Investigation of HWRF Model Error Associated With Surface-Layer and Boundary-Layer Parameterizations To Improve Vortex-Scale, Ensemble-Based Data Assimilation Using HEDAS

(*In Response To NOAA-NWS-NWSPO-2011-2002893*)

Principal Investigator: Dr. Altuğ Aksoy, CIMAS, University of Miami/RSMAS

Co-Investigators: Dr. Jun Zhang, CIMAS, University of Miami/RSMAS
Mr. Bradley Klotz, CIMAS, University of Miami/RSMAS

Project Period: August 1, 2011 – July 31, 2013 (second year provisional)

ABSTRACT

This proposal is in response to the NOAA HFIP announcement (NOAA-NWS-NWSPO-2011-2002893) and aims to address program priority 1, "Advancement in data assimilation techniques for hurricane NWP", as well as program priority 2, "Advancements in hurricane NWP".

This research will be carried out as part of the Cooperative Institute for Marine and Atmsopheric Studies (CIMAS) program under the "Tropical Weather" and "Sustained Ocean and Coastal Observations" themes. It will be conducted in a manner consistent with NOAA's goal to serve society's needs for weather and water information.

We propose to investigate representation of model error in ensemble-based estimates of background error covariances. We envision our results to be of significant scientific and practical value for both ensemble-based and ensemble/variational hybrid data assimilation systems with NOAA's Hurricane Weather Forecasting and Research (HWRF) model. Specifically, we will target processes within the surface-layer (SL) and boundary-layer (BL) parameterizations of the HWRF model because they are known to control vortex dynamics in the inner core of a hurricane and therefore directly relate to the forecast of intensity.

We hypothesize that an improved knowledge of HWRF BL sensitivity to identified parameters of the SL and BL parameterizations of the model should allow us to perturb such parameters in an ensemble, in a manner consistent with the identified sensitivity relationships. This should also help us account for some portion of model error that is otherwise not accounted for in an ensemble with pure initial-condition perturbations. Consequently, enhanced ensemble variability and information content in background error covariances is expected, especially in the SL/BL structure, so as to improve high-resolution hurricane vortex analyses during data assimilation with inner-core hurricane observations.

To identify the sensitivity of the hurricane SL/BL structure to some of the key parameters of the SL and BL parameterizations of the HWRF model, we will investigate model BL behavior and its variability in an idealized environment, where modeled hurricane intensity can be controlled through specified sea surface temperatures (SST), and vertical profiles of atmospheric temperature, humidity, and horizontal wind in and outside the hurricane core. We will use the Hurricane Ensemble Data Assimilation System (HEDAS) to investigate the impact of representing model error in the ensemble estimates of the background error covariances.

Investigation of HWRF Model Error Associated With Surface-Layer and Boundary-Layer Parameterizations To Improve Vortex-Scale, Ensemble-Based Data Assimilation Using HEDAS
(*In Response To NOAA-NWS-NWSPO-2011-2002893*)

Principal Investigator: Dr. Altuğ Aksoy, CIMAS, University of Miami/RSMAS
Co-Investigators: Dr. Jun Zhang, CIMAS, University of Miami/RSMAS
Mr. Bradley Klotz, CIMAS, University of Miami/RSMAS

PROJECT DESCRIPTION

1. Scientific Objectives

(1) Quantify the structures of the HWRF surface layer (SL) and boundary layer (BL) and the variabilities therein relative to those observed due to the uncertainties in surface momentum and heat exchange coefficients and specific BL parameters that control vertical eddy diffusivity and BL depth.

(2) By using information obtained from objective (1) as to the expected mean values and variances of the surface momentum and heat exchange coefficients and specific BL parameters, quantify the impact of accounting for such variability in SL and BL parameters in the HEDAS ensemble on the performance of HEDAS and the resulting estimates of vortex structure and TC intensity in such HEDAS analyses.

(3) By using information obtained from objectives (1) and (2),

(a) Quantify the impact of accounting for such variability in SL and BL parameters in the HEDAS ensemble on the evolution of vortex structure and intensity in the short-range (up to 24 hours) deterministic/ensemble forecasts initialized with the corresponding HEDAS vortex analyses.

(b) Investigate how and by how much the findings in objective (2) are correlated with the findings in objective (3a). In other words, examine how frequently improvements in SL/BL structures in HEDAS analyses lead to improvements in the forecast of these structures.

2. Project Duration

2 years.

3. Background

a. Introduction

Tropical cyclones (TCs) are high-impact weather phenomena that have had significant impacts on the US population and economy. Exacerbating the situation, vulnerability to TCs is only projected to amplify with the ever-growing population along the US coastline (Pielke 1997).

Predicting the societal/economic impacts of a TC critically depends on the successful prediction of both its track and intensity. In recent years, there has been a marked improvement in our ability to predict hurricane tracks. A major challenge that still remains today is to skillfully forecast changes in hurricane intensity (especially episodes of rapid intensification). According to the National Hurricane Center's (NHC) most recent forecast verification statistics covering the period between 2000-2009[1], official track forecast skill has improved by almost 50%. However, TC intensity forecast skill over that same time has remained virtually unchanged.

Based on data from the operational Statistical Hurricane Intensity Prediction Schemes (SHIPS) model, a recent study by Kaplan et al. (2010) found that large-scale atmospheric factors outside the hurricane core (e.g., vertical wind shear, upper-level divergence, and low-level moisture) are only able to capture 35% of the variance in predicting rapid intensification (RI) in the Atlantic basin[2]. This result suggests that up to 65% of the remaining variance may be explained by factors associated with the inner-core vortex dynamics and near-surface ocean-atmosphere, pointing to the need to initialize hurricane prediction models with realistic, three-dimensional initial vortex structures. This is also supported by recent findings on the importance of the asymmetric vortex structure in determining the subsequent evolution of storm intensity (e.g., Reasor et al. 2004; Mallen et al. 2005; Nguyen et al. 2008; Rogers 2010).

b. *HRD's Hurricane Ensemble Data Assimilation System (HEDAS) and Key Findings from the 2010 Hurricane Season*

The ensemble Kalman filter (EnKF), as an advanced data assimilation technique, is expected to provide realistic asymmetric initial vortex structures by employing flow-dependent background error covariances from an ensemble. Examples of recent success with assimilating radar observations of continental convective storm cases using the EnKF (e.g., Snyder and Zhang 2003; Zhang et al. 2004; Dowell et al. 2004; Dowell et al. 2010; Aksoy et al. 2009, 2010) raise hopes that high-resolution hurricane initialization, too, can benefit from the same technique. In a proof-of-concept study to evaluate impact of radar observations on TC analysis, Zhang et al. (2009) demonstrated that the EnKF exhibited skill that was superior to a 3DVAR scheme.

Recently, HRD has taken the initiative to build a high-resolution hurricane data assimilation system that is coined Hurricane Ensemble Data Assimilation System (HEDAS). Within NOAA, HRD has been collecting high-resolution airborne observations in hurricanes for over 30 years using WP-3D (P-3) aircraft (e.g., Aberson et al. 2006) in the hurricane core, and for over 10 years using the high-altitude Gulfstream-IV jet (G-IV) (e.g., Aberson 2009) for the hurricane environment. In addition, a wealth of data from the U.S. Air Force Reserve C-130J aircraft (Rappaport et al. 2009) are also available for assimilation in HEDAS.

A key aspect of HEDAS is that it is interfaced with the HWRF system. Therefore, despite being a research system by design, findings from HEDAS are expected to have direct implications for NOAA's regional modeling interests and for the operational HWRF modeling system, specifically in terms of providing information such as value of inner-core observations in initializing a realistic three-dimensional vortex structure and value of ensemble-based, flow-dependent covariance information in constructing a high-resolution, three-dimensional initial vortex structure.

---

[1] The NHC periodically updates its forecast verification statistics on its webpage at the following address: www.nhc.noaa.gov/verification.

[2] RI, in this context, is defined as an increase in hurricane intensity (measured by the maximum 2-min sustained 10-m wind speed) by a minimum of 30 kt within a 24-hour period.

Some preliminary findings from HEDAS are summarized by Aksoy et al. (2011), Sellwood et al. (2011), and Vukicevic et al. (2011). The performance of HEDAS, both in the context of simulated aircraft observations and real observations, has been found to be very satisfactory: In Figure 1, we demonstrate that forecasts using HRD's HWRF configuration with HEDAS initial vortex lead to improvement in intensity error over same model without HEDAS initial vortex as well as operational HWRF, at 24-72 h forecast lead times, underlining the advantages of initializing with a more realistic three-dimensional vortex structure that results from advanced data assimilation.

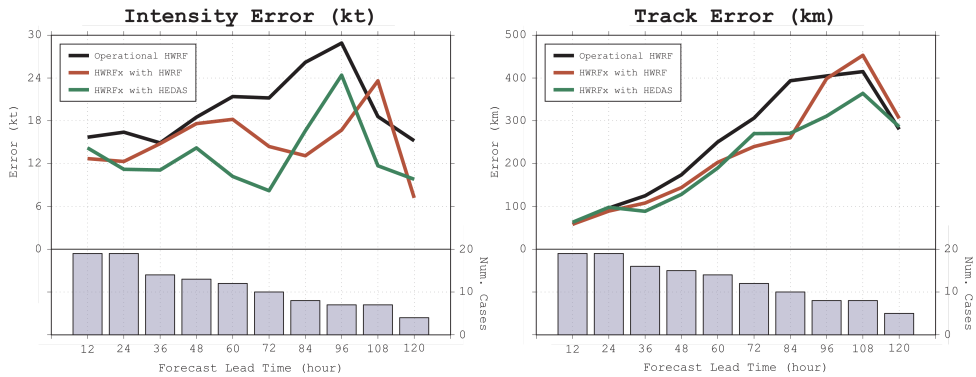

Figure 1: Comparative maximum 10-m wind speed intensity forecast error (kt, left panel) and track forecast error (km, right panel) statistics, as a function of forecast lead time (hour), for HRD's HWRF configuration with HEDAS (green) vs. operational HWRF (red) initial vortex, and operational HWRF (black). Number of homogeneous cases used is also shown.

Despite considerable success, an important outcome of the 2010 hurricane season semi-real-time HEDAS runs was that hurricane intensity tended to be under-estimated when observed intensity was high (Sellwood et al. 2011). This is demonstrated in Figure 2a, where hurricane intensity in HEDAS analyses is compared to NHC's corresponding operational best estimates for all Hurricane Earl (2010) cases.

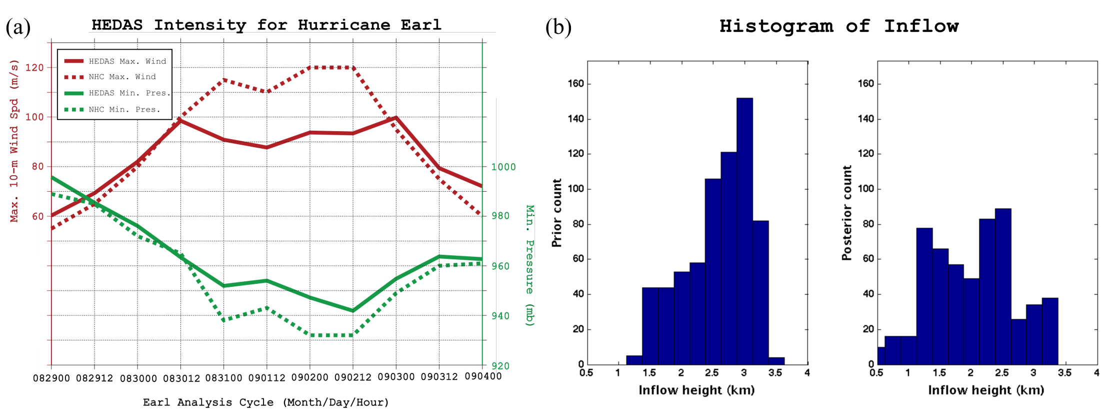

Figure 2: (a) HEDAS analysis intensity (solid, red: 10-m wind speed, m s^{-1}, green: minimum sea-level pressure, mb) and NHC operational intensity (dashed lines) for Hurricane Earl (2010). **(b)** Comparison of boundary layer inflow probability distribution (histogram) as a function of height from all HEDAS assimilation cycles during Hurricane Earl's (2010) strong phase (category 3 or 4 between 31 August 00Z and 2 September 12Z). Prior count (left): Short-range background forecast distributions. Posterior count (right): Analysis distributions.

Exploring the potential reasons for such preferred analysis bias in HEDAS by Vukicevic et al. (2011) revealed that the under-estimation of intensity in the final vortex analyses of HEDAS was closely linked to how the model behaved in these weak vs. strong hurricane situations, through the underlying connection between the filter and the model during the cycling with observations. More specifically, a pattern of more pronounced discrepancy between the modeled and observed SL/BL structures during the stronger phases of Hurricane Earl was discovered. An example of this behavior is shown in Figure 2b, where it is evident that the model tends to over-predict the depth of the inflow layer in short-range forecasts (as assimilations are assimilated in hourly cycles in HEDAS, short-range forecasts here are of 1-hour lead times) by as much as 1 km.

We believe that the sub-optimal BL behavior in HEDAS analyses and the underlying HWRFX model leads to significant and rapidly-developing model bias in high-wind-speed regimes. Such cycle-to-cycle fluctuations due to BL adjustments are currently thought to be the primary cause of intensity under-estimation in HEDAS in high-wind-speed regimes.

c. *Review of Theoretical and Observational Studies on Surface-Layer and Boundary-Layer Processes in Tropical Cyclones*

The transport of kinetic energy and heat through the boundary layer of a TC has long been known to be the primary controlling factor of TC intensity (e.g., Malkus and Riehl 1960, Emanuel 1986). It has been demonstrated that hurricane intensity in both idealized, axisymmetric, quasi-balanced models (Emanuel 1995) and “full-physics” nonhydrostatic models (e.g., Nolan et al. 2009a, b) exhibits significant sensitivity to the ratio of the bulk exchange coefficient for enthalpy flux (C_K) to the exchange coefficient for momentum (C_D), or C_K/C_D, and to the selection of BL schemes. Based on the comparison of model predictions with observations of the hurricane intensity for a number of hurricanes, Emanuel (1995) concluded that C_K/C_D lies in the range of 1.2-1.5 in the high-wind regime and suggested 0.75 as the lowest threshold to maintain TC intensity. Clearly, the underlying assumption here was that increasing surface drag led to a decrease in TC intensity. In a recent study, Montgomery et al. (2010) analyzed the impact of C_D on TC evolution using an idealized three-dimensional model with a bulk-aerodynamic BL scheme and warm-rain microphysics. They suggested a critical role of the BL formulation characteristics in determining TC intensity, independent of the effects of surface drag. The sensitivity of a three-dimensional numerical model to the BL formulation was further investigated by Smith and Thomsen (2010), where a variety of BL parameterization schemes were used with identical formulations of SL/BL processes. An interesting outcome of this study was that the MRF scheme was overly diffusive and resulted in the largest BL depths and smallest inflow angles. It is curious to note here that the HWRF model (in both operational and HRD’s research configurations) also employs this same MRF-based BL parameterization scheme.

Over the last several decades, much effort has been made to determine the values of C_K and C_D empirically (e.g., Large and Pond 1981; Fairall et al. 2003). Drennan et al. (2007) and French et al. (2007) review previous field and laboratory experiments of turbulent flux measurements including the recent results of Powell et al. (2003) and Donelan et al. (2004) showing C_D leveling off at wind speeds over 30 to 40 m s^{-1} (Figure 2a). They also summarize the results of the first direct measurements of latent heat and momentum fluxes in high wind speeds using data from the Coupled Boundary Layer Air-Sea Transfer (CBLAST) hurricane experiment. Zhang et al. (2008), based on CBLAST results, and Haus et al. (2010), based on laboratory experiments, report that C_K is independent of surface wind speed up to 40 m s^{-1} (Figure 2b).

An extensive observational database of near-surface atmospheric variables within hurricanes has been assembled over the past several years. Cione et al. (2000) and Cione and Uhlhorn (2003) documented the radial distribution of buoy-observed temperature, humidity, wind speed, and sea-surface temperature relative to translating hurricanes since the mid 1970's. Over 15,000 individual observations in the database indicate that the near-surface inflow layer temperature typically cools 2 °C or more relative to the ambient tropical environment prior to reaching the eyewall, while specific humidity shows a 2-3 g/kg drying trend, before rapidly moistening at the eyewall. Average eyewall RH conditions can vary on the order of ±5% (±1 g/kg). Such (seemingly subtle) variability can significantly modify inner core surface moisture fluxes by ±20-25%.

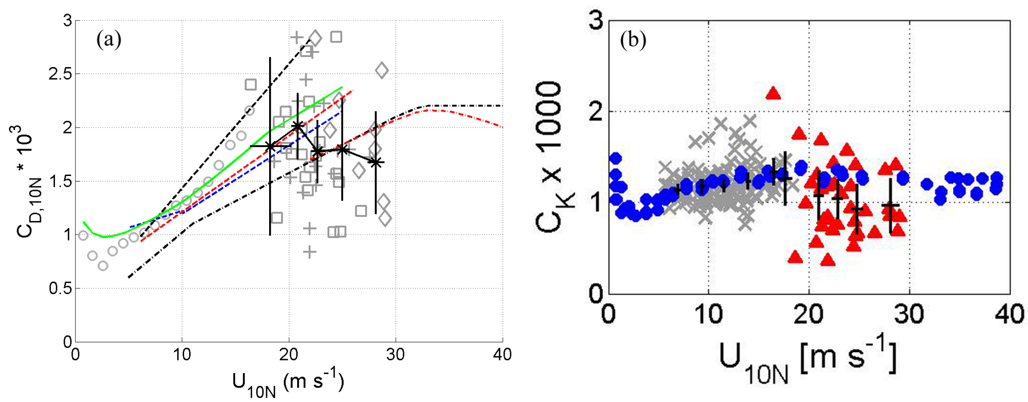

Figure 2: (a) Drag coefficient as a function of 10 m wind speed from the CBLAST experiment (Black et al. 2007). The blackdash-dot line represents the values from Donelan et al. (2004); the red dash-dot line from Powell et al. (2003); **(b)** Wind speed dependence of C_K from the ASIST laboratory results (●) (Haus et al. 2010) and CBLAST (▲) (Zhang et al. 2008) and the HEXOS results (x) (DeCosmo et al. 1996).

The mean BL structure in individual TCs has been broadly studied (e.g., Powell 1990a, b). Especially since 1997, when the global positioning system (GPS) dropwindsonde (Franklin et al. 2003) became available, the mean hurricane BL structure has been sampled in great detail (e.g., Kepert 2006a, b; Bell and Montgomery 2008). However, observations of turbulence structure have been scarce. Recently, Zhang et al. (2009) presented vertical profiles of directly measured fluxes in the hurricane BL between rainbands within four intense hurricanes. They showed that turbulent momentum fluxes are near zero at a height which is close to the depth of the inflow layer, not at the top of the mixed-layer. Meanwhile, using flight-level data during low-level eyewall penetrations, Zhang et al. (2011) found that the turbulence parameters estimated during eyewall penetration legs are nearly an order of magnitude larger than those for the legs outside the eyewall.

4. Underlying Hypotheses

Given that NOAA's operational HWRF model has limited horizontal resolution in the TC core and its MRF-based BL parameterization scheme is overly diffusive, it seems natural to expect unique model climatology of SL and BL behavior from it. Consequently, our proposal is founded on the following hypotheses:

(1) Intensity under-estimation issues in HEDAS, observed in high-wind-speed regimes, at least partially arise from the misrepresentation of SL and BL processes in the HWRF model.

(2) The misrepresentation of SL and BL processes in the HWRF model lead to both systematic deviations and a lack of variability of SL and BL structures from those observed.

(3) As model error is not explicitly accounted for in HEDAS, SL and BL variability is under-represented in the background covariance matrix.

(4) Under-representation of model error in the background covariances limits the variability in ensembles, leading to insufficient ensemble spread. This results in potential issues such as filter divergence that impedes the performance of a data assimilation system.

(5) In the TC inner core in high-wind-speed regimes, the HWRF model exhibits short-range sensitivity to SL exchange coefficients of heat and momentum as well as BL vertical eddy diffusivity and depth.

(6) Representing uncertainty of SL exchange coefficients of heat and momentum and BL vertical eddy diffusivity and depth within the operational SL and BL parameterization schemes is a viable approach to accounting for model error due to SL and BL processes.

(7) Only replacing the current SL and BL schemes with alternatives that may have more favorable representation of observed BL structure is not desirable, because not only would this lead to unknown new model biases, but also prevent the stochastic nature of model error from being represented in the background error covariances.

5. Proposed Methodology

We plan to approach the proposed research project in three phases, as described below:

1. Investigate HWRF Bias and Sensitivity in Surface- and Boundary-Layer Parameterizations

In the first phase of the proposed work, we will investigate the details of short-range HWRF sensitivity to the various aspects of its current SL and BL parameterizations, thereby addressing objective (1). Figure 3 summarizes our approach in a schematic.

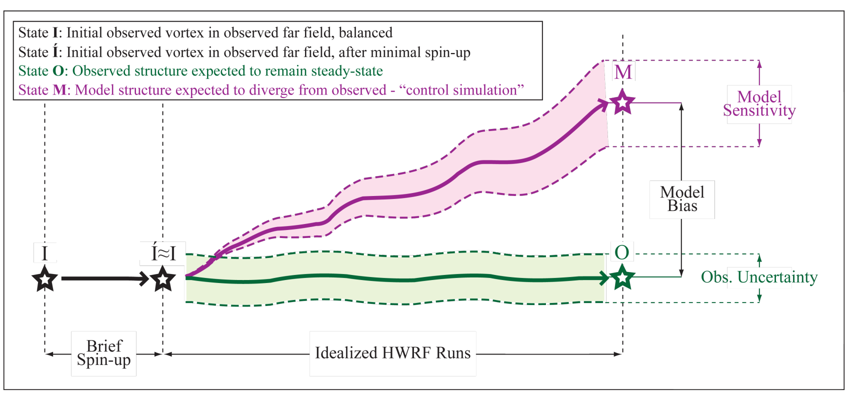

Figure 3: Schematic description of idealized HWRF experiments to investigate model sensitivity to SL and BL parameters. Trajectories specifically depict SL/BL behavior.

Based on hypothesis (2), we expect systematic differences to develop in the SL and BL between an idealized HWRF model run and observations. We will initialize our model runs with a balanced vortex/environment combination that is consistent with composite observations obtained in steady-state mature hurricanes. As these observed SL/BL structures are sub-sampled within steady-state hurricanes, they are expected not to vary much in time (solid green in Fig. 3), so that any model deviation from such structure can be attributed entirely to the model's SL and

BL formulations (solid purple in Fig. 3). To assess model sensitivity to SL and BL parameters, we will then proceed to perturb parameters about the assumed mean values. The magnitudes of these perturbations will be consistent with the variability in observations, when available. Using identical initial balanced vortices and environments as before, idealized HWRF ensembles will be constructed where ensemble members only differ in their perturbed parameter values, thereby altering their trajectories as compared to the mean model SL/BL structure. This ensemble of possible model SL/BL trajectories is depicted with the purple shading in Figure 3. The resulting model SL/BL variability at the end of the simulation period will then be compared against model bias, as well as the corresponding observed uncertainty, through means of statistical significance.

In the following, the details of the tasks to be undertaken within the first phase of the study are described:

1.1. Configure idealized HWRF simulations

Gopalakrishan et al. (2010) describe the details of the HWRFX idealized hurricane modeling system framework. We will utilize the existing capabilities of this system, only modifying the physics options to mimic the operational HWRF configuration. As typical in HEDAS, 2 nested domains of 9 km and 3 km horizontal resolutions, respectively, will be used.

As our overall focus in this proposed research is on improving HEDAS analyses through accounting for HWRF SL/BL model error, we will limit the durations of idealized HWRF simulations to 12-24 hours, with special emphasis on very short range (<1 h) error growth rate characteristics. (In the current implementation of HEDAS, we observe significant BL departures and intensity fluctuations within cycle-to-cycle ensemble forecasts.)

1.2. Construct initial axisymmetric vortex, far field profiles, SSTs

Following Gopalakrishnan et al. (2010), we will embed an axisymmetric vortex within prescribed environmental profiles of wind velocity, temperature, and humidity. Based on a large sample of GPS dropwindsondes, co-PI Zhang has developed lower-to-middle troposphere composite analysis of temperature and humidity within the TC inner core. The upper troposphere in TCs is comparatively under-sampled due to aircraft limitations; however a few recent field campaigns (e.g. NASA CAMEX, TCSP) have obtained profiles from higher altitude (>3 km) to allow construction of composite fields throughout the troposphere. An extensive database of 3-D airborne Doppler radar wind velocity has also been constructed at HRD (Rogers et al. 2011) which will aid the development of the initial vortex. The SST will be prescribed so that radial profiles of ΔT and Δq within the vortex are consistent with observed composite buoy observations from hurricanes with similar characteristics. Additional balance constraints will be imposed and a vortex spin-up period will be necessary to further balance the thermodynamic and wind fields. The intensity of this initial balanced vortex will be controlled in part by the environment constraints (e.g., shear, SST, outflow-level temperature) to yield an initial vortex of optimal steady-state intensity, while retaining as much of the observed axisymmetric structure as possible.

1.3. Select key surface-layer and boundary-layer parameter values and their uncertainties

The idealized HWRF runs with the mean values of the parameters of interest will constitute the “control simulation” (as depicted by the thick purple line in Figure 3). In the SL of the control simulations, we plan to use a constant C_K = 0. 0012 following Zhang et al. (2008), while C_D will be a function of wind speed based on the CBLAST results, extrapolating it beyond 30 m s^{-1}

following Smith et al. (2009). It should be noted that for the 2010 hurricane season, the operational HWRF model's GFDL SL parameterization scheme was modified to incorporate wind-speed-dependent C_D values (Kwon et al. 2010), which we will also use. As for the BL depth, we will experiment with modifying the critical Bulk Richardson number, with the control value being set to $R_i = 0.5$. We will attempt to cap the vertical eddy diffusivity to 100 m^2 s^{-1} following Zhang et al. (2011). The observed scatter in all of these SL and BL parameters, when such information is available, will be used as a first guess to determine the maximum and minimum limits allowed when perturbing them.

1.4. Construct idealized HWRF experiments based on ensemble perturbations of key parameters

In this proposed research, we plan to measure HWRF sensitivity to SL and BL parameters in an ensemble framework. An ensemble of idealized HWRF runs will be generated where all ensemble members use the same initial and boundary conditions but only differ in the realization of parameter values assigned. This method ensures that the only reason ensemble members diverge from one another will be the perturbed SL and BL parameters. We plan to have 50 members in our ensembles.

We will allow parameters of interest to only vary within specific ranges of physical values to ensure realistic physical model response. To obtain pseudo-random perturbations for a model parameter *p* defined within specified values of *A* and *B*, we will first produce pseudo-random values of a synthetic parameter y_p that is normally distributed (mean 0; variance 1). We will then perform a $y_p \rightarrow p$ transformation (Nielsen-Gammon et al. 2010):

$$\boldsymbol{p} = \boldsymbol{A} + \left[0.5 + \frac{\arctan(\boldsymbol{y}_p)}{\pi} \right] (\boldsymbol{B} - \boldsymbol{A}). \quad (1)$$

This transformation ensures that, while y_p varies from $\pm\infty$ with a Gaussian probability distribution, almost 70% of the variation of *p* follows a fairly flat distribution within [A:B] (Nielsen-Gammon et al. 2010).

To give an example, when C_D is being perturbed, 50 random values of y_p will be selected from a Gaussian (mean 0; variance 1). These 50 values will then be converted to actual random C_D values by using equation (1), where *A* and *B* will represent C_D's observed lower and upper limits of variation, respectively. These 50 random C_D values will then be used in each of the 50 ensemble member model integrations.

Four ensembles will be generated each containing only one perturbed parameter with the others held fixed at their control values. We will also create additional ensembles by simultaneously perturbing multiple parameters to investigate nonlinear. However, when multiple parameters are perturbed, sampling a *D*-dimensional parameter space at resolution *N* increases computational expense increases by N^D. Methods to efficiently sample a high-dimensional parameter space with low resolution exist in the literature. The technique known as the Latin Hypercube Sampling (LHS) with the mean distance maximization constraint (Hacker et al. 2011) results in evenly distributed parameter combinations throughout the parameter space and is appropriate for our purposes.

1.5. Analyze idealized HWRF experiments

In addition to the standard global metrics of track and intensity, analyses that focus on the structure of the forecast/analysis vortex will be compiled. These structure-related analyses include diagnostics of axisymmetric primary/secondary circulations and thermal structure, statistical analysis of convection using contoured frequency by altitude diagrams (CFAD), and detailed analysis of boundary layer structure (e.g., depths of the inflow layer and well-mixed layer, distributions of turbulent kinetic energy and momentum/heat fluxes). Analysis of how specific parameters and model variables are correlated in the hurricane vortex, both in terms of their radial/vertical distributions and time evolutions, will also be carried out.

2. <u>Investigate HEDAS real-data performance with and without parameter perturbations</u>

In the first phase of the proposed work, we will investigate the impacts of parameter perturbations on HEDAS analyses in real-data cases. As depicted in Figure 3, how large model sensitivity is in comparison to model bias will ultimately determine how likely it is to capture the observed SL/BL structure within an ensemble when SL/BL parameters are perturbed. If sufficient ensemble spread can be generated through parameter perturbations (phase 1) such that at least a few ensemble members with appropriate parameter combinations would reproduce realistic SL/BL structures, HEDAS analyses could be expected to benefit from this added information content in the background covariance matrix.

We should note in passing that it is also possible for the HWRF model to be not very sensitive to SL/BL parameters even under high-wind conditions (i.e., the situation when the null hypothesis cannot be rejected). However, based on our own observations of HWRF behavior within HEDAS (e.g., Fig. 2b) and other results in the literature (e.g., Nielsen-Gammon et al. 2010), we do not see this as a likely outcome. Should this alternative nevertheless be realized, a traditional state-based bias correction may be a more appropriate approach to mitigating HWRF model error in the SL and BL.

In the following, the details of the tasks to be undertaken within the second phase of the study are described:

2.1. <u>Configure HEDAS for real-data experiments</u>

With some minor possible modifications to the 2010 real-time configuration (Aksoy et al. 2011; Sellwood et al. 2011), the 2010 system will likely run in real time during the 2011 hurricane season. We plan to use this real-time configuration with HWRF physics as in our idealized experiments. HEDAS uses a square-root EnKF (Whitaker and Hamill 2002), employs covariance localization (Gaspari and Cohn 1999) with 240-km radius of influence, and can be configured to use isotropic covariance inflation and/or covariance relaxation (Zhang et al. 2009). Its cold-start ensemble perturbations are obtained from GFS/EnKF global system (Hamill et al. 2010) that also operates on the t-jet computer.

2.2. <u>Select real-data cases</u>

We will select real-data cases of mature, steady-state hurricanes. In order to obtain diagnostics of both HEDAS analyses and ensemble forecasts from HEDAS analyses (phase 3), we require that Doppler radar data also exist at most 12 hours after a case of interest. Two well-observed recent hurricanes fit our above criteria (Hurricane Bill (2009) on August 19 00Z and 12Z and August 20 00Z, and Hurricane Earl (2010) on September 1 12Z and September 2 00Z). In addition to these cases, we are also planning to use cases with similar characteristics that could likely be observed by the NOAA Hurricane Field Program during the 2011 hurricane season.

2.3. Process data to be assimilated

Standard HEDAS real-time aircraft data will be assimilated in the proposed research project. From NOAA P-3 aircraft, HEDAS assimilates the following observations (observational errors in parantheses): Doppler radar wind speed (2 m s^{-1}), dropwindsonde atmospheric profiles of wind speed (2 m s^{-1}), temperature (0.5 K), and specific humidity (0.1 g kg^{-1}), in situ flight-level observations of wind velocity (2 m s^{-1}), temperature (0.5 K), and specific humidity (0.1 g kg^{-1}), and stepped frequency microwave radiometer (SFMR) surface wind speed (error is wind-speed- and rain-rate-dependent as in Uhlhorn et al. 2007). Dropwindsonde, flight-level, and SFMR measurements from the U.S. Air Force Reserve flights are also assimilated when available.

2.4. Construct HEDAS experiments with and without parameter perturbations

HEDAS is already completely automated on the NOAA t-jet computer. Although we plan to use 50-member ensembles for HWRF sensitivity experiments (phase 1), we will continue to adhere to the 30-member real-time HEDAS ensemble configuration here. In these HEDAS experiments, in addition to the usual initial-condition and boundary-condition perturbations, each ensemble member will contain pseudo-random realizations of SL/BL parameters of interest during spin-up and cycle-to-cycle model integrations. The magnitude of these parameter perturbations will be consistent with our findings in phase 1.

2.5. Diagnose HEDAS analyses in observation and model space

A wealth of observation-space and model-space diagnostic tools already exist within the HEDAS framework. Observation-space diagnostics include such metrics as root-mean-square (rms) innovation, mean innovation, ensemble spread, and spread consistency, as explained in detail in Aksoy et al. (2009). These measure the goodness of fit of forecasts and analyses to observed quantities, as well the sufficiency of ensemble spread in comparison to rms error and observational error. In model space, diagnostics of HEDAS analysis structures will be similar to the analysis procedure described for idealized HWRF runs (item 1.5). In addition, these diagnostics will also be carried out for the available observations to obtain a direct comparison of modeled vs. observed SL/BL structures.

3. Investigate ensemble forecasts initialized with HEDAS analyses with and without parameter perturbations

3.1. Configure ensemble forecasts

We will configure ensemble forecasts so that each ensemble member will contain the same pseudo-random realizations of SL/BL parameters of interest as in the corresponding HEDAS analysis runs. These forecasts will be directly initialized with analysis vortex structures as determined by HEDAS.

3.2. Diagnose ensemble forecasts

Ensemble forecasts will be diagnosed in a similar fashion to the model-based diagnostics of HEDAS analyses. In addition to comparing ensemble-mean and ensemble-member forecast fields to those observed at the 12-hour forecast time (aircraft observations will be available at these times as cases are chosen as such), we will also analyze how the ensemble transitions from the HEDAS analysis at the initial time to forecasts and assess the additional impact of parameter perturbations in this context.

6. Timetable and Tasks

Following the breakdown of proposed work as explained in the previous section, below we show the detailed list of tasks we propose to perform during the project for each year in tables:

Task	Duration (months)
<u>**Year 1**</u>	
1. HWRF Sensitivity: Analyze HWRF model sensitivity to SL and BL parameters	**12**
1.1. Configure idealized HWRF runs (Aksoy)	*1*
1.2. Construct initial axisymmetric vortex structure, far fields, SSTs (Aksoy: 3 mo, Zhang: 1 mo, Uhlhorn: 0.5 mo, Cione: 0.5 mo)	*5*
1.3 Select SL/BL parameters to perturb	*1.5*
(a) Analyze HWRF GFDL BL code to determine key parameters that control vertical diffusivity and BL depth (Klotz)	.0.5
(b) Determine SL/BL parameter mean values and ranges (Zhang)	1
1.4 Run ensembles of idealized HWRF experiments with single-parameter and multiple-parameter perturbations (Aksoy: 1 mo, Klotz: 0.5 mo)	*1.5*
1.5 Analyze idealized HWRF experiments (Aksoy: 1 mo, Zhang: 1 mo, Uhlhorn: 0.5 mo, Cione: 0.5 mo)	*3*
<u>**Year 1 Totals:**</u> Aksoy .... 6 months; Zhang .... 3 months; Klotz .... 1 month; Uhlhorn .... 1 month; Cione .... 1 month; **Total .... 9 months**	
<u>**Year 2**</u>	
2. Impact of SL/BL parameter perturbations on HEDAS: Diagnostics of HEDAS analyses	**7**
2.1. Configure HEDAS real-data experiments (Aksoy)	*0.5*
2.2. Prepare GFS/EnKF global analysis/forecast data for Hurricane Bill (2009) (Aksoy)	*0.5*
2.3 Re-process aircraft data for Hurricane Bill (2009) (Aksoy)	*0.5*
2.4 Run HEDAS experiments with and without parameter perturbations (Aksoy: 1 mo, Zhang: 0.5 mo, Klotz: 0.5 mo)	*2*
2.5 Diagnostics of HEDAS analyses (Aksoy: 1.5 mo, Zhang: 1 mo, Uhlhorn: 0.5 mo, Cione: 0.5 mo)	*3.5*
3. Impact of SL/BL parameter perturbations on HEDAS: Diagnostics of ensemble forecasts from HEDAS analyses	**5**
3.1. Configure HWRF ensemble forecasts to be initialized from HEDAS analyses (Aksoy)	*0.5*
3.2 Run HWRF ensemble forecasts with and without parameter perturbations (Aksoy: 0.5 mo, Zhang: 0.5 mo, Klotz: 0.5 mo))	*1.5*
3.3 Diagnostics of ensemble forecasts (Aksoy: 1 mo, Zhang: 1 mo, Uhlhorn: 0.5 mo, Cione: 0.5 mo)	*3*
<u>**Year 2 Totals:**</u> Aksoy .... 6 months; Zhang .... 3 months; Klotz .... 1 month; Uhlhorn .... 1 month; Cione .... 1 month; **Total .... 9 months**	

Notice: Dr. Eric W. Uhlhorn and Dr. Joseph J. Cione from NOAA/AOML/HRD will provide valuable expertise in running the idealized HWRF, as well as in hurricane surface- and boundary-layer processes. Their contributions do not require financial support as their salaries are fully covered as part of HRD's base budget. A letter of support from NOAA/AOML/HRD is provided.

7. Project Deliverables

We expect our findings to be very informative for NOAA's next-generation hybrid ensemble/variational hurricane regional data assimilation and modeling framework. From recent research, it is becoming clear that ensemble perturbations that not only account for initial-condition uncertainty but also for model error are necessary to construct near-optimal ensembles. Therefore, our research should be expected to directly feed into NOAA's efforts to build a hybrid regional data assimilation system where optimality of ensemble perturbations is critical for successful operational implementation.

8. Metrics for Success

The work described in this proposal will be considered a success upon completion of all the tasks and reporting of findings in scientific meetings and journals.

9. References

Aberson, S. D., 2009: 10 years of hurricane synoptic surveillance (1997-2006). *Mon. Wea. Rev.*, **138**, 1536-1549.

Aberson, S. D., M. L. Black, R. A. Black, R. W. Burpee, J. J. Cione, C. W. Landsea, and F. D. Marks, Jr., 2006: Thirty years of tropical cyclone research with the NOAA P-3 aircraft. *Bull. Amer. Meteor. Soc.*, **87**, 1039–1055.

Aksoy, A., S. Lorsolo, T. Vukicevic, K. Sellwood, and S. Aberson, 2011: NOAA/AOML/HRD's Hurricane Ensemble Data Assimilation System (HEDAS): A baseline study using simulated Doppler radar observations from hurricane Paloma (2008). *15th Symp. on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans and Land Surface*, Seattle, WA, Amer. Meteor. Soc., J11.4.

Aksoy, A., D. Dowell, and C. Snyder, 2010: A multicase comparative assessment of the ensemble Kalman filter for assimilation of radar observations. Part II: Short-range ensemble forecasts. *Mon. Wea. Rev.*, **138**, 1273-1292.

Aksoy, A., D. Dowell, and C. Snyder, 2009: A multicase comparative assessment of the ensemble Kalman filter for assimilation of radar observations. Part I: Storm-scale analyses. *Mon. Wea. Rev.*, **137**, 1805-1824.

Bell, M. M., and M. T. Montgomery, 2008: Observed structure, evolution, and intensity of category five Hurricane Isabel (2003) from 12-14 September. *Mon. Wea. Rev.*, **136**, 2023-2036.

Black, P. G., E. A. D'Asaro, W. M. Drennan, J. R. French, P. P. Niiler, T. B. Sanford, E. J. Terrill, E. J. Walsh, and J. A. Zhang, 2007: Air-Sea Exchange in Hurricanes: Synthesis of Observations from the Coupled Boundary Layer Air-Sea Transfer Experiment, *Bull. Amer. Meteor. Soc.*, **88**, 357-374.

Cione, J. J., P. G. Black, and S. H. Houston, 2000: Surface observations in the hurricane environment. *Mon. Wea. Rev.*, **128**, 1550-1561

Cione, J. J. and E. W. Uhlhorn, 2003: Sea surface temperature variability in hurricanes: Implications with respect to intensity change. *Mon. Wea. Rev.*, **131**, 1783-1796.

DeCosmo, J., K. B. Katsaros, S. D. Smith, R. J. Anderson, W. A. Oost, K. Bumke, and H. Chadwick, 1996: Air-sea exchange of water vapor and sensible heat: The humidity exchange over the sea (HEXOS) results. *J. Geophys. Res.,* **101 (C5)**, 12001-12016.

Donelan, M. A., B. K. Haus, N. Reul, W. J. Plant, M. Stianssnie, H. C. Graber, O. B. Brown, E. S. Saltzman, 2004: On the limiting aerodynamic roughness of the ocean in very strong winds. *Geophys. Res. Lett.,* **31,** L18306.

Dowell, D. C., F. Zhang, L. J. Wicker, C. Snyder, and N.A. Crook, 2004: Wind and temperature retrievals in the 17 May 1981 Arcadia, Oklahoma, supercell: Ensemble Kalman filter experiments. *Mon. Wea. Rev.*, **132**, 1982-2005.

Dowell, D. C., L. J. Wicker, and C. Snyder, 2010: Ensemble Kalman filter assimilation of radar observations of the 8 May 2003 Oklahoma City supercell: Influences of reflectivity observations on storm-scale analyses. *Mon. Wea. Rev.*, in print.

Drennan, W. M., J. A. Zhang, J. R. French, and P. G. Black, 2007: Turbulent fluxes in the hurricane boundary layer, II. Latent heat flux, *J. Atmos. Sci.*, **64**, 1103-1115.

Emanuel, K. A., 1986: An air–sea interaction theory for tropical cyclones. Part I: Steady state maintenance. *J. Atmos. Sci.*, **43**, 585-604.

Emanuel, K. A., 1995: Sensitivity of tropical cyclones to surface exchange coefficients and a revised steady-state model incorporating eye dynamics. *J. Atmos. Sci.*, **52**, 3969-3976.

Fairall, C. W., E. F. Bradley, J. E. Hare, A. A. Grachev, and J. B. Edson, 2003: Bulk parameterization of air-sea fluxes: Updates and verification for the COARE algorithm. *J. Climate,* **16**, 571-591.

Franklin, J. L., M. L. Black, and K. Valde, 2003: GPS dropwindsonde wind profiles in hurricanes and their operational implications. *Wea. Forecasting,* **18,** 32–44.

French, J. R., W. M. Drennan, J. A. Zhang, and P. G. Black, 2007: Turbulent fluxes in the hurricane boundary layer, I. Momentum Flux, *J. Atmos. Sci.*, **64**, 1089-1102.

Gaspari, G., and S. E. Cohn, 1999: Construction of correlation functions in two and three dimensions. *Quart. J. Roy. Meteor. Soc.*, **125**, 723–757.

Gopalakrishnan, S. G., F. Marks, Jr, X. Zhang, J.-W. Bao, K.-S. Yeh, and R. Atlas, 2010: The experimental HWRF system: A study on the influence of horizontal resolution on the structure and intensity changes in tropical cyclones using an idealized framework. *Mon. Wea. Rev.*, in press.

Hacker, J. P., C. Snyder, S.-Y. Ha, and M. Pocernich, 2011: Linear and non-linear response to parameter variations in a mesoscale model. *Tellus A*, doi: 10.1111/j.1600-0870.2010.00505.x.

Hamill, T. M., J. S. Whitaker, M. Fiorino, and S. G. Benjamin, 2010: Global ensemble predictions of 2009's tropical cyclones initialized with an ensemble Kalman filter. *Mon. Wea. Rev.*, in print.

Haus, B., D. Jeong, M. A. Donelan, J. A. Zhang, and I. Savelyev, 2010: The relative rates of air-sea heat transfer and frictional drag in very high winds. *Geophys. Res. Lett.*, **37**, doi:10.1029/2009GL042206.

Kaplan, J., M. DeMaria, and J. A. Knaff, 2010: A revised tropical cyclone rapid intensification index for the Atlantic and Eastern North Pacific basins. *Wea. Forecasting*, **25**, 220-241.

Kepert, J. D., 2006a: Observed boundary layer wind structure and balance in the hurricane core. Part I: Hurricane Georges. *J. Atmos. Sci.*, **63**, 2169-2193.

Kepert, J. D., 2006b: Observed boundary layer wind structure and balance in the hurricane core. Part I: Hurricane Mitch. *J. Atmos. Sci.*, **63**, 2194-2211.

Kwon, Y. C., R. Tuleya, H.-L. Pan, V. Tallapragada, W. Lapenta, and S. Lord, 2010: Implementation of new air-sea exchange coefficients (Cd/Ch) to the operational HWRF model: Impact on hurricane intensity forecast skill. *29th Conf. on Hurricanes and Tropical Meteorology*, Tucson, AZ, Amer. Meteor. Soc., 13C.1.

Malkus, J. S. and H. Riehl, 1960: On the dynamics and energy transformations in steady-state hurricanes. *Tellus*, **12**, 1-20.

Mallen, K. J., M. T. Montgomery, B. Wang, 2005: Reexamining the near-core radial structure of the tropical cyclone primary circulation: Implications for vortex resiliency. *J. Atmos. Sci.*, **62**, 408-425.

Nielsen-Gammon, J. W., X.-M. Hu, F. Zhang, and J. E. Pleim, 2010: Evaluation of planetary boundary layer scheme sensitivities for the purpose of parameter estimation. *Mon. Wea. Rev.*, **138**, 3400-3417.

Nguyen, S. V., R. K. Smith, and M. T. Montgomery, 2008: Tropical-cyclone intensification and predictability inthree dimensions. *Q. J. R. Meteorol. Soc.*, **134**, 563-582.

Nolan, S. D., J. A. Zhang and D. P. Stern, 2009: Validation and comparisons of planetary boundary layer parameterizations in tropical cyclones by comparison of in-situ observations and high-resolution simulations of hurricane Isabel (2003). Part I: Initialization, track and intensity, and the outer core boundary layer. *Mon. Wea. Rev.*, **137**, 3651–3674.

Nolan, S. D., D. P. Stern, and J. A. Zhang, 2009: Validation and comparisons of planetary boundary layer parameterizations in tropical cyclones by comparison of in-situ observations and high-resolution simulations of hurricane Isabel (2003). Part II: Inner core boundary layer and eyewall structure. *Mon. Wea. Rev.*, **137**, 3675–3698.

Pielke, Roger A., 1997: Asking the Right Questions: Atmospheric sciences research and societal needs. *Bull. Amer. Meteor. Soc.*, **78**, 255–255.

Powell, M. D., 1990a: Boundary layer structure and dynamics in outer hurricane rainbands. Part I: Mesoscale rainfall and kinematic structure. *Mon. Wea. Rev.*, **118**, 891 – 917.

Powell, M. D., 1990b: Boundary layer structure and dynamics in outer hurricane rainbands. Part II: Downdraft modification and mixed layer recovery. *Mon. Wea. Rev.*, **118**, 918 – 938.

Powell, M. D., P. J. Vickery, and T. A. Reinhold, 2003: Reduced drag coefficient for high wind speeds in tropical cyclones. *Nature*, **422**, 279-283.

Rappaport, E. N., and Coauthors, 2009: Advances and challenges at the National Hurricane Center. *Wea. Forecasting*, **24**, 395-419.

Reasor, P. D., M. T. Montgomery, and L. D. Grasso, 2004: A new look at the problem of tropical cyclones in vertical shear flow: Vortex resiliency. *J. Atmos. Sci.*, **61**, 3-22.

Rogers, R. F., S. Lorsolo, P. Reasor, J. Gamache, F. D. Marks, Jr., 2011: Multiscale analysis of tropical cyclone kinematic structure from airborne Doppler radar composites. *Mon. Wea. Rev.*, in review.

Rogers, R., 2010: Convective-scale structure and evolution during a high resolution simulation of tropical cyclone rapid intensification. *J. Atmos. Sci.*, **67**, 44-70.

Sellwood, K., A. Aksoy, S. Aberson, and T. Vukicevic, 2011: NOAA/AOML/HRD's Hurricane Ensemble Data Assimilation System (HEDAS): Results of semi-operational implementation during the 2010 Atlantic Hurricane Season. *15th Symp. on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans and Land Surface*, Seattle, WA, Amer. Meteor. Soc., J11.5.

Smith, R. K., and G. L. Thomsen, 2010: Dependence of tropical-cyclone intensification on the boundary-layer representation in a numerical model. *Q. J. R. Meteorol. Soc.*, **136**, 1671-1685.

Snyder, C. and F. Zhang, 2003: Assimilation of simulated Doppler radar observations with an ensemble Kalman filter. *Mon. Wea. Rev.*, **131**, 1663-1677.

Uhlhorn, E. W., P. G. Black, J. L. Franklin, M. Goodberlet, J. Carswell, and Al. S. Goldstein, 2007: Hurricane surface wind measurements from an operational Stepped Frequency Microwave Radiometer. *Mon. Wea. Rev.*, **135**, 3070-3085.

Vukicevic, T., A. Aksoy, K. Sellwood, P. Reasor, S. Gopalakrishnan, L. Bucci, S. Aberson, and F. Marks, 2011: Diagnostic analysis of short-term hurricane vortex evolution in high-resolution ensemble Kalman Filter data assimilation. *15th Symp. on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans and Land Surface*, Seattle, WA, Amer. Meteor. Soc., J11.3.

Whitaker, J. and T. M. Hamill, 2002: Ensemble data assimilation without perturbed observations. *Mon. Wea. Rev.*, **130**, 1913–1924.

Zhang, F., C. Snyder, and J. Sun, 2004: Impacts of initial estimate and observation availability on convective-scale data assimilation with an ensemble Kalman filter. *Mon. Wea. Rev.*, **132**, 1238 – 1253.

Zhang, F., Y. Weng, J. A. Sippel, Z. Meng, and C. Bishop, 2009: Cloud-resolving hurricane initialization and prediction through assimilation of Doppler radar observations with an ensemble Kalman filter. *Mon. Wea. Rev.*, **137**, 2105-2125.

Zhang, J. A., P. G. Black, J. R. French, and W. M. Drennan, 2008: First direct measurements of enthalpy flux in the hurricane boundary layer: The CBLAST results. *Geophys. Res. Lett.*, **35**, L14813, doi:10.1029/2008GL034374.

Zhang, J. A., W. M. Drennan, P. G. Black, and J. R. French, 2009: Turbulence structure of the hurricane boundary layer between the outer rain bands. *J. Atmos. Sci.,* **66**, 2455-2467.

Zhang, J. A., F. D. Marks, M. T. Montgomery, and S. Lorsolo, 2011: Estimation of turbulence characteristics of the eyewall boundary layer of Hurricane Hugo (1989). *Mon. Wea. Rev.*, in press.