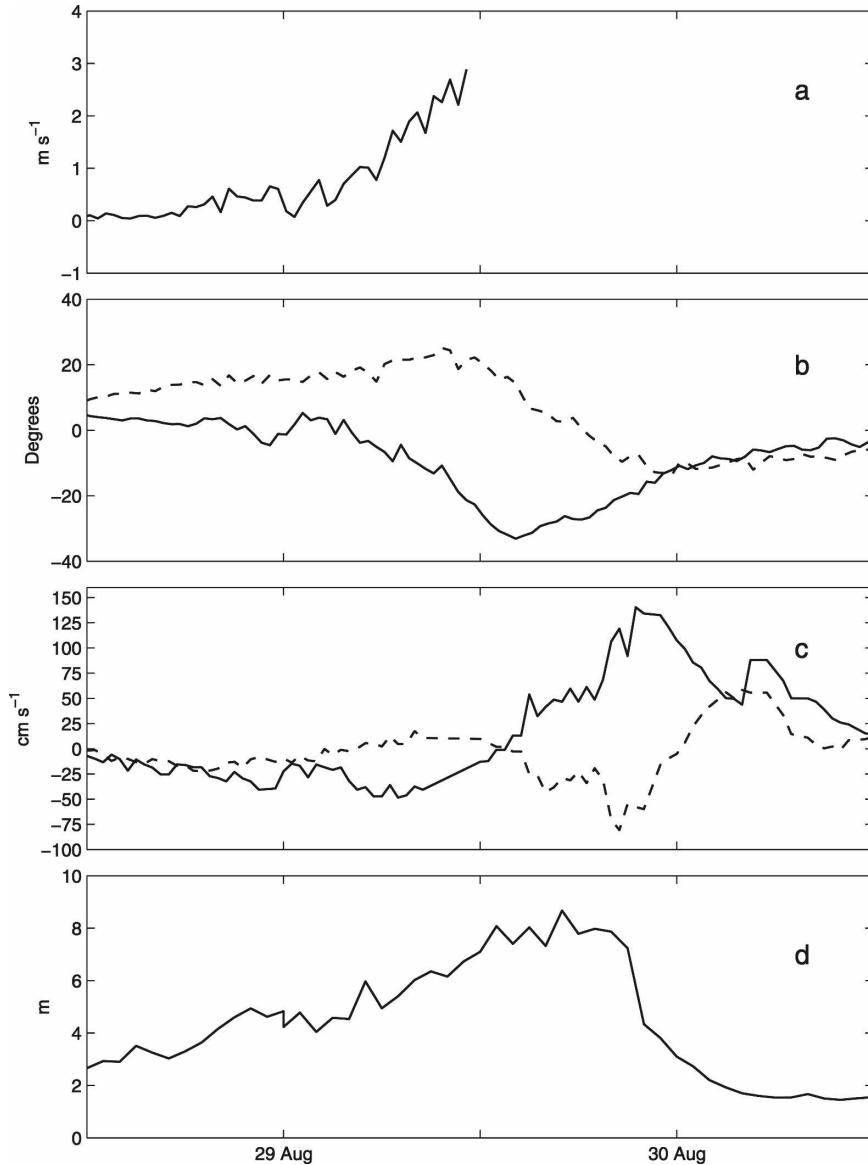
FIG. 6. (a) Gill WindSonic wind speed minus R. M. Young wind speed; (b) 10-min-averaged buoy east roll (dashed) and buoy north pitch (solid); (c) northward (dashed) and eastward (solid) currents relative to the buoy centered 3 m deep from ADCP; (d) significant wave height from Crossbow IMU and Honeywell magnetometer.

HMR3300 and the Crossbow Inertial Measurement Unit (Table 2). The wind speeds begin to diverge at about 1800 UTC 28 August 2005. At that time, buoy roll is about 14°, SWH is about 3 m, average winds are at 13 m s^{-1}, and currents relative to the buoy are over 20 cm s^{-1}.

Figure 7 is a vector wind plot of the Gill data over the period of 25 August through 1 September 2005. The wind veers as the hurricane passes from south to north to west of the buoy. Maximum sustained winds are 34.4 m s^{-1} from the south-southeast; maximum gusts (Fig. 5) are 48.01 m s^{-1} from the south-southeast.

During the storm, some of the data cables to the instruments were damaged and the buoy itself dragged its anchor. The buoy initially moved about 2 km to the northwest and then 15 km to the southeast. In September, the Canadian Coast Guard vessel *Sir William Alexander* recovered the buoy for USM. After recovery of the buoy the Gill WindSonic was shipped to the National Weather Service (NWS) testing facility in Sterling, Virginia, for a comprehensive postcalibration. The instrument was tested in accordance with ISO 16622 at tunnel wind speeds of 6.4, 11.0, 20.4, and 36.5 m s^{-1},
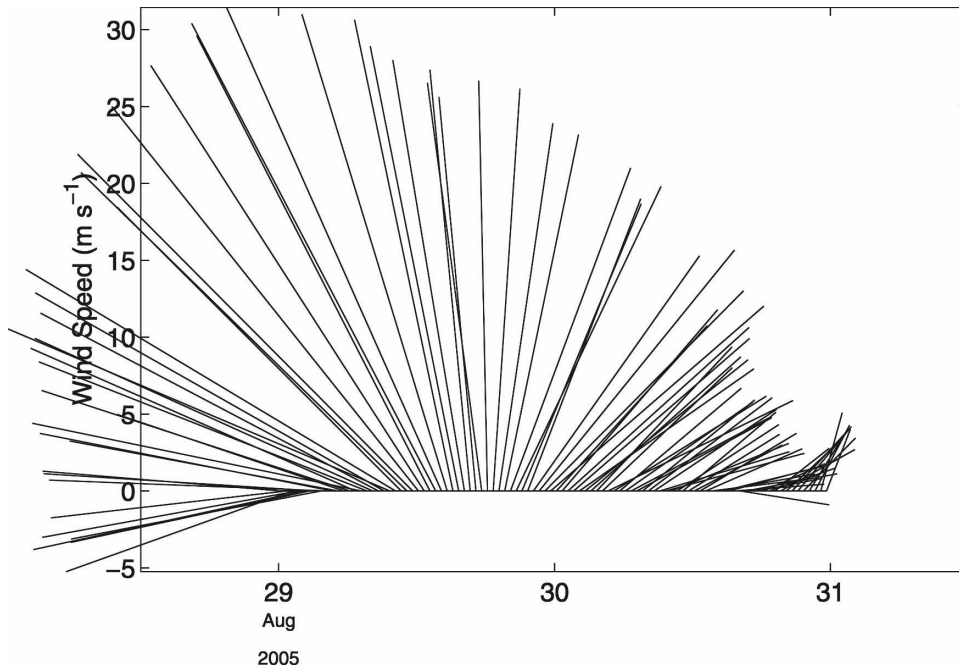
Fig. 7. Half-hourly, 10-min vector-averaged vector winds from the Gill WindSonic.

3. Discussion

with directions stepped from 0° to 360° in 5° increments. At all wind speeds the instrument met WMO (1996) requirements for wind speed retrieval. For wind direction, the WMO (1996) requirements ($\pm 5°$) were met for all measurements, except for the angular ranges of 70°–105° and 250°–275° at speeds of 36.5 m s^{-1} where the directional error was between 5° and 7°. The detailed results of the calibration are in the appendix.

3. Discussion

The nonlinear relationship between wind speeds from the two anemometers for winds greater than about 15 m s^{-1} results from the lack of a correction for pitch and roll for the R. M. Young. The mean (mid-December 2004 until late August 2005) buoy pitch and roll are $-0.13°$ and $0.92°$, respectively, and do not contribute to any significant biases. However, during strong events these results show that there are shorter-term mean values of pitch and roll that will cause a significant underestimation of the winds, at least for those measured from 3-m discus buoys.

It is difficult to ascertain how much of the 10-min-averaged buoy pitch and roll are due to strong winds, currents relative to the buoy (Fig. 6c), and waves (Fig. 6d). However, the buoy tilt remains over 20° when the currents drop to zero as the surge switches from flowing in toward the northwest to flowing out toward the southeast, and the SWH never reached the 11-m

threshold for significant buoy tilt computed in the Gilhousen (1987) study. Thus it is concluded that the wind, or the combination of wind and waves, explains the discrepancy of the buoy tilt measurements with the computed results of Gilhousen's study. This may mean that buoy winds measured by anemometers uncorrected for buoy tilt on NDBC buoys during extreme events are biased low. This is in addition to the wind-sheltering effect of large-amplitude waves that has been acknowledged but has not yet been well characterized (e.g., Skey et al. 1993).

The response of the two anemometers used on the buoy to winds oblique to the horizontal plane needs to be fully determined to correct winds properly for buoy tilt. A potentially complicating factor for the WindSonic is the plate above the transducers (see Fig. 2), which while serving to shelter them from precipitation and fouling from birds, may prevent a free flow of air when the anemometer is tilted relative to the wind. Wind tunnel tests need to be carried out on both anemometers to characterize their responses completely to winds that are not parallel to their respective horizontal planes.

In this particular application, the Gill WindSonic anemometer has proven to be a robust instrument for extreme events. A sonic anemometer is an attractive option for offshore buoy deployments because there are fewer mechanical points of failure. A caveat to this is the failure of the WindSonic in the postcalibration to

meet WMO (1996) specifications for angular accuracy during winds of 36.5 m s^{-1} when the wind direction was near anemometer 90° and 270°. In the precalibration tests, the WindSonic was not tested at these wind angles for high wind speeds. During the precalibration, the WindSonic was tested at a constant wind direction of 180° for all wind speeds greater than 4 m s^{-1}, and no wind direction error was detected. The postcalibration results showed negligible wind direction error at all wind speeds under 36.5 m s^{-1} for winds at 180°, which underscores the need to calibrate sonic anemometers over a range of wind directions for each wind speed.

During the postcalibration another WindSonic instrument, owned by the National Weather Service, was also tested in an identical manner and met WMO (1996) specifications throughout the entire range of wind parameters used in the tests. Presently, it is unclear whether the buoy WindSonic anemometer did not perform quite as well during the postcalibration because of stress from the hurricane or because of inherent variations introduced during the manufacturing process. Clearly, even with larger error in wind direction at a high wind speed for certain wind directions, it is better to have degraded data than no information at all.

One question that has not been fully addressed for sonic anemometers is their performance under high-precipitation conditions. As mentioned, the plate above the transducers on the WindSonic does provide some protection from precipitation. The combination of strong winds and buoy tilt would have allowed some amount of precipitation to reach the region on and between the transducers. Although the buoy did not have a rain gauge, there are some independent estimates of total precipitation during Hurricane Katrina at the mooring site. National Aeronautics and Space Administration (NASA) Multisatellite Precipitation Analysis total precipitation estimates (unpublished) are about 9–12 cm. Strong precipitation events can also be expected to occur throughout the 8-month deployment. Only one large anomaly appears in the scatterplot of Fig. 3, and it does show a lower WindSonic-measured wind speed. However, the data do not show sporadic anomalies that might be expected if strong precipitation events affected the wind speed retrieval of the WindSonic. Clearly, land-based testing of sonic anemometers during precipitation events, or with more controlled artificial precipitation, would be useful.

Finally, the fast response times of sonic anemometers would allow for turbulence measurements if the anemometer and datalogger were configured to sample and log the highest-frequency data (4 Hz for the WindSonic). However, the plate above the WindSonic transducers would be of concern in this application; thus, another sonic anemometer design may be more appropriate.

APPENDIX

Anemometer Calibrations

a. Predeployment calibration

The predeployment calibration was conducted at the test facilities of NDBC. WMO (1996) states that surface wind accuracies of 0.5 below 5 m s^{-1} and better than 10% above 5 m s^{-1} is usually sufficient, with wind direction accurate to 5°. Both anemometers easily met the WMO (1996) requirements in predeployment calibration tests.

b. Postdeployment calibration

After recovering the buoy, the Gill WindSonic was shipped to Virginia to the NWS Sterling test facility. The instrument was tested at tunnel wind speeds of 6.4, 11.0, 20.4, and 36.5 m s^{-1}, with directions stepped from 0° to 360° in 5° steps. At all wind speeds the instrument met WMO (1996) requirements for wind speed retrieval. The postcalibration results showed negligible wind direction error at all wind speeds under 36.5 m s^{-1} for winds at 180°, which underscores the need to calibrate over a range of wind directions for each wind speed (Sturgeon 1999). During the postcalibration another WindSonic instrument, owned by the National Weather Service, was also tested in an identical manner and met WMO (1996) specifications throughout the entire range of wind parameters used in the tests (Sturgeon 2005). Presently, it is unclear whether the buoy WindSonic anemometer did not perform quite as well because of stress from the hurricane or because of inherent variations introduced during the manufacturing process.

For wind direction, the WMO (1996) requirements ($\pm 5°$) were met for all measurements, except for the angular ranges of 70°–105° and 250°–275° where the directional error was between 5° and 7°.

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