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4301 Rickenbacker Causeway
Miami, Florida 33149

TITLE: Drag Coefficient Distribution and Wind Speed Dependence in Tropical Cyclones

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Drag Coefficient Distribution and Wind Speed Dependence in Tropical Cyclones

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Abstract

This project will update the most recent measurements of surface drag coefficient (Cd) in hurricanes to extend the measurements to mean boundary layer (MBL) winds over 70 m/s. All available GPS sonde profiles collected in hurricanes from 1997-2004 will be processed, stored in a modern relational database, quality controlled, and organized by mean boundary layer wind speed, storm relative location, and water depth. Profiles will be averaged and analyzed to provide updated values of surface stress, roughness, and Cd as a function of wind speed, storm-relative azimuth, and water depth. These mean profiles and associated derived surface exchange quantities will be made available to modelers to evaluate existing model surface layer momentum flux packages as well as develop new parameterizations for the coupled H-WRF model. The proposed effort is applied towards numerical weather prediction priorities EMC-1 and EMC-2.

Statement of Work

1. Proposal duration: 2 years

Points of Contact: Isaac Ginis, URI; Hua -lu Pan, EMC

2. Project Description

Sea surface momentum flux or stress (τ) in numerical weather prediction of tropical cyclones is modeled using the "bulk aerodynamic method" as:

$$\tau = \rho C_D U_{10}^2 = \rho u_*^2 \qquad (1)$$

based on a drag coefficient (C_D) and the 10 m wind speed (U_{10}) which varies logarithmically with height as described by the "log law" :

$$U_{10} = \frac{U*}{k} Ln\left(\frac{z}{zo}\right) \qquad (2)$$

where U* is the friction velocity, k is a constant, z is the height. The aerodynamic roughness length (Zo) is typically modeled through the Charnock (1955) relationship, which implies that the aerodynamic roughness of the sea surface increases with wind speed according to:

$$Zo = \alpha \frac{u_*^2}{g} \qquad (3)$$

where g is the gravitational constant. The Charnock coefficient, α in this expression takes on values ranging from 0.015 to 0.035.

The surface momentum flux is therefore governed by the drag or friction at the sea surface which in turn depends on a roughness which is parameterized as increasing with increasing wind speed. Measurements support this parameterization only up to wind speeds of ~28 m/s. For higher wind speeds the roughness dependence is extrapolated e.g. Large and Pond (1981). The surface enthalpy flux is also modeled using the bulk aerodynamic method and employs an enthalpy exchange coefficient that is dependent on C_D. According to the theory of Emanuel (1995), a hurricane is only maintained if kinetic energy is supplied by oceanic heat sources at a rate exceeding dissipation, suggesting a ratio of enthalpy exchange coefficient (C_E) to C_D ranging from 1.2 to 1.5 for mature hurricanes. At extreme wind speeds > 50 m/s, the typical extrapolations of wind speed dependent drag coefficients found in most models cause kinetic energy to be destroyed too rapidly to sustain a hurricane (Donelan et al., 2004).

In Powell et al., (2003), hereafter "PVR", analysis of mean profiles documented a logarithmic change of wind speed with height, suggesting the applicability of surface layer similarity in conditions associated with MBL winds up to 70 m/s. A fit of the profiles provided information on the surface stress or friction velocity (slope) and roughness (intercept) as a function of wind speed. This analysis determined a leveling off of the surface stress and drag coefficient in wind speeds > 34 m/s and a reduction in roughness length. This was the first time that measurements of drag coefficient were made in winds > 28 m/s.

The PVR findings have recently been corroborated by wind flume experiments (Donelan et al., 2004) and are already influencing model parameterizations of momentum flux in the hurricane boundary layer (Andreas 2004, Moon et al., 2004, Wang and Wu 2004). Moon et al., 2004 reports significant improvement of momentum flux parameterization using the WAVEWATCH wave model coupled with a new wave-wind model. Their model estimates of the surface roughness and drag coefficient in hurricanes compare favorably with PVR and the wave spectrum variation of Wright et al., 2001. The Moon et al., 2004 study suggested that higher and more developed waves produce higher sea drag in the right-front quadrant and lower and younger waves produce lower sea drag in the rear-left quadrant. This asymmetry increased with hurricane translation speed. The group at University of Miami lead by Mark Donelan and Shuyi Chen are also investigating wave dependent momentum flux parameterizations. Wang and Wu (2004) commented on the PVR work in a review article: "This breakthrough can lead to reduction of the uncertainties in the calculation of surface fluxes, thus improving TC intensity forecasts by numerical weather prediction models."

The basis for the PVR method is that each sonde profile is a realization or snap shot of tropical cyclone conditions. By organizing numerous realizations as a function of wind speed, the ergodic hypothesis (Panofsky and Dutton 1984) is invoked to consider each profile as an instance from an ensemble of profile samples in nearly identical conditions. The primary feature controlling the turbulence in these conditions is the ocean surface roughness and this quantity is dependent on the wind stress and sea state, hence the organization by wind speed. The profiles are organized by the "mean boundary layer" wind speed, defined as the average of all values below 500 m. Profiles are filtered to remove under-sampled flow (turbulent eddies, convective- and swell-related features) and noise due to satellite switching. Averaging the profiles removes larger scale convective features such as transient wind maxima or minima and provides information on the mean state and how it changes with the wind forcing.

PVR analyzed 331 GPS sondes dropped in 15 storms from 1997-1999. The recent CBLAST experiments, together with several additional years of research flights and operational reconnaissance should increase the number of high wind GPS sonde profiles to > 1000. Numerous sonde profiles are unwieldy for analysis with spreadsheet-type tools but ideal for a modern objectrelational database. AOML has an existing Oracle database and skilled technical specialists with expertise in database management,design, and query programming.

The large number of sondes will make possible more accurate ensemble mean profiles, as well as examination of how the mean profiles change with storm-relative quadrant. The intensive CBLAST investigations of 2003 Hurricanes Fabian and Isabel, together with experiments conducted in Hurricanes Frances, Ivan, and Jeanne of 2004 provide a wealth of high wind GPS sonde profile measurements that can extend the work of PVR. In particular, observational determination of the spatial distribution of roughness relative to the hurricane center to account for azimuthal variation of wave age and steepness as a function of wind speed will provide a data set for validating the current model parameterizations and developing new ones. To evaluate the effect of sea state, which varies azimuthaly because of the variation in swell characteristics relative to the wind, a larger (than PVR) data set is needed, ideally containing ~150 profiles for a given MBL grouping. The GPS sonde data through 2004 should provide sufficient profiles to study the azimuthal variation of surface stress and roughness.

Current models used to predict hurricane track and intensity use methods similar to (1). For example, an early version of the coupled GFDL model Bender et al., (1993) uses (3) with a constant of 0.0185. A new coupled version of GFDL model uses a coupled wave-wind model in which α increases with the input wave age and the surface wind speed. The planned HWRF model has a modular design that allows using different boundary layer physics packages. Careful testing will determine the final package used in the operational version of the model but regardless of the version, proper modeling of the surface momentum flux will need to account for the observed change in roughness as the wind speed increases, wave interactions with the wind that cause azimuthal variation in the roughness, and changes in the roughness caused by breaking and shoaling waves in shallow water. These processes will all be diagnosed through this project so our results will contribute to development and validation of momentum flux parameterizations in HWRF and the coupled GFDL model. In addition, it is expected that our results will also be valuable for wave and storm surge modeling with the coupled HWRF/ocean/ wave model.

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3. Proposed work plan

Year 1

In the first year of our JHT project, we will obtain sonde data from the 2000-2004 hurricane seasons, process and quality control the data. A database schema will be designed and tested and > 1000 available profiles will be loaded into an existing Oracle relational database. Additional information will be added to the database including storm position, water depth, and flight level observations at sonde launch. Storm tracks will be constructed for each flight mission in the database to allow storm-relative positioning of each profile, and partitioning the flow into radial and tangential components. Water depth information will be acquired, stored, and indexed to each sonde profile to allow organization by shallow or deep ocean. Queries will be designed to help organize the profiles and index to ancillary data.

Year 2

In the second year we will construct mean wind profiles grouped according to the mean boundary layer wind speed (MBL) in 10 m/s bands from 30-70 m/s. If sufficient data are available we will construct a mean wind profile for MBL winds > 70 m/s. If sufficient sonde profiles are available for specific MBL groups, we will study the azimuthal variation of the mean profiles and provide these results to modelers for investigation of possible wave interactions. Also in the second year we will add any new profiles collected the first year and document water depths associated with each profile. If sufficient profiles are available in shallow water for a given MBL wind speed group, we will evaluate the profiles to see if there are systematic differences in wind profiles near the coast. Recent observations from a coastal tower deployed at Cape Hatteras in Hurricane Isabel suggest that marine roughness for onshore flow is similar to that for open terrain over land. Coastal wind profiles are expected to be associated with larger drag coefficient values due to increased roughness associated with breaking and shoaling waves; we hope to accept or reject this hypothesis if sufficient data are available.

Hardware/Software Needs: Hard disk storage, statistical analysis software upgrades and water depth data sets will be purchased in the first year. No additional special hardware / software needs are recognized other than the communications and computing costs associated with the realtime LAN between AOML and TPC indicated in the budget.

Testing and evaluation approach: In the second year, as the results from each analysis phase are completed, we will supply the exchange coefficient relationships to modeling community for testing and evaluation.

Success Metrics: Development of wind speed- and/or azimuth- and/or water depth-dependent surface drag coefficient, roughness, and stress relationships. Successful incorporation of these relationships, or new methods based on these relationships, in the HWRF and GFDL coupled models.

Timeline with Deliverables and Key Milestones:

Year 1

0-6 months Assemble existing processed sondes from 1997-1999. Process and QC sondes form 2000-2003. Design and test database schema. Acquire water depth database. Process storm tracks for 2000-2003 to attempt to reach targets of ~150 profiles per ten m s^{-1} MBL group.

7-12 months Complete processing of sondes and storm tracks for 2004. Load all processed sonde profiles into the Oracle database. Begin query programming to organize sondes by MBL wind speed, storm relative azimuth, scaled radial coordinate, and water depth within each MBL group.

Year 2

1-3 months Analysis of mean profiles by MBL group. Provide relationships to modelers.

4-6 months Analysis of mean profiles by storm relative azimuth within each MBL group. Provide relationships to modelers.

7-9 months Analysis of mean profiles by water depth. Provide relationships to modelers.

Months 10-12 Discuss impact of new relationships on model results. Prepare manuscript on results.

Plan to port necessary codes: Results will be supplied to the modelers at EMC, GFDL, URI, and other interested institutions for building model parameterizations of momentum exchange in high wind conditions. Testing and eventual implementation of resulting parameterization codes in the operational HWRF and GFDL models would be conducted by URI, GFDL, and EMC, with our cooperation.

4. Scientific and technical documentation and training material timeline

Documentation on development of the flux coefficient relationships will be provided to EMC, GFDL, URI, and other modelers when each analysis phase is completed.

5. Travel

We anticipate one trip each year to consult with modelers at EMC and/or URI and one trip to present results at the IHC and possibly another conference each year.

6. Estimates of JHT staff requirements

Few JHT staff requirements are anticipated. As HWRF requirements become established, we will work with EMC to facilitate evaluation and testing of wind speed-, azimuth-, and water depth-dependent drag coefficient and roughness relationships.

7. Budget

Budget Justification:

Labor: Labor involves the NOAA PI and CIMAS scientific and technical support .

Equipment: Storage hardware for the GPS sonde database, statistical analysis software upgrade, water depth data cd/dvd.

Travel: PI visits to EMC, and/or other modeling centers, IHC and other relevant conferences

Publications: Costs for describing the results of the project in papers submitted to peer-reviewed journals.

F. Budget:

	JHT Year 1 Requested		JHT Year 2 Requested	
Personnel	mm	Amount	mm	Amount
AOML Powell	2.0	21.0	2.0	22.2
Technical and scientific support	5.0	14.0	5.0	14.8
Fringe Benefits:				
23.5% NOAA		5.5		6.0
CIMAS		4.2		4.8
Total Salaries and Fringe Benefits:		44.6		47.8
Indirect costs:				
39% NOAA		10.4		11.4
CIMAS		4.7		5.1
Total Labor Costs		59.7		64.3
Equipment:		3.0		0.0
Travel:		2.0		2.0
Publications:		0.0		2.0
Total requested funds:		64.7		68.3

Current federal support as PI: None

Pending proposals in review:

1. NASA TCSP: "Integrating and Blending Diverse Observing Platforms to Assess Observations and Forecasts of Tropical Cyclone Genesis, Wind Structure, and Intensity Change", 2 mm /yr, $499K, 3 years.

2. NOAA HPCC: "Real-time hurricane monitoring onboard NOAA aircraft", no PI labor, $106k, 1 year

3. DOC Pioneer Fund: "Real-time Hurricane Wind Field Input to FEMA-HAZUS", Equipment only, $50 k, 1 year

4. NASA Decision Support through Earth Science Results, "Real time hurricane monitoring for decision support to DHS-FEMA's HAZUS Model", Step 1 (letter of intent) proposal, no budget as yet.

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Higher Education: Meteorology

BS 1975, PhD 1988: The Florida State University; MS 1978 Pennsylvania State University

Professional Certification: AMS Certified Consulting Meteorologist (#475)

Employment: Atmospheric scientist, NOAA Hurricane Research Division, AOML (1978-)

Awards: Department of Commerce Gold Medal, 1992 (Unit Award, Hurricane Andrew)
Special Recognition Award, 1996: SOO for the NOAA Olympic Marine Forecast Team
NOAATech 2000 H*Wind "Best JAVA Implementation Award",
NOAATech 2002 H*Wind "Best Transition to Operations Award"

Selected Refereed Journal Publications:

Powell, et al.,, 2004: Tropical Cyclone Winds at Landfall: The ASOS-CMAN Wind Exposure Documentation Project. *Bull. Amer. Met. Soc.*, 85, 845-851.

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