Development and Deployment of an Extreme Turbulence (ET) Probe for Hurricane and High Wind Research

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LONG-TERM GOALS

The Coupled Boundary Layers Air-Sea Transfer (CBLAST) Departmental Research Initiative and the U. S. Weather Research Program (USWRP) Hurricane at Landfall Initiative identify hurricanes as the least understood yet most important high-wind event. A paucity of measurements in the atmospheric boundary layer, both in research and operations, is recognized as an important source of uncertainty in hurricane forecast models. Such measurements have been very difficult to obtain since the most turbulence sensors function poorly or not at all in winds and rain above 20 m s^{-1}. Filling this knowledge gap is crucial to improving predictions of hurricane track, size and intensity, and to understanding air-sea exchange under high winds. The Extreme Turbulence (ET) probe is being developed to acquire turbulent flux data in the atmospheric surface layer in hurricane-force winds.

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OBJECTIVES

The scientific and technical objectives of this effort are:

1. To design, test and build six ET Probes suitable for deployment in extreme turbulent conditions such as hurricane landfall or wave boundary layers near the shore in hurricane-force winds;

2. To deploy three to five probes prior to hurricane landfall to observe wind gradient and structure changes; and

3. To collaborate with other scientists in deploying the ET probe in high-wind experiments in the wave boundary layer.

The first objective responds to ONR's interest in robust scientific instrumentation, currently not available, to observe boundary-layer turbulence and surface fluxes in hurricane-force wind with high rain rates and salt spray. The ET probe design will adapt the rugged and well proven pressure-sphere gust probe from research aircraft to an omni-directional configuration. Special consideration will be given to the need for stand-alone operation, ease of deployment, and hardiness in the harsh environment. The ET probe will create exciting opportunities for new observations, first during hurricane landfall, later in the wave boundary layer during hurricanes and other strong winds.

The second objective provides a first step into the real world of boundary-layer measurement during a hurricane. We will attempt two ground-zero observations (through the most intense part of the storm) each year for three consecutive years. This difficult task will be facilitated by collaboration with the NOAA's Hurricane Research Division (HRD), drawing on their record of successful deployments of this type. For the USWRP, the new data directly address the huge gap in boundary layer structure and surface fluxes during the landfall. The ET probe is the fundamental instrument needed to observe the changes in boundary layer structure as hurricanes pass from ocean to land. For the ONR, the shoreline deployment provides a real-world step toward an instrument that will also function in the wave boundary layer.

The third objective allows important independent high-wind intercomparisons in less adverse operational environments. It also advances deployment in the wave boundary layer. We are committed to creating exciting opportunities for new observations by supporting other scientists in their efforts at high-wind research measurements.

APPROACH

The basic design goal is the development of a simple, low-cost probe which is robust, easy to calibrate, and accurate for high-frequency eddy-flux determinations. The probe must be easily mounted and must survive in an environment of salt, heavy rain, and high wind.

A pressure-sphere anemometer’s function improves as wind speed increases. The design has proved rugged in airborne applications. Its resistance to rain and salt can be provided in several different ways. The mathematical expressions relating the pressure distribution to the direction and speed of the incident flow are simple and well-validated. Thus, calibration of the probe need only consider the pressure sensors themselves. Extensive wind tunnel calibrations of the whole system are unnecessary. The probe's small size, light weight, and low power requirements allow flexibility in deployment in harsh environments with questionable power availability.

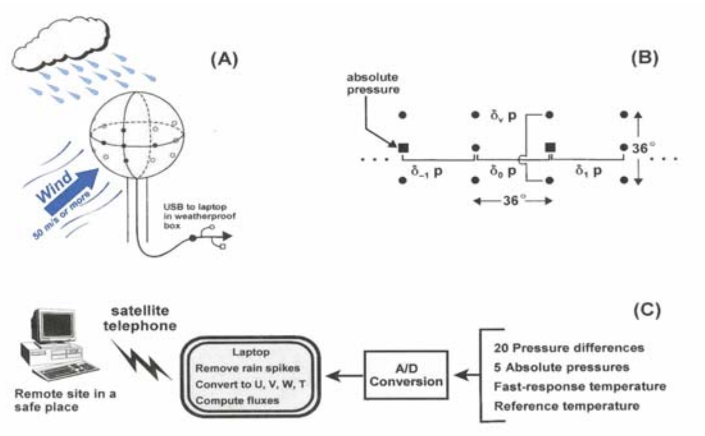

Fig.1. Concept schematic of the ET probe operation.

Fig. 1 presents the ET probe concept. In (A), the general appearance is indicated. The schematic of port arrangement and pressure measurement is illustrated in (B). Absolute pressure, in addition to pressure difference, is measured at squares. Vertical pressure differences skip the "equator", reducing the required number of sensors. (C) schematically illustrates the satellite link from sensors located within a hurricane to the receiver in safe place.

WORK COMPLETED

Five ET probe spheres have been constructed of fiberglass-epoxy composite. This lightweight material is highly versatile. It does not corrode in salty environments. The sphere's 40-cm diameter sphere is large enough to house the necessary sensors and electronics and to maintain sufficiently high Reynolds numbers to ensure turbulence (Fig. 2). The electronics package has been designed, built, and installed within the first prototype sphere. To avoid fouling by spray and rain, all pressure ports are back-flushed with air fed by a pump through a tubing network. Sensors' analog signals pass through two commercial analog-to-digital converters (ADC), providing a total of 32 channels of data.

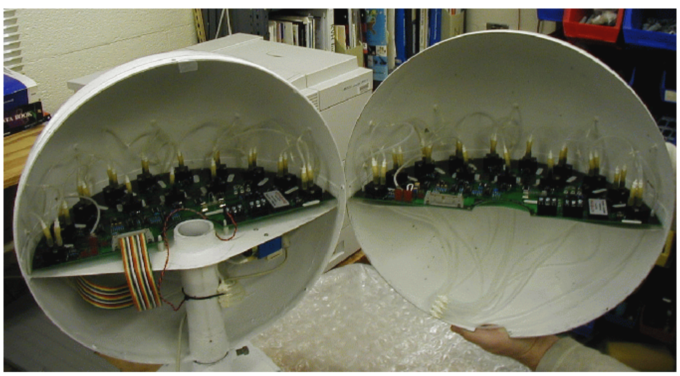

Fig. 2. Inside view of the ET probe.

Data are retrieved from the ADCs at 1000 samples per channel per second (S/s). These are filtered and subsampled to an unaliased working signal at 50 S/s. Data from an eight-channel pattern, sensors facing into the wind, are selected from each sample and converted to wind and temperature. This 50 S/s signal is significantly faster than a sonic anemometer/thermometer. The current software can record the 32-channel data stream at 50 S/s and can compute winds in post-processing. The next priority is detection and removal of spikes in the initial (1000 S/s) signal, caused by rain strikes. Real-time computation of winds, and then turbulent fluxes and other statistics will follow next.

Software, the other fundamental of modern design, has been developed in C++ for its object orientation and its compatibility with the ADCs' associated C-language control components. The ADCs' sophistication requires use of their own software, which in turn requires the Windows Operating System.

RESULTS

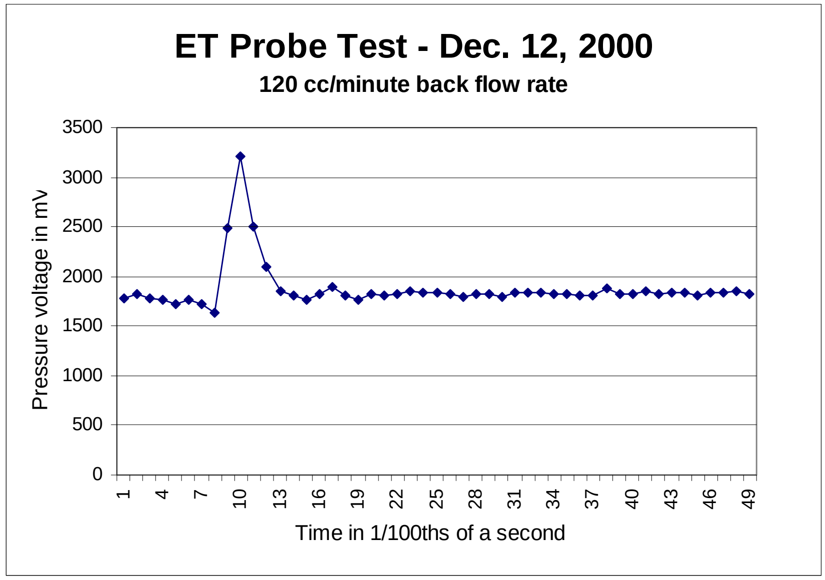

Fig. 3. Graph showing response to rain drop impact on ET probe pressure port.

To explore the response to rain, a droplet accelerator was built to simulate the impact of high velocity rain drops on the surface of the ET Probe sphere. The pressure side of a shop vacuum was used in conjunction with a tapered probe to accelerate well formed rain drops in a laminar flow of air. This allows the rain drops to be consistent in size, velocity and impact position. In particular, we were interested in the effect of the droplets as they impacted the small pressure ports that are used to measure wind velocity and turbulence on the ET probe. Initially back flow air was set at 1 cm min^{-1} to keep water out of the pressure ports. However, at 1 cm min^{-1}, pressure pulses caused by rain impact were longer lasting and of similar amplitude as those pulses caused when flow was increased to 30 or even 120 cm min^{-1}. Droplets seem to be driven farther into the pressure ports and pushed out slower at the lower flow rates causing the longer rain (noise) pulses. The expected increase in the pressure transducer output offset voltage will cancel on the differential pressure sensors. A graph showing the effect of a single rain drop impact with a back flow of 120 cm min^{-1} is shown in Fig. 3. Note that the impact of the rain on the sensor port creates a very sharp pressure spike.

With hardware and software sufficiently developed to record data and compute winds, the first prototype unit of the ET probe was mounted on top of a vehicle (Fig. 4). Highway runs to simulate hurricane force winds have begun.

IMPACT/APPLICATIONS

Development and deployment of the ET Probe responds to both ONR's CBLAST program, and the U. S. Weather Research Program's (USWRP) Hurricanes-at-Landfall initiative. Both programs identify hurricanes as the least understood of important high-wind events. A paucity of measurements in the atmospheric boundary layer, both for research and operations, is recognized as an important source of uncertainty in a hurricane forecast models. Filling this knowledge gap is crucial to improving predictions of hurricane track, size and intensity, and to understanding air-sea exchange under high winds in general.

Fig. 4. ET probe mounted on vehicle for testing.

TRANSITIONS

Collaborations are being created for deploying and testing the ET probe in strong wind environments. We are working with James Edson (Woods Hole Oceanographic Institution) to mount the ET probe on a 10-m meteorological mast located at the edge of a beach in Martha's Vineyard Coastal Observatory (MVCO). Primary evaluation will occur during the winter months during the passage of strong coastal storms. Similarly, the ET probe will be tested at the Pacific Ocean coastline with Larry Mahrt (Oregon State University).

RELATED PROJECTS

The ET probe development effort will be closely tied with other CBLAST hurricane research programs. In particular, the aircraft measurement technology used to develop the ET probe will be installed on the NOAA P3 aircraft for turbulent flux measurements in the lower portion of the marine atmospheric boundary layer. The primary goal of the hurricane project is to develop new surface wave-dependent flux parameterizations for the high wind boundary layer in and around hurricanes.

PUBLICATIONS

Crawford,T. L., R. J. Dobosy, D. L. Auble, G. H. Crescenti, and R. C. Johnson, 2001: The extreme turbulence (ET) probe for measuring boundary-layer turbulence during hurricane-force winds. Preprint, *Eleventh Symposium on Meteorological Observations and Instrumentation*, Albuquerque, NM, Amer. Meteor. Soc., 50-54.