LOCALLY-FORCED WIND EFFECTS ON SHALLOW WATERS WITH EMERGENT VEGETATION

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1. INTRODUCTION

Over the past century, the Everglades region of south Florida has experienced dramatic declines in the health and abundance of many of the plant and animal species that make it one of the world's most unique ecosystems. These declines have been attributed in large part to anthropogenically influenced changes in the quality and quantity of water entering the Everglades. Residential, commercial and agricultural use of water in south Florida has dramatically altered the timing, location and volume of its delivery to the wetlands.

As part of regional plans to restore the health of the ecosystem and to bolster the plant and animal populations, changes in methods used for water storage, treatment, and delivery are being proposed. Many of these changes are expensive, extensive, and sometimes at odds with each other. Consequently, there is great interest in being able to predict the effects of any changes before they are implemented. Toward this end, a numerical fate and transport model of flow in the Taylor Slough area of the Everglades is being developed at the U. S. Geological Survey (USGS) as part of its South Florida Place-Based Study Program.

A reliable fate and transport model requires both sound characterization of the physical processes governing the flow and accurate representation of the domain being modeled. In the Everglades, a model must include characterization of the effects of wind on flow patterns as well as characterization of vegetative resistance, rainfall, evapotranspiration, ground-water/surface-water exchange, and canal/wetland interaction. A model of the Everglades must also include skillful mapping of the topography and overlying vegetation populations. Projects at the USGS are dedicated to the study of each of these.

The project described in this paper was designed to determine the effects of wind on flow in shallow waters with emergent vegetation, such as those found in the Everglades. Little is known about these effects, and very few attempts have been made to include them in numerical flow models (Reid and Whitaker, 1976). Therefore, laboratory experiments, supplemented by the analysis of historical south Florida wind data, were designed and conducted to determine the magnitudes, time scales, and spatial scales relevant to wind forcing in the Everglades and to the USGS fate and transport model.

2. WIND FORCING

2.1 Local vs. Remote Wind Forcing

Wind can influence flow in a body of water by two distinct mechanisms. The first, local forcing, is by the direct transfer of momentum from the air to the water at the air-water interface. This transfer is the result of friction between the two fluids and results in a shearing of the vertical profile of horizontal velocity in the water. The second mechanism, remote forcing, is by the indirect transfer of momentum from one water body to an adjacent but contiguous water body. When water levels in one water body are altered by winds, a difference in water surface elevation can be created between the two bodies. This, in turn, can drive a flow in the second water body. Although both local and remote wind forcing occur in the Everglades, only local forcing was studied in the laboratory experiments considered here.

2.2 Drag Coefficients

The physics of local wind forcing is included in numerical flow models as a surface wind stress. This term in the model equations is typically calculated as the mathematical product of a reference wind velocity squared and a non-dimensional parameter known as the drag coefficient. Therefore, accurate representation of the local wind forcing requires accurate representation of both the local wind velocity and drag coefficient. The historical data analysis mentioned in the Introduction above is focused on accurately representing local wind velocities in the Everglades, but will not be reported here. The laboratory experiments are focused on determination of the drag coefficient for sawgrass, *Cladium jamaicense*, one of the predominant vegetation types in the Everglades.

Much research has gone into the determination of drag coefficients over open water (e.g. Large and Pond, 1981). The open-water drag coefficient is nearly a constant with a slight increase at high wind speeds due to roughening of the water surface, which creates a more efficient momentum transfer. In waters with emergent vegetation, however, the drag coefficient is expected to depend not only on the wind speed, but also on the geometric and structural properties of the vegetation, which control the wind's ability to penetrate the canopy and transfer momentum to the water surface.

The drag coefficient cannot be measured directly, but must be inferred experimentally by measuring the wind stress and wind velocity squared and taking the quotient of the two. Wind velocity is fairly simple to measure using conventional anemometers. However, wind stress is very difficult to measure, and must often be inferred by calculating the remaining terms in an equation representing conservation of momentum in the water column. These terms include acceleration of the water, pressure gradients created by sloping of the water surface, pressure gradients created by differences in atmospheric pressure above the water surface, friction at the water/sediment interface, and friction caused by vegetative resistance to flow within the water. All of these are more easily calculated or estimated than wind stress, with the exception of friction caused by vegetative resistance to flow. Experiments conducted by J. K. Lee as part of the USGS Place-Based Study Program are designed to estimate vegetative resistance to flow and will be used to estimate this term in the momentum balance.

3. METHODS

3.1 Flume and Wind-Cowling Construction

Laboratory experiments were conducted in a 60-m-long, 2-m-wide, 1.2-m-deep tilting flume in which a bed of sawgrass was growing actively for nearly 3 years (Figure 1). A removable-lid wind cowling, 30 m long and 1.2 m high, covered the upstream half of the flume. Because the density of sawgrass in the flume was approximately that of sawgrass in the Everglades (Virginia Carter, oral communication), it was possible to adjust the discharge in the flume to give simultaneously small water-surface slopes and flow velocities typical of those found in the Everglades.

The wind cowling was a rectangular channel made of plywood with various structural modifications to ensure a nearly uniform, steady wind field with minimal secondary circulation patterns. Wind was generated in the cowling by a bank of four 1.2-m-diameter fans arranged in a two-by-two array positioned to draw air through the enclosed flume. The cross-sectional area of the fan bank was substantially larger than that of the wind cowling itself. Therefore, an expansion section was constructed between the two. The expansion section and fan bank were constructed to be portable so that they could be moved from one end of the cowling to the other in order to create winds that either opposed or were in the same direction as water flow in the flume. Additional construction details are reported by Jenter (1999).

The test section of the cowling was constructed with removable plywood panels on top so that the roof could be removed nightly to allow a bank of mercury-halide grow lamps to illuminate the sawgrass. Some of the top panels were modified to allow deployment of instrumentation through the roof of the cowling. In addition, plexiglass side panels were installed in the flume to allow access to the instruments and to allow observation during experiments.

3.2 Instrumentation and Measurements

For each experimental run, the cowling was instrumented with three anemometers positioned at different heights through a lateral cross section to measure the vertical profile of wind speed. The flume was instrumented with two

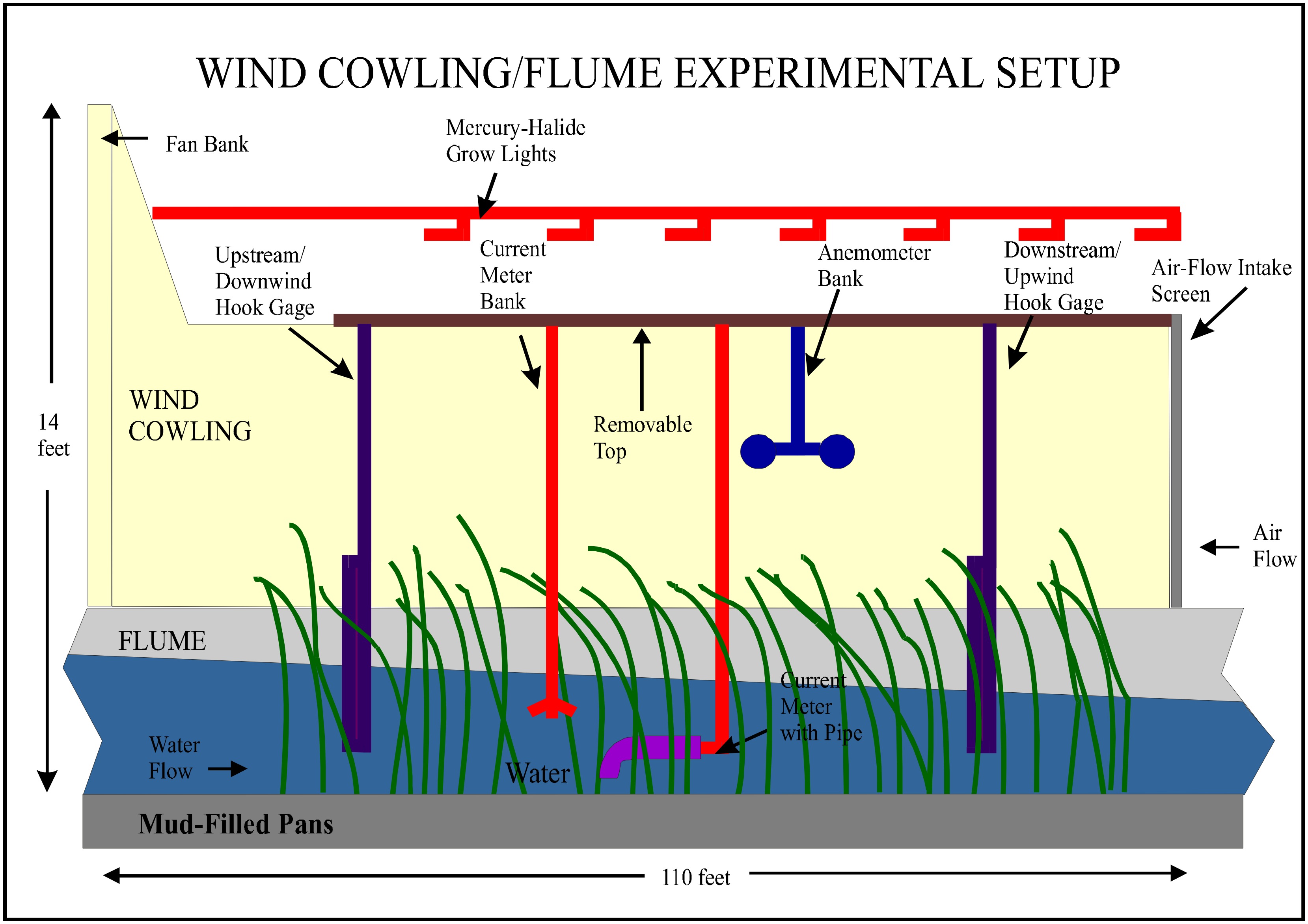

Figure 1. Schematic of the wind cowling and flume experimental setup.

acoustic Doppler current meters that could be positioned at a number of depths to measure vertical profiles of velocity. A third acoustic Doppler current meter was used to measure flow through a horizontal pipe manometer used for determining the along-flume pressure gradient. Two hook gages positioned near the upstream and downstream ends of the test section were used to estimate the water-surface slope.

3.2.1 Water Velocity

All three acoustic Doppler current meters have a rated precision of .1 mm/s in a range of 0 to 3 cm/s. Velocity components in all three directions were collected at 20 Hz in bursts of two-minute duration. One of the paired current meters was fitted with an upward-looking probe that allowed it to sample within 3 cm of the water surface. The other was fitted with a downward-looking probe that allowed it to sample within 3 cm of the mud bottom. Velocity measurements were collected in increments of 6 cm from the surface to the bottom with each current meter. Once complete profiles were collected, the current meters were exchanged and the profiles were repeated. This allowed a highly resolved profile of velocity to be collected from the water surface to the mud bottom in both locations. Samples of velocity profiles collected in this manner are shown on the left side of Figure 2. The two curves represent measurements at the two current meter locations.

3.2.2 Water-Surface Slope

The third acoustic current meter was fitted with a sideward-looking probe that allowed it to sample the centerline velocity inside an 8-ft-long plastic pipe with a short elbow at one end. The pipe was positioned horizontally below the water surface and parallel to the flow direction with the elbow at the upstream end and pointing down. The centerline velocity is used along with a rating equation developed under very carefully controlled flume conditions to infer the along-flume pressure gradient (J. K. Lee, oral communication). The accuracy of this technique appears to be sufficient to measure water surface slopes such as those found in the Everglades. The pipe current meter was sampled at 20 Hz in two-minute-duration bursts every time the paired current meters were sampled. Thereby, producing 10-30 estimates of the centerline velocity in the pipe during each experiment. An example of these estimates is shown on the right side of Figure 2.

Hook gages were used during each experiment to estimate the water-surface slope. At each of the two hook-gage locations, a datum was established by making measurements with a horizontal water surface under no-flow conditions. This reference elevation was then subtracted from measurements during the experiments to establish the slope created by the wind. Numerous technical difficulties were involved in obtaining accurate hook-gage measurements. These difficulties are described by Jenter (1999) and Lee (this volume).

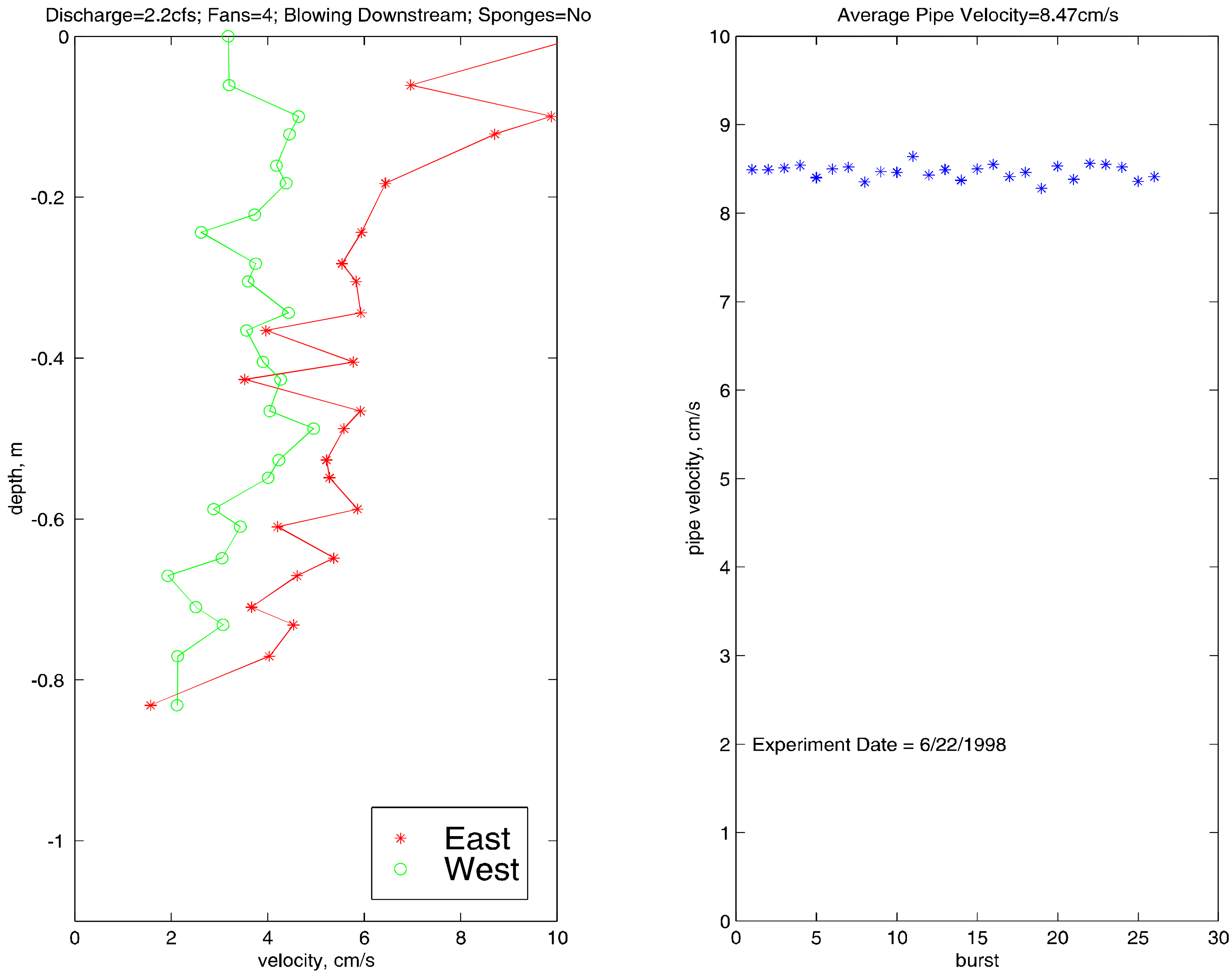

Figure 2. Sample plots of horizontal velocity (left) and pipe velocity (right) measured in the flume.

3.2.3 Wind Velocity

The anemometers used in the experiments were cup-type anemometers with a rated accuracy of 18 cm/s. The anemometers were positioned nominally 30, 60 and 90 cm above the vegetation. Average wind speed was recorded every 30 seconds for the duration of each experiment.

3.2.4 Vegetation Characteristics

Vegetation-sampling surveys were conducted four times during the course of the experiments (Carter et al., this volume). Each survey consisted of samples collected in eight 30-cm-by-45-cm areas distributed randomly throughout the test section of the flume. These biomass samples are being analyzed to create vertical profiles of vegetation density and other geometric properties, such as leaf area index, that can be used both to estimate vegetative resistance to flow and, later, to relate drag coefficients to vegetative properties measurable in the Everglades.

3.3 Experimental Parameters

The experiments conducted were designed to replicate a representative range of wind, water-depth, and flow-velocity conditions found in the Everglades. Figure 3 shows a month-by-month analysis of the mean and maximum 15-minute-averaged wind speeds collected at the USGS Old Ingraham Highway meteorological station in the Everglades during 1996 and 1997. The range of wind speeds that were used during the flume experiments was 0 m/s (0 fans) to nominally 9 m/s (4 fans), thereby simulating all but the most extreme wind conditions observed in the Everglades.

Water depths were maintained at either 30 or 76 cm by fixing the height of a barrier at the end of the flume. Discharges were varied from 0 to .024 m^3/s in the case of experiments conducted with a 30-cm water depth and from 0 to .055 m^3/s in the case of the experiments conducted with a 76-cm water depth. Both of these conditions correspond roughly to a range of 0 to 4.5 cm/s for the cross-sectionally averaged velocity in the flume. This range also simulates all but the most extreme conditions observed in the Everglades.

Most of the experiments were conducted with the water surface sheltered only by the emergent vegetation. However, a small subset of experiments was also conducted with the water surface covered by sponges distributed densely between plant stems. The purpose of these experiments was to simulate the effect of periphyton, commonly occurring algal mats found in the Everglades.

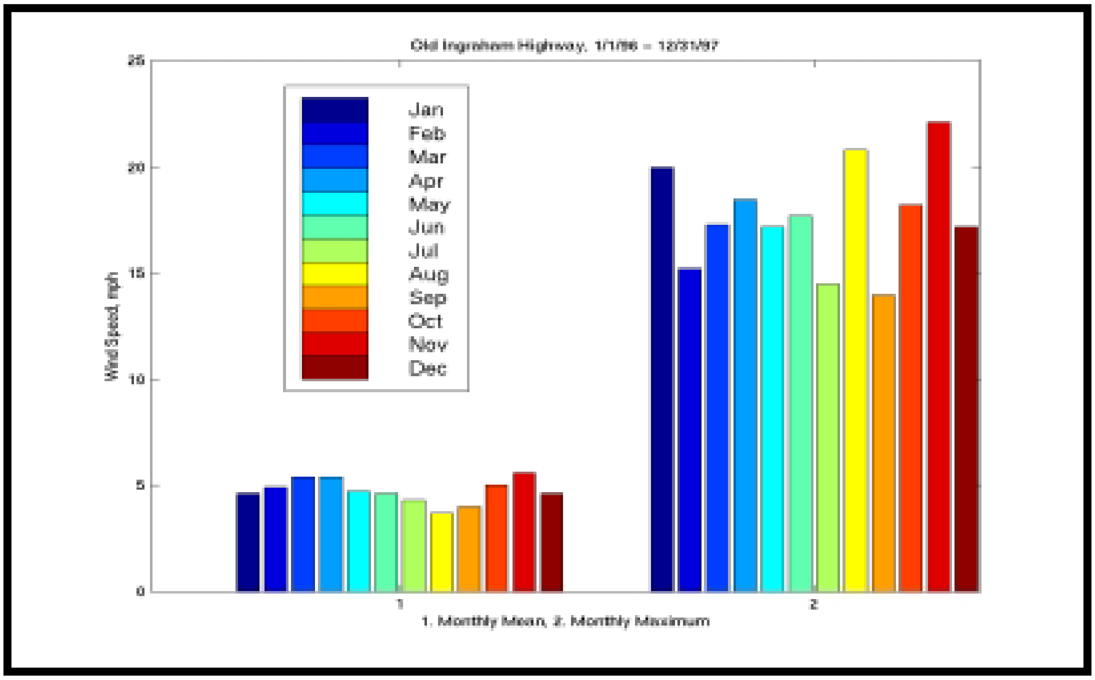

Figure 3. Histograms of average wind speed (left) and maximum 15-minute-averaged wind speed (right) as a function of month.

4. Experimental Status and Conclusions

The full suite of nearly 60 laboratory experiments has been completed. Each experiment consisted of hook-gage measurements, anemometer measurements, two vertical profiles of velocity and multiple burst measurements of pipe velocity. Approximately two thirds of these data has been reviewed and quality-assured at this time.

Some preliminary conclusions can be drawn from examining the velocity profiles. The first, as seen on the right side of Figure 2, is that the pipe velocity remained steady throughout the course of an experiment, which normally lasted one day. This result is typical of all the experiments analyzed so far. The implications of this are that the flow in the flume remained steady throughout each experiment, and that it is acceptable to assume that the horizontal acceleration term in the momentum balance is negligible for each experiment.

A second, more important, conclusion can be drawn from the plot on the left side of Figure 2. In cases where there were no sponges in the flume and the wind was blowing at its maximum speed, a detectable layer of high shear could be seen in the top 15 cm of the water column. This layer is particularly evident in the profile labeled 'East" in the plot, as well as in other profiles not shown. This is an indication of the presence of a local wind-stress effect.

Data from all four vegetation surveys have been compiled and will be published shortly (Virginia Carter, oral communication). Likewise, the calibration curve necessary to convert pipe centerline velocity to along-flume pressure gradient will be published shortly (J. K. Lee, oral communication). These publications along with the laboratory experiment data will allow calculation of the drag coefficient as a function of wind speed and vegetative properties. Further information on this and other USGS South Florida Place-Based Studies is available at http://www.sofia.gov.

5. References

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