10C.4 IN SITU MEASUREMENTS OF 3D TURBULENCE IN HURRICANES FRANCES AND IVAN USING A PRESSURE-SPHERE ANEMOMETER

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1. INTRODUCTION

Turbulence within the hurricane boundary layer plays important roles both in air-surface exchange and in the destruction caused by the storms at landfall. Direct measurements of 3D turbulence within hurricanes are rare, because standard instrumentation is not designed to function in extreme winds and rain. Under a joint partnership between NOAA and the CBLAST Hurricane program, the NOAA Air Resources Laboratory has developed an Extreme Turbulence (ET) probe specifically for hurricane measurements (Eckman et al. 2004, 2006). This probe is a pressure-sphere anemometer similar in concept to aircraft gust probes, but it is designed to be deployed at the surface.

Major successes were scored in the 2004 hurricane season when ET probes were deployed near the coast in Hurricanes Frances and Ivan. Over 80 hours of turbulence data were collected in the two storms, and the data appear to be of high quality. This paper describes preliminary results from these deployments.

2. RAIN DEFENSE

Pressure-sphere anemometers are susceptible to having their ports fouled by rain or spray. A working rain defense was still in development when Eckman et al. (2004) was written, but two different approaches have since been investigated. The first is a passive defense that uses gravity to drain any water that enters the ports before it can affect the measurements. The second is an active approach that uses an air pump to flush any water in the ports.

During both testing and the hurricane deployments, the passive defense was highly effective in stopping water from fouling the pressure ports. Hence, all the results reported here are from ET probes using the simpler passive defense. Probes employing the active defense were also deployed into the hurricanes, but the resulting data are more difficult to analyze because of rain spikes in the data.

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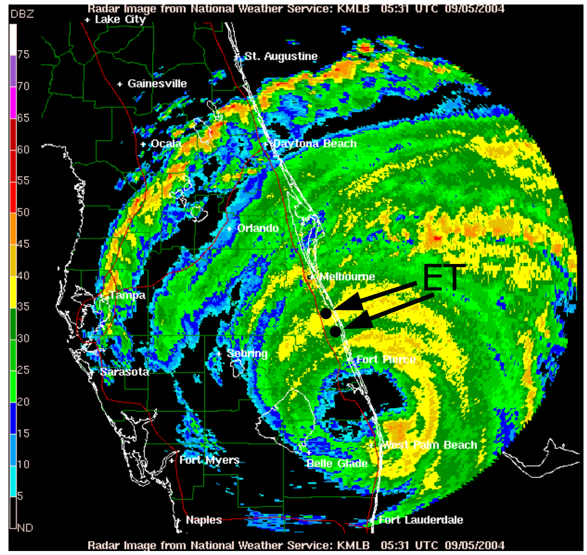

Figure 1: Radar image from 5 September 2004 showing the two ET probe deployment locations relative to Hurricane Frances.

3. HURRICANE FRANCES

Hurricane Frances made landfall along the East Coast of Florida as a Category 2 storm on 5 September 2004 (Beven 2006). Three ET probes were deployed for this storm at two sites: Sebastian (north) and Vero Beach, FL (Fig. 1). Passive-defense probes were deployed at both sites, and an active-defense probe was deployed at Vero Beach. At both locations the probes were deployed near more conventional towers operated by Texas Tech University (Lorsolo and Schroeder 2006). All three probes were activated on 3 September and retrieved on 6 September.

As can been seen in Fig. 1, the probes were on the right side of the storm with onshore flow, but they were too far north to see the eye. Later analysis of the Frances data indicated that the passive defense worked well, with little or no evidence of water fouling of the pressure ports. The maximum sustained (i.e., 1 min average) winds observed at both sites were near 27 m s^{-1}; this lower speed is not unexpected given that the probes were north of the eyewall and some distance inland from the coast. Peak gusts observed at both locations were near 45 m s^{-1}.

Figure 2a shows example 50 Hz wind time series from the passive-defense probe at Sebastian. The data were

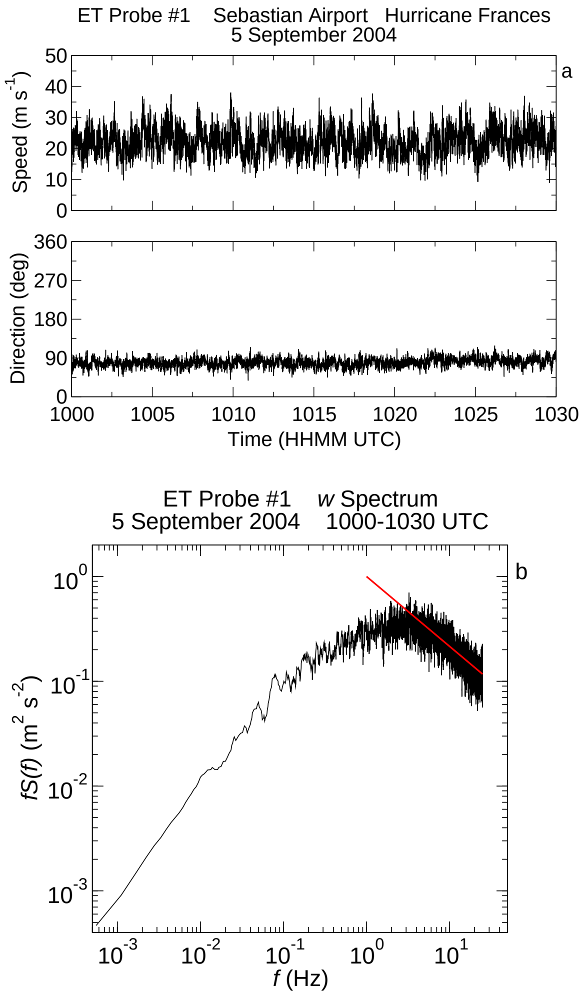

Figure 2: For the ET probe at Sebastian, (a) shows half-hour time series of wind speed and direction for the period starting at 1000 UTC 5 September 2004. (b) shows the vertical velocity spectrum for the same period. The red line corresponds to a -2/3 slope.

collected over a half-hour period starting at 1000 UTC 5 September, which was the period with the peak winds at this site. Little evidence of water fouling is indicated in the data, as is true of most of the data collected with the passive-defense probes. The mean wind speed for the entire period is 22.4 m s^{-1}.

Figure 2b shows the vertical-velocity power spectrum for the same time period as in Fig. 2a. A well-developed inertial subrange is present beyond the spectral peak at 3 Hz. Given the observed mean wind speed, the peak corresponds to a length scale of about 7 m. In contrast, the spectrum for the 3D wind speed (not shown) has a peak corresponding to a length scale of about 500 m. Note that a standard sonic anemometer configured to sample at 10 Hz would have difficulty resolving the inertial subrange even though the average winds during

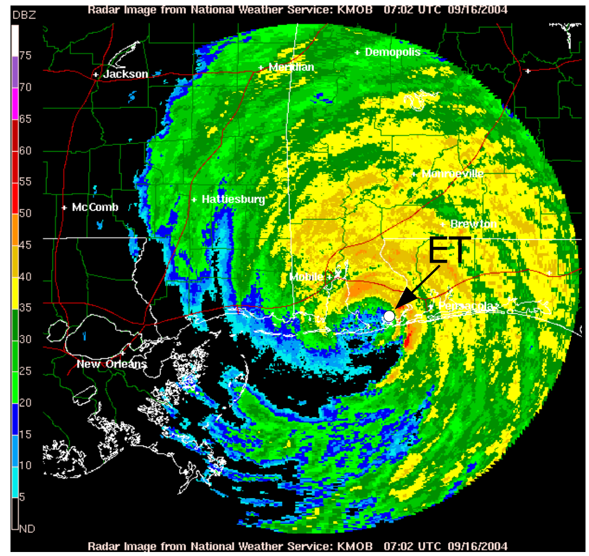

Figure 3: Radar image from 16 September 2004 showing the ET probe deployment location relative to Hurricane Ivan.

this period were only typical of a tropical storm rather than a hurricane.

4. HURRICANE IVAN

After returning from the Frances deployment, the ET-probe team had only a few days of recovery before redeploying along the Gulf Coast for Hurricane Ivan. This storm made landfall near Gulf Shores, AL on 16 September 2004 as a Category 3 hurricane (Stewart 2006). Two ET probes—one passive and one active defense—were deployed at an inactive military airfield called Navy Outlying Field (NOLF) Wolf. Figure 3 shows that the probes were near the eastern eyewall of Ivan at landfall.

The probes at the NOLF Wolf site observed a minimum pressure of 949 hPa. The maximum sustained (1 min average) wind was 29.6 m s^{-1}, with a maximum gust of 50.3 m s^{-1}. This is significantly below the official 54 m s^{-1} sustained winds reported for Ivan (Stewart 2006). As was the case in Frances, the Ivan deployment location was far enough inland that the winds had already adjusted to the land roughness at the 3 m height of the deployed probes. However, the turbulent gusts observed at NOLF Wolf are consistent with the presence of sustained winds exceeding 50 m s^{-1} just offshore from the deployment site.

Figure 4 shows both the turbulent kinetic energy TKE and the friction velocity u_* for a 30-hour period centered on the time of landfall of Hurricane Ivan. These statistics were computed using sequential 30-min velocity time series from the passive-defense probe

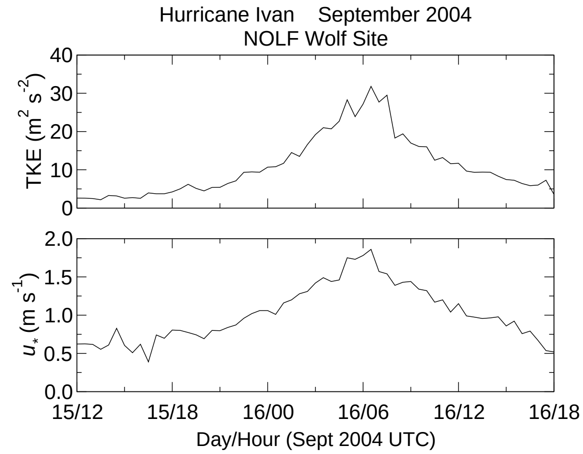

Figure 4: TKE and friction velocity u_* observed by an ET probe at NOLF Wolf during the landfall of Hurricane Ivan.

at NOLF Wolf. The TKE rose by an order of magnitude during the storm, peaking at about 30 m^2 s^{-2}. The friction velocity increases by about a factor of three during the same period, reaching nearly 2 m s^{-1}.

One of the early motivations for the development of the ET probe was to provide in-situ observations of the drag coefficient C_d in hurricanes. Current modeling of the air-sea turbulent fluxes in tropical cyclones is based on extrapolations from lower wind speeds, but there is evidence that these extrapolations are inaccurate (e.g., Powell et al. 2003). Since C_d in neutral conditions is derived from u_*, Fig. 4 demonstrates that the ET probe is capable of directly measuring C_d in hurricane conditions. In fact, C_d computed from u_* in Fig. 4 has a nearly constant value of 0.005, which is reasonable for a land deployment location. Of course, the land-based Frances and Ivan data described here do not address any issues related to drag coefficients over the sea.

5. FUTURE DEVELOPMENT

The ET probe work completed so far has largely been a proof-of-concept effort to demonstrate that the instrument is capable of providing reliable turbulence measurements in hurricane conditions. Time and funding constraints led to the use of many "office" hardware components that are not particularly rugged and use more power than desired. One plan for future development is to replace some of the computer components with embedded PC/104 modules or something similar. These would consume far less power and make the system more rugged and compact.

There is also interest within NOAA for deploying ET probes in a sea environment where they could directly address the C_d and other air-sea exchange issues discussed previously. The easiest approach with the existing design would be to deploy the probes on fixed sea platforms such as piers or pilings. One obvious target of opportunity would be the NOAA Coastal-Marine Automated Network (C-MAN) stations. A more ambitious effort would be to install the probes on moored buoys. This would require the addition of platform-motion sensing equipment similar to what is used for aircraft turbulence measurements. Since the ET probe was derived from previous NOAA research with aircraft gust probes, much of the development work for detecting platform motion could be directly adapted from the aircraft work.

6. ACKNOWLEDGMENTS

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