**Studying the Impact of Saharan Air Layer (SAL) on Atlantic Tropical Cyclone Intensity and Intensity Change**

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# PROJECT DESCRIPTION

#### Abstract

The interaction between the Saharan Air Layer (SAL) and tropical cyclones (TCs) is a very complex problem that may be influenced by interactions between vertical wind shear, prevailing moisture, stability in the lower atmosphere, and mineral dust effects (i.e., aerosol direct and indirect effects). In order to evaluate the effects of each of these various factors (i.e., the thermodynamic and kinematic impacts of the SAL) on TC intensity and intensity change, we propose a comprehensive research approach that will use idealized numerical sensitivity experiments and real case studies, using the experimental version of the Hurricane Weather, Research, and Forecasting (HWRF) modeling system embedded with the WRF-Chemistry modules. The use of satellite remote sensing data and NASA conducted the Genesis and Rapid Intensification Processes (GRIP) and the near future (2012-2014 hurricane seasons) NASA’s Hurricane and Severe Storm Sentinel (HS3) experiments data will also be an integral part of this work. Such a comprehensive approach will ensure an adequate understanding of the complex interactions between the SAL and TCs.

#### 1. Introduction

The Saharan Air Layer (SAL) is an elevated layer of dry, dusty air that forms over the Sahara Desert and moves over the tropical North Atlantic during the hurricane season. Although the SAL has been investigated for several decades (Prospero and Carlson, 1972; Braun and Shie, 2008), its interaction with North Atlantic tropical cyclones (TCs) is an emerging area of research. Recent investigations have suggested that the SAL can inhibit the formation and intensification of African easterly waves (AEWs) and TCs via three mechanisms: entrainment of mid-level dry air, enhanced vertical wind shear, and increased static stability through solar absorption by the SAL’s suspended mineral dust (Dunion and Velden, 2004; Evan et al., 2006). Moreover, some recent studies have suggested that the SAL’s suspended mineral dust may also have an influence on the microphysical properties of clouds (Zhang, 2008). Other studies have indicated that the SAL can amplify the initial development of TCs (Karyampudi and Carlson, 1988).

Clearly, the interaction between the SAL and TCs is a very complex problem that may be influenced by interactions between vertical wind shear, prevailing moisture, stability in the lower atmosphere, and mineral dust effects (i.e., aerosol direct and indirect effects). In order to evaluate the effects of each of these various factors (i.e., the thermodynamic and kinematic impacts of the SAL) on TC intensity and intensity change, we propose a comprehensive research approach that will use idealized numerical sensitivity experiments and real case studies, using the experimental version of the Hurricane Weather, Research, and Forecasting (HWRF) modeling system embedded with the WRF-Chemistry modules (hereafter we will refer this modeling system as “HWRF-Chem” and a brief description of the model is provided in Section 4). The use of satellite remote sensing data and NASA conducted the Genesis and Rapid Intensification Processes (GRIP) and the near future (2012-2014 hurricane seasons) NASA’s Hurricane and Severe Storm Sentinel (HS3) experiments data will also be an integral part of this work. Such a comprehensive approach will ensure an adequate understanding of the complex interactions between the SAL and TCs.

This proposal describes a collaborative work between George Mason University (GMU) and the Cooperative Institute for Marine and Atmospheric Studies (CIMAS) at the University of Miami and our comprehensive approach to meet the solicitation objectives of “What impact does the large-scale environment, particularly the Saharan Air Layer have on intensity change” in the National Aeronautics and Space Administration (NASA) broad agency announcement. Specifically, we will investigatethethermodynamic, kinematic, and aerosol aspects of SAL-TC interactions to improve our understanding and prediction of North Atlantic TC intensity change (i.e., weakening and deepening). Although the most well-known and perhaps most important factor that influence TC development and intensity change is sea surface temperature (SST), the SAL interaction with TCs still remains largely an unknown and may be yet another piece of the puzzle in advancing our understanding of TC intensity and intensity change in the Atlantic basin.

Section 2 provides background and motivation. Section 3 discusses the main objectives, statement of work, technical approach to each task, and project reporting. Section 4 includes a brief discussion of the numerical model that will be used in this study. Section 5 describes our management approach, responsibilities, and personnel qualifications. Section 6 provides project schedule and milestones. Section 7 describes computational facilities and resources. References are given in Section 8. Resumes are included in the appendix. The cost information is provided in a separate Cost Proposal.

#### 2. Background and Motivation

An elevated Saharan Air Layer (SAL) occurs during the late spring and summer (during the Atlantic hurricane season) over extensive portions of the North Atlantic Ocean between the Sahara Desert, the West Indies, and the United States (Prospero and Carlson, 1972; Dunion and Velden, 2004). These SAL outbreaks typically move westward off the northwest African continent every 3-5 days during the summer months and can reach as far west as the Caribbean, Central America, and Gulf of Mexico (Karyampudi and Carlson, 1988). Dunion and Velden (2004) and Dunion (2011) suggested that there are several characteristics of these frequent outbreaks that can act to suppress TC formation:

*i. Low to Mid-Level Dry and Increased Static Stability*

The SAL contains dry and stable air that can diminish local convection by promoting convectively driven downdrafts in the TC environment. Significant arc clouds (hundreds of km in length) can be generated by these downdrafts. As they propagate away from the TC inner core, they help promote low-level outflow in the quadrant/semicircle of the TC in which they form. This outflow pattern suppresses the typical low-level inflow that is vital for TC formation and maintenance. SAL outbreaks sustain low humidity levels (~40-50% drier than the typical moist tropical atmosphere) for extended periods of time (several days) and over great distances (1000s of km) as they traverse the North Atlantic.

Dunion (2011) recently developed new mean soundings for the tropical North Atlantic and Caribbean by examining 6,000 Caribbean rawinsondes for the period July-October 1995-2002. He found that three distinct atmospheric soundings dominate the tropical North Atlantic and Caribbean Sea region during the months of the Atlantic hurricane season: 1) moist tropical (MT), 2) SAL, and 3) mid-latitude dry air intrusions (MLDAIs). These various soundings account for 66%, 20% and 14% of all Caribbean region July- October soundings, respectively, and are associated with distinct thermodynamic, kinematic, and stability characteristics.

Figure 1 shows an example of the relative humidity and mixing ratio for the mean MT, SAL, and MLDAI soundings. The MT sounding exhibits a very moist vertical profile in the lower to middle levels of the atmosphere. However, the SAL and MLDAI sounding are significantly drier than the MT sounding above ~850 mb (the typical base of the SAL) with a moisture content that is 40-50% drier than the MT sounding. The new mean soundings (MT, SAL and MLDAI) presented by Dunion (2011) represent a new benchmark for the tropical North Atlantic and Caribbean and could have important implications related to our understanding of the climatology for this part of the world. These new soundings also have applications for use as an initial background state in model simulations and can be used to diagnose various thermodynamic and kinematic impacts of air masses such as the SAL on African Easterly Waves (AEWs), and TC development and intensity change. We will use these new mean soundings in Task 1 of this proposed study (see discussions in Sections 3.2 and 3.3).

Figure 1: Mean July-October (1995-2002) moist tropical (MT), SAL, and mid-latitude dry air intrusion (MLDAI) soundings of (a) RH (%) and (b) mixing ratio (g kg-1).

To better understand the TC intensity change problem, Gopalakrishnan et al., (2010) performed some preliminary experiments with the HWRF model at an adaptive grid resolution of 3 km using an idealized vortex in a uniform easterly flow without any wind shear (initial vortex condition is described in Bao et al., under preparation). Figure 2, for instance, illustrates the pressure traces from model simulations of idealized hurricane vortices in environments with different initial moisture distributions. In each of the simulations, other than the control, they varied the initial moisture distribution to assess the impact of dry air on this idealized TC vortex. Three scenarios were examined: vortex embedded in an extremely dry environment, dry environment following the vortex, and dry environment ahead of the vortex.

While, other factors discussed in this section (e.g. vertical wind shear and aerosol effects) related to TC intensity change will also be examined under this proposal, this preliminary study indicates that even in a simple, highly idealized model run, humidity can have a marked impact on the evolution of a modeled TC. The new mean soundings described by Dunion (2011) will be incorporated into idealized modeling simulations such as these just described to improve our understanding of how the thermodynamics, wind shear, and stability of various air masses (e.g., MT and SAL) can affect AEW formation and TC intensity change.

*ii. Mid-Level Easterly Jet (Enhanced Vertical Wind Shear)*

The SAL contains a mid-level easterly jet, which significantly increases the local vertical wind shear. The low-level circulations of TCs under the influence of this jet often race out ahead of their mid and upper-level convection, thereby decoupling the storm and weakening it. Figure 3 shows the representative mean wind speed and wind direction for the mean MT, SAL, and MLDAI soundings. The MT sounding exhibits a deep layer (surface to 400 hPa) of light easterly winds and low to moderate vertical wind shear (16 kt, not shown). However, the SAL sounding is associated with a slightly deeper layer (surface to 300 hPa) of easterly trade winds. The SAL’s low to mid-level (~500-850 hPa) winds are also about twice stronger and more easterly than the MT sounding and vertical wind shear (not shown) for this sounding is also higher: a moderate to high (19 kt).

Figure 2: Influence of environmental moisture on the evolution of an idealized TC. Pressure traces for 96 hours of simulation obtained from HWRF system at 3 km horizontal grid resolution for an idealized hurricane vortex moving in a shear-free easterly flow: (i) control (blue curve), (ii) initial moisture reduced to 1% (pink curve), (iii) moisture advected in the easterly flow along with the vortex (green curve), and (iv) dry air advected in the easterly flow along with the vortex (red curve). In cases (iii) and (iv), the moisture gradients were set only along the east-west direction.

It is well known that vertical wind shear and mid-level dry air can negatively impact AEWs and TCs. However, what is less understood is how shear and dry air seem to act together against disturbances and how they can even act together in a nonlinear way to amplify the effects of both. Vertical wind shear can increase the entrainment of dry air by convection, which can, in turn enhance the detrimental impact of dry air on the environment. This aspect of vertical wind shear and mid-level dry air will be investigated using idealized HWRF-Chem runs and the new mean soundings presented by Dunion (2011), (discussed in detail in Section 3.1 and Section 3.2).

*iii. Mineral Dust*

The mineral dust suspendedwithin the SAL absorbs solar energy and subsequently releases longwave infrared energy. These thermal emissions act to warm the SAL and can re-enforce the tropical inversion that already exists in the tropical North Atlantic. This warming helps to stabilize the environment and also limits vertical mixing throughout the SAL, allowing the SAL to maintain its distinctive characteristics. Saharan dust may even serve as effective cloud condensation nuclei (CCN) and increases cloud droplet number concentrations. This can lead to an increase in cloud optical depth and albedo because a greater number of smaller droplets have a higher total surface area for a given mass of liquid water. This is known as the first indirect aerosol effect. In addition, the indirect aerosol effect can lead to lower precipitation efficiency. Increasing the cloud droplet number concentration decreases the average cloud droplet size. As a result, clouds will retain higher liquid water contents and have a longer lifetime. This is termed the second indirect effect. In short, the African mineral dust suspended in the SAL may alter microphysical and radiative properties of clouds and the environment in which TCs are embedded and hence influence AEW formation and TC intensity change.

In recent years, there has also been a growing interest in understanding the influence of aerosols on the tropical clouds. Cotton et al. (2007) found a reduction in intensity of TCs with small hygroscopic particles. The Cotton et al. (2007) study was based on preliminary results of simulations of the impact of African dust on hurricane intensity (Zhang et al., 2007). These simulations showed that dust acting as CCN influenced the storm development by inducing changes in the hydrometeor properties, modifying the storm diabatic heating distribution and thermodynamic structure, and influencing the storm intensity through complex dynamical responses. A number of simulated storms showed a monotonic decrease in the intensity with increasing concentrations of CCN, but this trend was easily modified just by introducing slight variations in the CCN profile. Thus, Zhang et al. (2007) conclude that the physical processes responsible for the impact of dust as nucleating aerosols on hurricane development need to be examined further under a wide range of environmental conditions.

Figure 3: Mean July-October (1995-2002) moist tropical (MT), SAL, and mid-latitude dry air intrusion (MLDAI) soundings of (a) wind speed (m s-1) and (b) wind direction.

In short, the SAL interaction with TC still remains largely an unknown and may be yet another piece of the puzzle in advancing our understanding of AEW formation and TC intensity change in the North Atlantic basin. These advancements in understanding require the use of a comprehensive modeling system like HWRF embedded with the WRF-chemistry module (HWRF-Chem) to capture the complex influences of dry air, vertical wind shear, and dust aerosols on AEWs and TCs.

#### 3. Scope of Proposed Work

### 3.1 Primary Objective

As discussed in previous sections, past studies have suggested that TC formation and intensity change may be influenced by the SAL. SAL-TC interactions are, however, a highly complex research problem involving processes and feedbacks that span scales ranging from microphysical (e.g., dust aerosols) to meso-gamma (e.g., convection), to synoptic scale (e.g., the SAL). Particularly, SAL processes such as dry Saharan air advection, vertical wind shear, atmospheric stability, and mineral dust (aerosol) effects might play an important role in TC intensity and intensity change.

The primary objective of this study is to evaluate the effects of each of these factors on TC intensity and intensity change using the HWRF-Chem modeling system.

### 3.2 Statement of Work

Toward the primary goal of this study, we propose a comprehensive research plan to ensure an adequate understanding of the complexities of SAL-TC interactions. It is then convenient to describe our research plan under the following three main tasks. The period of performance for this proposed study is three years. Details of schedule and milestones are provided in Section 6.

*Task 1*: *Idealized Cases for Studying SAL-TC Interactions*

Study the SAL processes that control TC intensity and intensity change in an idealized environment with idealized vortices. The rationale for this task is that in studying the SAL-TC interaction, the largest challenge is in determining how to separate the thermodynamic and kinematic effects of the SAL processes from mineral dust (aerosol) effects. Simple statistical correlations between observed or retrieved aerosol and cloud properties do not imply causality. Using the HWRF-Chem model where certain variables or processes can be controlled in sensitivity simulations, SAL-TC casual relationships will be examined in detail under specific conditions.

*Task 2:* *Real Cases for Studying SAL-TC Interactions*

Study the SAL processes that control TC intensity change using cases where SAL-TC interactions have been documented particularly during the GRIP and HS3 experiments. The rationale for this task is that SAL-TC interactions are inherently linked, and need also to be investigated using real case studies where rich data environment exists.

*Task 3*: *Uncertainty Analysis for SAL-TC Interactions*

The influence of atmospheric stochastic forcing and uncertainty in initial conditions of mineral dust loading and SAL properties on the limit of predictability of the HWRF-Chem model will be quantified. The rationale for this task is that it is not always clear whether the knowledge gained from real cases could be applied to more general scenarios, since each real case represents a single realization. This, in turn, demands an uncertainty analysis to better assess SAL-TC interactions.

The intellectual meritof the proposed work is the likelihood of a significant advance in our understanding of SAL-TC interactions and hence prediction of TC tracks and particularly intensity change (i.e., possible improvement of operational aspects of TC predictions). The broader impacts will lead to a better understanding and prediction of TCs that can potentially will provide substantial societal benefits. It is expected that this project will provide the research topic for a Ph.D. student, thereby creating an educated professional who have the requisite training to support the future TC research.

The technical approaches for each proposed task are discussed in detail in the following section.

### 3.3 Methodology

On the scale of weather prediction, TC behavior is characterized by strong multi-scale interactions: the TC vortex is hundreds of km in horizontal size (synoptic-scale), the eye is tens of km (mesoscale), and the embedded convective clouds are on the order of km (cloud-scale), with a vertical scale of up to 20 km. The environmental flow in which the TC vortex is embedded is the main factor that determines its track. The internal structure of the TC and its interaction with the surrounding environment (e,g, the SAL and SST) are the primary influences on TC intensity. These space-time scales and scale interactions should be represented as accurately as possible, when TC behavior is studied. Otherwise, significant components of the problem may be neglected.

In order to achieve the primary objective of this study, one needs to adequately represent each of the scales and scale interactions that are described above. This, in turn, requires the use of a sophisticated forecast model. We propose to use the HWRF-Chem model version that is available at George Mason University and CIMAS to investigate the impact of the SAL on TC intensity and intensity change. HWRF-Chem has the capability to model the relationship between aerosols and meteorological parameters (i.e., includes aerosol modules for the calculation of **aerosol-radiation-cloud-chemistry feedbacks**). HWRF-Chem also has the capability to dynamically provide finer grid resolutions to evolving TCs (i.e., moveable nested grid). In other words, HWRF-Chem focuses the model’s fine horizontal grid resolution during the run on regions of complex and critical phenomena (e.g., providing grid resolutions ≤1 km that are appropriate to resolve the smallest scales of interest, such as the eye, eyewall, and spiral bands of an evolving TC). This improves the overall quality and efficiency of simulations and simulations of SAL-TC interactions.

Satellite remote sensing data and NASA conducted the Genesis and Rapid Intensification Processes (GRIP) and the near future (2012-2014 hurricane seasons) NASA’s Hurricane and Severe Storm Sentinel (HS3) experiments data will also be an integral part of this work. Satellite observations are especially useful in data sparse ocean areas where TCs occur. Primarily, we will explore to use of several instruments onboard various NASA A-Train satellites: aerosol index (AI) extracted from the Ozone Monitoring Instrument (OMI) (Aura satellite), dust aerosol optical depth (AOD) extracted from the MODIS instrument (Terra and Aqua), aerosol information extracted from the Clouds and Aerosol Lidar for Pathfinder Spaceborne Observation (CALIPSO), temperature and humidity profiles extracted from the AIRS instrument (Aqua satellite), and rainfall rate from TRMM*.* The aerosol data sets will help us to identify and initialize the African dust outbreaks in HWRF-Chem, while the profiles will assist in our improvements on initial meteorological condition for the model. The use of the above remote sensing data does not preclude the consideration of other remote sensing datasets. For example, the SAL distributions derived from the brightness temperature difference between the two split-window channels of the GOES observations (Dunion and Velden, 2004) can also be used to identify the SAL outbreaks. The observations collected by NASA during GRIP and future HS3 experiments will also be utilized in this study.

The research methods for each task are discussed in detail below.

##### ***3.3.1. Task 1: Idealized Cases for SAL-TC Interaction***

Under this task, we will perform the following main subtasks:

* Create a functional prototype of HWRF-Chem framework by extending the WRF-Chem modules available within the WRF framework to the HWRF system.
* Develop a suite of idealized TC cases (i.e., idealized vortex cases) using the new mean soundings from Dunion (2011) for initialization of the model (cf. Figs. 1, 2, and 3) to perform a set of idealized numerical sensitivity runs (tests). The goal of these idealized sensitivity runs will be to assess the influence of SAL features on TC intensity change. Sensitivity runs will be performed to identify the relative variation of outputs for variations in 1) input variables, and 2) model physics options and parameters. For example, input variables may include environmental wind speed, wind direction, stability category, humidity, and TC characteristics (i.e., size and intensity) at the initial stage. Model physics options and parameters may include SST values, aerosol physical, chemical and optical properties, and aerosol distribution in space and time;
* Numerical sensitivity runs will first be performed in a one-at-a-time mode where every selected input variable, and model physics option and parameter will be changed individually while holding the others fixed. Sensitivity runs will then be performed in a simultaneous-change mode where more than one selected variable will be changed at a time;
* From the idealized model runs we will;
	1. Analyze the development of the SAL’s mid-level easterly jet that results from the north-south thermal gradients that exist between the warm SAL and the relatively cooler tropical air to the south;
	2. Investigate the combined impact of dry air and vertical wind shear on TC intensity change;
	3. Investigate the effects of dust aerosols (direct and indirect effects) on microphysical and radiative properties of clouds;
	4. Investigate the scale dependency of microphysical processes and their effect on simulations. We will use various horizontal and vertical model grid resolutions to determine if the HWRF-Chem model is capable of representing the entrainment of mid-level dry air (i.e., the SAL) toward the outer edge of the TC inner core. If so, we will then determine if the model can also represent the strong convectively driven downdrafts and resulting arc clouds that result from this interaction between the mid-level dry air and the TC.

*Deliverable of Task 1:*

The deliverable of this task shall be a report containing tables and figures, with the inputs ranked with respect to HWRF-Chem’s sensitivity to relative variations. This report shall also be a part of the final consolidated report.

##### ***3.3.2 Task 2: Real Cases for Studying SAL-TC Interactions***

Under this task, we will perform the following main subtasks:

* Identify real cases (at least 2-4 cases will be examined in this task) where significant data sets are available during the GRIP and HS3 experiments to evaluate SAL-TC interactions. This set of TC cases does not preclude the consideration of other cases (e.g., TCs Irene 2005, Debby 2006, Florence 2006, and Helene 2006) to achieve the objective of this task.
* Using the selected cases, perform a detailed observational analysis of the SAL-TC environment (primarily observations from GRIP and HS3 experiments, AIRS temperature and humidity profiles, GPS dropsondes, AI from OMI, AOD from MODIS, aerosols from CALIPSO, and rainfall rate from TRMM) with a focus on SAL features and their interactions with TC intensity change.
* Perform numerical simulations with HWRF-Chem model using its online dust module for dust aerosols calculation and **aerosol-radiation-cloud-chemistry feedbacks** and its moveable nested grid that follows evolving TC with very high grid resolution. The resolution limit for the moveable grid will be chosen so that the convective phenomena of interest and the inner core structure of TC are satisfactorily resolved (e.g., 1 km). This is important when TC intensity and intensity changes are studied. Initial aerosols spatial distribution can, for example, be obtained from the CALIPSO data by determining where in the model the dust should be located and at what concentration.  The initial condition of aerosols can then have the dust fields modified to include this data.  These simulations will serve as benchmarks.
* Evaluate the benchmarks using all available observations to identify the model-resolved SAL features and their influences on TC intensity change. Particularly, substantial observations (e.g.,…….) were collected by NASA. These data will be used to verify the thermodynamics and winds in the model simulations. This step and its predecessor provide the validation of the benchmarks.
* Assimilate all available observations (primarily temperature and humidity profiles) into the model at the initial time using 3DVAR to better represent the dynamical forcing of SAL features and hence to improve subsequent accuracy of the simulations. We propose to perform three data assimilation strategies; 1) assimilate only temperature information, 2) assimilate only humidity information, and 3) assimilate both temperature and humidity information. In this way, we can investigate which factor (warm and dry air) play the key role to TC intensity and intensity change. The focus of data assimilation will be the location of SAL in a targeted manner (Boybeyi et al., 2007, demonstrated that targeted data assimilation can improve a certain important feature of the environment in which a TC embedded and hence can improve TC track forecast by about 30 %). The rationale for targeted data assimilation is that since the SAL’s temperature structure is initially related to the its origins over the hot Sahara desert and later maintained by solar absorption by suspended mineral dust, it is important that the HWRF-Chem model adequately represents the following SAL features to compare the results with the benchmarks:
	1. The initial warmth of the SAL as it emerges from the African coast;
	2. The movement and structure (horizontal and vertical) of the SAL as it propagates across the North Atlantic;
	3. The horizontal and vertical distribution of Saharan dust in the SAL;
	4. The shortwave and longwave properties of the Saharan dust to adequately represent the net cooling of the SAL as it propagates across the North Atlantic;
	5. The strong (2-10 °C) temperature inversions that are typically found near the base of the SAL (~850 hPa) from the eastern North Atlantic to as far west as the western North Atlantic and Caribbean;
	6. The strong horizontal temperature gradients that exist between the SAL and the relatively cooler moist tropical environment to the south. Thermal wind balance dictates that this temperature contrast is associated with a mid-level easterly jet along the southern edge of the SAL.
* Perform HWRF-Chem simulations using the same model settings of the benchmarks. The only difference will be targeted data assimilation.
* Identify features which were resolved by the HWRF-Chem model using data from aircraft and satellite observations (e.g., GPS dropsondes and AIRS profiles) to;
	1. Assess whether the HWRF-Chem model adequately represents the 3D moisture associated with the typical moist tropical atmosphere as well as SAL outbreaks that may be positioned in the surrounding TC environment;
	2. Assess whether the HWRF-Chem model adequately represents the vertical wind shear associated with SAL outbreaks that may be positioned near (especially just north and east of) the TC environment.
	3. Assess whether the HWRF-Chem model adequately represents the 3D temperature characteristics of the SAL, including temperature inversions that are typically seen near the base of the SAL.
		+ Compare the results of these simulations (from targeted data assimilation cases) with benchmarks. The difference will reveal the impact of SAL on TC intensity change.
* Investigate the impact of the African dust aerosols associated with the SAL on TC intensity change. This will be accomplished by separating effects of dust aerosols on TC intensity change by;
	1. Turning off the HWRF-Chem model’s online dust module interaction with radiation scheme to examine the direct aerosol effect on TC intensity change (i.e., there will be no **aerosol-radiation feedbacks). All other** model settings will be kept same as in the targeted data assimilation cases.
	2. Turning off the HWRF-Chem model’s online dust module interaction with microphysics to examine the indirect aerosol effects on TC intensity change (i.e., there will be no **aerosol-cloud interaction). All other** model settings will be kept same as in the targeted data assimilation cases.
	3. Turning off the HWRF-Chem model’s online dust module completely to examine the aerosol effects on TC intensity change (i.e., there will be no **aerosol-radiation-cloud feedbacks). All other** model settings will be kept same as in the targeted data assimilation cases.
		+ Compare the results of these simulations with the results of targeted data assimilation cases and observations. The differences will reveal the impact of dust aerosols on TC intensity change.

*Deliverable of Task 2:*

The deliverable of this task shall include a report summarizing all the findings of this task, with supporting tables and figures. This report shall be a major part of the final consolidated report.

##### ***3.3.3 Task 3: Uncertainty Analysis for SAL-TC Interactions***

Complex computer models (such as HWRF-Chem) are used pervasively in scientific research for the simulation of real world systems, and there have been increasing demands for these models to support policy- and decision-making. One prominent example is the prediction of the fate of TCs. However, models are always a simplified version of the reality of the system being simulated, since they involve aggregation and exclusion of physical processes. More importantly, model simulations represent a single realization. Therefore, there are always errors and uncertainties associated with model simulations. Two key questions are **“**how good are these complex computer models really for their intended purposes, and what uncertainties are involved in their predictions?”

The focus of this task in the case of SAL-TC interactions will be on two model uncertainty areas using ensemble modeling technique; 1) atmospheric stochastic forcing (i.e., noise due to internal dynamics of the atmosphere) and 2) uncertainty in initial conditions of mineral dust (i.e., initial condition noise of dust loading) to determine which one is the primary factor in limiting the predictability of the SAL-TC interaction study presented in Task 2. In other words, the ensemble experimental design and the analysis will separately consider how uncertainty in the dust aerosols (i.e., initial condition noise) versus uncertainty in the forecast evolution (i.e., noise due to internal dynamics of the atmosphere) has an impact on estimates of the limits of predictability of SAL-TC interactions. These two areas of uncertainty will be quantified using two different ensemble simulation strategies. In the first method, HWRF-Chem simulations (i.e., benchmarks of Task 2) will be coupled to the ensemble average of multiple realizations of the HWRF-Chem aerosol module. In this case noise in the initial conditions of mineral dust plays an active role in the coupled system. For example, initial aerosol spatial distributions (multiple realizations) can be obtained from either the surface scouring (erosion factor) or specified from the CALIPSO data with different strategies.  In the second method, ensemble runs will be specifically designed to reduce the internal dynamic fluctuations that are unrelated to aerosol distribution anomalies via ensemble simulations of the meteorological conditions (i.e., initial meteorological fields will be perturbed to generate ensemble averaging of the meteorology). In this case, the atmospheric noise (i.e., stochastic forcing) plays an active role in the coupled system. Estimates of the limit of predictability (i.e., uncertainties) will be based on both deterministic measures (ensemble spread and root mean square error) and probabilistic measures (relative operating characteristics).

*Deliverable of Task 3:*

The deliverable of this task shall include a report summarizing all the findings of this task, with supporting tables and figures in the final consolidated report.

### 3.4 Deliverables

We will provide periodic reports on technical progress and expenditures required by this contract. While each work task has its own deliverable as indicated above, at the end of the project these tasks will also lead to a final consolidated report, summarizing the overall results and conclusions. The NASA shall be asked to comment on the draft version of the final report. These comments will then be incorporated into the final version of the report for the NASA’s approval. It is expected that two or more scientific papers will be written for submission to relevant conferences and/or peer-reviewed journals acknowledging the source of funding.

#### 4. Numerical Model

The Weather, Research, and Forecast (WRF) model is a collaborative effort among several government and research institutions, and universities. The WRF model was envisioned as a “community model” to provide a common framework for the development and implementation of advanced numerical techniques for mesoscale modeling. The code is open source and available to the public. The WRF model solves the fully compressible non-hydrostatic Navier-Stokes equations with higher-order advection schemes. Grid-nesting (multiple nests and nest levels) with two-way interactions has been implemented to provide increased spatial resolution in the regions of interest. The WRF model is under continuous development at NCAR, NCEP and other NOAA labs and also benefits from a wide base of users and model developers in academia as well as industry.

A version of the WRF model called Hurricane WRF (HWRF), developed at the National Center for Environmental Protection (NCEP) and was adopted for hurricane forecasting (Gopalakrishnan et al, 2010, Zhang et al., 2011). The experimental version of the HWRF system is specifically designed to study the TC intensity change problem at high model horizontal grid resolution of about 1-3 km. A general description of the model is provided in Yeh et al. (2010) and the model dynamics are described in Janjic at al., (2001).

The WRF model with Chemistry (WRF-Chem) is another version of WRF that simultaneously simulates the emission, turbulent mixing, transport, transformation, and fate of gases and aerosols. The WRF-Chem also includes the aerosol-radiation-cloud interactions. There are three choices for aerosol schemes in the WRF-Chem, including the Modal Aerosol Dynamics Model for Europe (MADE/SORGAM); the Model for Simulating Aerosol Interactions and Chemistry (MOSAIC); and the GOCART aerosol model. The direct effects of aerosols on incoming solar radiation can be simulated using these existing modules to relate aerosol sizes and chemical composition to aerosol optical properties. Fully interactive feedbacks can be created within the model, with aerosols affecting cloud droplet number and cloud radiative properties, and clouds altering aerosol size and composition via aqueous processes, wet scavenging, and gas-phase-related photolytic processes.

At CIMAS, in collaboration with the Hurricane Research Division (HRD) and the Developmental Test bed Center (DTC) (Boulder, CO), Global Systems division (GSD/ESRL/OAR) (Boulder, CO), and George Mason University (Fairfax, VA), we are developing and further advancing WRF by coupling HWRF with WRF-Chem model (i.e., HWRF-Chem) that will be used in this study.

#### 5. Management, Responsibilities, Personal Qualifications, and Prior Research

Dr. Boybeyi will be the Principal Investigator and Drs. Hristova-Veleva and Gopal and Mr. Dunion will be the Co-Investigators. They will be supported a doctoral graduate student (TBD). It is expected that this study will provide the research topic for a Ph.D. graduate students at George Mason University (GMU).

Dr. Boybeyi will coordinate all activities for this project. As such, Dr. Boybeyi will have the authority to direct available project resources and personnel, as necessary, to fulfill the objectives of this program. He will be responsible for the on-time transmission of all the project deliverables and financial statements. Dr. Boybeyi will maintain constant liaison with NASA to ensure our responsiveness to the project requirements.

The staffing of the proposed study by task is shown in Table 1. The graduate student (TBD) and Dr. Boybeyi will be in charge of carrying out all of the numerical simulations. Dr. Gopalakrishnan (Co-I), as one of the developers of the HWRF model, will provide scientific advise and will advise student on the design of numerical experiments. Dr. Hristova-Veleva, as an expert on observations, will provide scientific advise and work with student. Mr. Dunion (Co-I), as an expert on the SAL, will provide scientific advise and work with student on the SAL-TC interaction. The key personnel qualifications are briefly summarized below.

Table 1: Staffing for the proposed study by task.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Personnel** | **Task 1** | **Task 2** | **Task 3** | **Years of Specialized Experience** |
| Boybeyi, Z., Ph.D. | • | • | • | 22 |
| Gopalakrishnan, G., | • | • | • | ?? |
| Hristova-Veleva, S., Ph.D. |  | • | • | ?? |
| Dunion, J., M.S. | • |  |  | ?? |
| GRA (TBD) | • | • | • |  |

Dr. Boybeyi is an Associate Professor and the Director of the Comprehensive Atmospheric Modeling Program (CAMP) in the Department of Atmospheric, Oceanic, and Earth Sciences of George Mason University. He has been focusing in his research on the utilization of computer science and scientific research to solve multidisciplinary, computationally intensive scientific problems. He has advised numerous Ph.D students. He is teaching “Severe and Unusual Weather” and “Numerical Methods for Climate Models” courses. Dr. Boybeyi has been developing and improving numerical weather prediction models past 20 years with focus on atmospheric hazards prediction. For example, hurricane prediction improvements supported by National Science Foundation (NSF), titled as “A Climatological Study of Atlantic Basin Tropical Storms to Provide Satellite Data Assimilation Guidance for Numerical Models”, was a most recent study that he was focusing on. He has also been conducting research in the areas of planetary boundary layer physics, computational fluid dynamics, remote sensing, model evaluation and uncertainty analysis, data analysis, observing system simulation, and aerosol effects.

Dr. Gopalakrishnan has about 12 years of post Ph.D experience in atmospheric modeling and numerical weather prediction (NWP). After completing his doctoral degree, which involved development of boundary layer physics for a mesoscale model and development of an advanced Lagrangian particle dispersion model for studying some aspects of the Stable Boundary Layer flows, Dr. Gopal has been concentrating on problems related to NWP of the TCs, dry and moist convection and turbulence in the atmosphere and studies related to dispersion and transport in the atmospheric boundary layer. Dr. Gopal has made significant contributions towards the development of complex, next generation Atmospheric, Ocean coupled modeling systems, including the Operational Multiscale Environmental Model with Grid Adaptivity (OMEGA) for Hurricane Forecasting and is currently leading the effort of developing an Ocean Coupled, Moving Nested grid, operational hurricane modeling system, called the “HWRF” system, that is currently used for operational hurricane forecasting and other mesoscale applications at the national weather services, USA. Lately, he is also mentoring students and scientists on Atmospheric Modeling. Dr. Gopal, in the past, has served as the Associate Editor of the Monthly Weather Review. Currently Dr. Gopal is leading the hurricane modeling activities at the Hurricane Research Division, AOML, NOAA.

Dr. Hristova-Veleva is …….

Mr. Dunion is a research meteorologist at the University of Miami’s Cooperative Institute for Marine and Atmospheric Studies (CIMAS). He specializes in satellite remote sensing of hurricanes and has led the development of several new satellite products for monitoring tropical cyclones and their interactions with Saharan dust storms. He was recently funded on a project through NOAA’s Joint Hurricane Testbed to assess the impact of GPS dropsonde humidity data on TC track and intensity forecasts of NOAA’s Global Forecast System (GFS) Model. This project was accepted for transition to operations and resulted in the successful routine assimilation of GPS dropsonde humidity integration into the GFS model. He is currently completing a project that examined the impact of SAL outbreaks on the climatological mean sounding for the tropical North Atlantic that was developed over 50 years ago. This study has resulted in a significant re-write of this long-standing climatology and will provide a new baseline for understanding the climatology of the tropical North Atlantic. Dunion has acted as chief scientist on several Hurricane Hunter research missions aboard NOAA’s G-IV high altitude jet and P-3 Orion hurricane hunters and has flown on over 40 hurricane hunter flights.

It is clear that all the personnel have the desired qualifications to carry out the proposed study.

#### 6. Schedule and Milestones

Work described above would commence immediately upon receipt of an award notification. The expected period of performance is two years. Table 2 shows our suggested schedule for the three main tasks. Table 2 also identifies project milestones, mostly marked by progress and final reports. Note that we assumed the start date as 1 August, 2012 and the complete date 31 July, 2015.

Table 2: The estimated schedule for the three main tasks (horizontal bars), milestones for the progress reports (solid diamonds), and milestone for final report (solid circle).

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Tasks****Start Date** **1 Aug’ 12** | Oct’ 12 | Jan’ 13 | Apr’ 13 | Jul’ 13 | Oct’ 13 | Jan’ 14 | Jun’ 14 | Apr’ 14 | Jul’ 14 | Oct’ 15 | Jan’ 15 | Jun’ 15 |
| Task 1 |  |  |    | ♦  |  |  |  |  |  |  |  |  |
| Task 2 |  |  |  |  |   |  |  |  ♦ |  |  |  |  |
| Task 3 |  |  |  |  |  |  |   |  |  |  |  |  • |

#### 7. Facilities, Equipment and Modeling Resources

The Comprehensive Atmospheric Modeling Program (CAMP) of the Department of Atmospheric, Oceanic, and Earth Sciences (AOES) is housed on the Fairfax campus of George Mason University (GMU), six miles from the Washington, D.C. beltway. The CAMP computing facility houses a PC clusters that use Linux as an operating system with 64 and 256 nodes for high performance parallel computing. The PC clusters have 2 gigabyte of RAM on each processor and 50 TB of disk space. The CAMP also has access to GMU’s 180 nodes SGI Altix 3000 cluster. The SGI cluster has 60 TB of disk space. The CAMP is connected to outside computational facilities by a T1 line which is part of a high-speed Internet network. The WRF-Chem modeling system is fully installed and operational for simulations on the CAMP PC clusters and being used by graduate students of CAMP.

#### 8. Total and Annual Budgets

The period of performance for this proposed study is three years with a total budget of $221,930. The first year budget is $109,445. The second year budget is $112,485.

This proposed research will evaluate the effects of various environmental factors (i.e., the thermodynamic and kinematic impacts of the SAL, such as vertical wind shear, prevailing moisture, stability in the lower atmosphere, and mineral dust effects) on TC intensity and intensity change using idealized numerical sensitivity experiments (Task 1, first year) and real case studies (Task2, first and second year), using the experimental version of the Hurricane Weather, Research, and Forecasting (HWRF) modeling system embedded with the WRF-Chemistry modules. The use of satellite remote sensing data will also be an integral part of this work.

#### 9. References

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Fast, J. D., W. I. Gustafson, Jr., R. C. Easter, R. A. Zaveri, J. C. Barnard, E. G. Chapman, G. A. Grell & S. E. Peckham (**2006**): Evolution of ozone, particulates, and aerosol direct radiative forcing in the vicinity of Houston using a fully coupled meteorology-chemistry- aerosol model. *J. Geophys. Res.,* **111,** D21305, doi:10.1029/2005JD006721.

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# APPENDIX A: Biographical sketch

**BIOGRAPHICAL SKETCH** **(Zafer Boybeyi, Ph.D.)**

Education:

North Carolina State University, Atmospheric Science, Ph.D. (1993)

San Jose State University, Meteorology, M.S. (1990)

Istanbul Technical University, Meteorological Engineering, B.S. (1984)

**Appointments:**

Associate Professor, Director of CAMP program (2003-Present): Department of Atmospheric, Oceanic, and Earth Sciences, George Mason University, Fairfax, Virginia.

Research Scientist (1993-2003): Center for Atmospheric Physics, Science Applications International Corporation (SAIC), McLean, Virginia.

Graduate Research Assistant (1990-1993): Marine, Earth, and Atmospheric Sciences Department, North Carolina State University, Raleigh, North Carolina.

Graduate Research Assistant (1988-1990): Meteorology Department, San Jose State University, San Jose, California.

Graduate Research Assistant (1986-1988): Meteorology Department, Istanbul Technical University, Istanbul, Turkey.

**Publications:**

Recent Most Closely Related Publications:

Boybeyi, Z., M. Kafatos, & D. Sun (**2009**): Tropical Storm Modeling. Hurricanes and Climate Change. *Springer,* 400 pp. ISBN-13: 978-0387094090 (Edited by J. Elsner & T. H. Jagger).

Bakosi, J., P. Franzese & Z. Boybeyi (**2008**): A non-hybrid method for the PDF equations of turbulent flows on unstructured grids. *J. Comput. Phys.,* ***227****, 5896-5935.*

Lindeman J., D. Broutman, S. D. Eckermann, J. Ma, J. W. Rottman & Z. Boybeyi (**2008**): Far-Field Mountain Waves Radiated from Nonlinear Orographic Flow Regimes. *Journal of Atmospheric Science,* **65***,* 2749-2756 (DOI: 10.1175/2008JAS2541.1).

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Ahmad N. N., Z. Boybeyi, R. Lohner & R. A. Sarma (**2006**): A Godunov-Type Scheme for Atmospheric Flows on Unstructured Grids. Part I - Scalar Transport. *Pure and Applied Geophysics*, **163**, 1699-1735.

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Bacon D. P., N. N. Ahmad, Z. Boybeyi, T. J. Dunn, M. S. Hall, P.C. S. Lee, R. A. Sarma, M. D. Turner, K. T. Waight, S. T. Young & J. W. Zack (**2000**): A dynamically adapting weather and dispersion model: The Operational Multiscale Environment Model with Grid Adaptivity. *Monhly Weather Review*, **128**, 2044-2067.

**Synergistic Activities:**

Dr. Boybeyi is the 1997 recipient of Achievement Award of the SAIC for “*Excellence in Science and Technology”,* the 2000 Publication Prize for “*Applied Mathematics & Computer Sciences”*, and the 2001 Publication Prize for “*Environment and Geophysics*”. From 1993-2001, he was one of the main developers of the Operational Multiscale Environment model with Grid Adaptivity (OMEGA).

**Collaborators & Other Affiliations:**

**a) Collaborators and Co-Editors**

Dr. Steve Ackerman (Computational Physics Inc.)

Dr. David P. Bacon (Science Applications International Corporation)

Dr. Steve Hanna (Harvard Public School of Health)

Dr. Ismail Gultepe (Canada Environment)

Dr. R. A. Sarma (Science Applications International Corporation)

**b) Graduate and Postdoctoral Advisors**

Prof. Robert D. Bornstein, San Jose State University, (Master Advisor)

Prof. Sethu Raman, North Carolina State University, (Ph.D. Advisor)

**c) Thesis Advisor and Postgraduate-Scholar Sponsor**

Dr. Jozsef Bakosi, Dr. John Lindeman, Dr. Elena Novakovskaia, Dr. Joseph Chang, Dr. Yimin Ma, Dr. Pasquale Franzese, Dr. Dingchen Hou, Ms. Laura Clemente, Ms. Priyanka Roy.

 **BIOGRAPHICAL SKETCH (S. G. Gopalakrishnan, Ph.D)**

**Education:**

Rutgers University, Department of Environmental Sciences, Post Doctoral Associate (1996-98)

Indian Institute of Technology, Atmospheric Science, India, Ph.D. (1996)

Poona University, Atmospheric Physics, India, Master in Technology (1990)

Poona University, India, Master in Physics (1989)

**Appointments:**

Meteorologist (2007-Present): Hurricane Research Division/AOML/NOAA/DOC4301 Rickenbacker Causeway, Miami, FL 33149

Senior Research Meteorologist (2001-2007): EMC/NOAA/NCEP/SAIC 5200 Auth Road, Camp Springs, Maryland 20746

Research Scientist (1998-2001): Center for Atmospheric Physics, SAIC, 1710 Goodridge drive, McLean, VA 22102

**Publications:**

Recent Most Closely Related Publications:

Panda, J., M. Sharan & S. G. Gopalakrishnan (**2009**): A Study of Regional-Scale Boundary Layer Characteristics over Northern India with a special reference to the role of Thar Desert in Regional-Scale Transport (accepted for publication in Journal of Applied Meteorology and Climate).

Gopalakrishnan, S. G., N. Surgi, R. Tuleya & Z. Janjic (**2006**): NCEP's Two-way-Interactive-Moving-Nest NMM-WRF modeling system for Hurricane Forecasting, 27th Conference on Hurricanes and Tropical Meteorology, **24-28 April, Monterey, California.**

Bacon, D. P., N. Ahmad, Z. Boybeyi, T. Dunn, S. G. Gopalakrishnan, M. S. Hall, Y. Jin, P. C. S. Lee, D. E. Mays, A. Sarma, M. D. Turner, T. R. Wait, K. T. Waight III, S. H. Young & J. W. Zack (**2003**): Dynamically Adapting Unstructured Triangular Grids: A New Paradigm for Geophysical Fluid Dynamics. *Modeling Proc. of Indian Academy of Science*, **69**, 457-471.

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Sharan M. & S. G. Gopalakrishnan (**1997**): Comparative evaluation of turbulent exchange coefficients for strong and weak wind stable boundary layer modeling. *J. Appl. Meteor*., **36**, 545-559.

**Awards and Accolades:**

NCEP/SAIC Outstanding Performance Award, 2005: “For his exceptional dedication and outstanding efforts in developing the movable, nested grid system for the Weather and Research Forecasting Modeling System (WRF) for advanced hurricane prediction and mesoscale modeling forecast applications.”

SAIC PUBLICATION AWARD, 2003: “An Operational Multi-Scale Atmospheric Model with Grid Adaptivity for Hurricane Forecasting, S. G. Gopalakrishnan et al., Monthly Weather Review, 2002, Vol. 130, No. 7, pp. 1830-1847” was awarded as the best paper of the year under the environmental sciences category.

**BIOGRAPHICAL SKETCH (Jason P. Dunion)**

**Education:**

Ph.D. in Atmospheric Science (Candidate), SUNY Albany, Albany, NY

M.S. in Atmospheric and Oceanic Science, 1999, *University of Wisconsin*, Madison, WI

B.A. inGeography/concentration in Geology, 1992, *University of New Hampshire*, Durham, NH

**Appointments:**

Oct 2009 – Present: Meteorologist, University of Miami/RSMAS/CIMAS, Miami

July 2006 – Sept 2009: Meteorologist, NOAA/AOML/Hurricane Research Division

Nov 1999 – June 2006: Meteorologist, University of Miami/RSMAS/CIMAS, Miami

June 1999 - Nov 1999: Meteorologist, Cooperative Institute for Meteorological Satellite Studies (CIMSS), University of Wisconsin‑Madison

July 1997 ‑ Nov 1997: Visiting Scientist, NOAA/AOML/Hurricane Research Division, Miami, FL

July 1998 ‑ Oct 1998: Visiting Scientist, NOAA/AOML/Hurricane Research Division, Miami, FL

Aug 1996 - May 1999: Research Assistant, Cooperative Institute for Meteorological Satellite Studies (CIMSS), University of Wisconsin‑Madison

**Publications:**

Recent Most Closely Related Publications:

Dunion, J.P. (**2011**): Re-Writing the Climatology of the Tropical North Atlantic and Caribbean Sea Atmosphere. *J. Climate*. (In Press).

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Jones, T., D. Cecil & J. P. Dunion (**2007**): The environmental and inner core conditions governing the intensity of Hurricane Erin (2001). *Wea. Forecast*. **24 no. 4**, 708-725.

Evan, A. T., J. P. Dunion, J. A. Foley, A. K. Heidinger & C. S. Velden (**2006**): New evidence for a relationship between Atlantic tropical cyclone activity and African dust outbreaks. *J. Geophys. Res.,* **33, L19813**, 1-5.

Rogers, R.F., S. Aberson, M. Black, P. Black, J. Cione, P. Dodge, J. P. Dunion, J. Gamache, J. Kaplan, M. Powell, J. Kaplan, M. Powell, N. Shay, N. Surgi & E. Uhlhorn (**2006**): The Intensity Forecasting Experiment: A NOAA multi-year field program for improving tropical cyclone intensity forecasts. *Bull. Amer. Meteor. Soc*. **87, no. 11**, 1523-1537.

Velden, C. S., J. Daniels, D. Stettner, D. Santek, J. Key, J. P. Dunion, K. Holmlund, G. Dengel, W. Bresky & W. P. Menzel (**2005**): Recent innovations in deriving tropospheric winds from meteorological satellites. *Bull. Amer. Meteor. Soc***. 86, no. 2**, 205-223.

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Dunion, J. P., S. H. Houston, C. S. Velden & M. P. Powell (**2002**): Application of surface adjusted GOES low-level cloud-drift winds in the environment of tropical cyclones. Part II: Integration into surface wind analyses. *Mon. Wea. Rev*., **130**, 1347-1355.

**Awards:**

Co-Recipient: NOAA AIRS Team for outstanding contributions to improving weather forecasting using data from the Atmospheric Infrared Sounder (AIRS);

Recipient: 2009 Editors’ Citation for Excellence in Refereeing for Geophysical Research Letters;

Recipient: 2005 NOAA David Johnson Award for “innovative research using environmental satellite observations on the influence and impact of the Saharan Air Layer on Atlantic tropical cyclones and the role it plays in development, decay, and intensity change of these storms.”

Recipient: 2004 Editors’ Citation for Excellence in Refereeing for JGR-Atmospheres.

Co-recipient: Best Transition to Operations Award, NOAATech 2002 Conference to the H\*Wind team.

Co-recipient: Best JAVA Implementation Award, NOAATech 2000 Conference for "A Distributed Real-Time Hurricane Wind Analysis System".

Recipient: 1997-1998 Wisconsin Space Grant Consortium Graduate Fellowship Award to integrate satellite winds into the NOAA/AOML/Hurricane Research Division's tropical cyclone surface wind analysis system.