Improving Understanding and Prediction of Hazardous Weather in the Southeastern United States: Landfalling Tropical Cyclones and Convective Storms

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Budget Period: 3 Years

The objectives of this collaborative project are to improve the understanding and prediction of hazardous convective and landfalling tropical weather systems in the Southeastern United States. The foci for the proposed effort are based upon input provided by regional NWS forecast offices as well as interactions with National Centers, and are aligned with NWS Eastern Region priorities. The specific weather hazards forming the basis of the proposed research program include **(i**) *inland wind accompanying tropical cyclones*, **(ii)** *heavy precipitation and localized flooding associated with tropical cyclones*, and **(iii)** *severe convective storms forming under conditions of marginal instability and strong vertical wind shear*.

Current practices for near-surface wind prediction suggest that improvement can be realized through observationally based climatological study in conjunction with physically based algorithm development and numerical weather prediction output. Improved quantitative precipitation forecasting will draw upon ensemble prediction techniques, including utilization of regional model runs in NWS offices. Land-threatening tropical cyclones are accompanied by coastal as well as inland prediction challenges, and improved techniques for near-surface wind forecasting will benefit residents of regional NWS county warning areas. Severe convection in high-shear environments with marginal instability have garnered attention at the Storm Prediction Center as well as regional NWS offices; improved understanding of the dynamics of such convective systems is a prerequisite for improved prediction.

Collaborative research and emphasis on transfer of research to operations will be emphasized through a structure that includes site visits to remote offices and national centers, regular meetings with the students, PIs, and NWS collaborative investigators, and the production of training materials to facilitate the operational application of research results. Additionally, state-of-the-art numerical weather prediction systems will serve as testbeds for algorithm development and numerical model configuration. For those aspects of the project related to tropical cyclone prediction, we will utilize a recently developed realtime system which has been run for the past two tropical seasons at the Renaissance Computing Institute (RENCI). While output from this system is available to NWS forecasters, our primary objective will be to utilize this system to develop and test wind and precipitation prediction techniques that can be applied independently at regional NWS offices. Additionally, an ensemble computing system will be further developed and utilized in the prediction of heavy precipitation.

PROJECT DESCRIPTION

A. Overview and Relevance

The program of research focuses on understanding and prediction of inland impacts of landfalling tropical cyclones (TCs), specifically severe wind and precipitation prediction, and severe convection taking place with high shear in marginally unstable environments.

1. Motivation and collaborative philosophy

The proposed research foci are based on input from 9 regional NWS Forecast Offices. In addition, collaborative ties at the Storm Prediction Center (SPC, contact: Steve Weiss), Tropical Prediction Center (TPC, contact: Michael Brennan), and Hydrometeorological Prediction Center (HPC, contact: David Novak) have been established. While the focus of our collaborations will be the regional NWS offices, interaction with the National Centers will extend the impacts of our work, and ensure coordinated efforts in areas of programmatic overlap.

2. Transfer of results to operations

Relative to previous CSTAR efforts undertaken at NCSU, a more direct and ambitious approach to technology transfer is proposed here. Past experience demonstrates that truly collaborative research benefits when an active collaborative investigator (CI) from the NWS is identified. Additionally, past workshops and meetings have brought about a synergistic exchange of ideas, such as the NW snow collaborative that developed as an offshoot of previous CSTAR efforts at NCSU (Keighton et al. 2009). We will build on the success of previous site visits and recorded presentations, we will seek to increase the frequency of student and PI visits to regional NWS field offices in an effort to strengthen collaborative ties. Use of GoTo Meeting or similar software will allow coordination of regularly-scheduled interactions between the university researchers and the NWS CIs. At NCSU, quarterly meetings between the faculty PIs and students, along with all available NWS collaborators, will increase the level of coordination among the research projects. These meetings will be summarized, and results made available to all collaborative partners at NWS field offices and National Centers. To facilitate collaboration with the HPC, SPC, and TPC, we will coordinate with visitor programs at those facilities to ensure a broad dissemination of our results.

While it is recognized that the transition to the AWIPS-II software package will influence the manner in which products are developed and transferred, it is expected that significant benefits may result from this transition. The lead PI is affiliated with the Unidata program, through which the AWIPS-II software will be distributed to the academic community (when available). This will allow, for the first time, workstations in the university environment to run the same software that NWS forecasters will be using in the forecast offices. Thus, a more direct conduit to operations will be realized by having the university researchers develop tools, case studies, and products that can be directly ported to the NWS offices.

Another novel aspect of the current proposal will be utilization of "testbed" numerical weather prediction systems, currently run at the Renaissance Computing Institute (RENCI). Experimental development of products and algorithms using real time modeling systems, which offers a more realistic proof-of-concept relative to purely retrospective case studies. Currently, a tropical prediction system dubbed "HUR-NC" as well as the "Carolinas

Ensemble", coordinated by Brian Etherton, are run at RENCI. The ensemble system includes several members run at regional NWS offices. These model runs, once compiled, enable the generation of a high-resolution ensemble with grid lengths significantly smaller than those available in the SREF ensemble from NCEP. Once 2-D fields are computed, these will be re-broadcast in the requisite format (AWIPS or AWIPS-II) for utilization at NWS field offices.

3. Programmatic relevance and regional collaboration

In addition to development around input from 9 NWS field offices, the proposal is relevant to the following NWS Eastern Region priorities listed in the Request for Proposals (RFP):

- The interaction of terrain features with hurricanes;
- Development of improved, region-specific conceptual models for high wind and flash flood events;
- Improved detection and warning techniques for low-topped severe convection;
- Improved forecasts and warnings of severe weather and heavy precipitation during tropical cyclone events;
- Development of innovative approaches to formulate, produce, display, and deliver high-resolution digital forecasts and products for the eastern United States;
- Development of new techniques to more effectively and efficiently utilize information from ensemble prediction systems in the forecast process;
- Development of innovative methodologies to communicate forecast uncertainties to a wide variety of users.

A major focus of this proposal is improved prediction of the wind field accompanying tropical cyclones. Severe winds are a high-priority area identified by NWS as outlined in the proposal announcement as well as in the NWS Strategic plan for 2005-2010 (http://www.weather.gov/sp/NWS_strategic_plan_01-03-05.pdf). The strong collaboration between NWSFO RAH and NCSU fostered through previous projects (see http://www4.ncsu.edu/~nwsfo) has broadened to include the coastal and western Piedmont offices mentioned above during the previous CSTAR project. As demonstrated by the previous project, *regional collaboration* represents an efficient and wide-ranging benefit to university researchers, operational weather forecasters, and ultimately to the citizens of the region (e.g., Keighton et al. 2009). For the current proposal, we are seeking to extend collaborations to three National Centers, including HPC, TPC, and SPC. The PIs have close contacts at these centers, including former NCSU CSTAR student Michael Brennan at TPC, and former SUNY Albany CSTAR student David Novak at HPC. PI Parker has strong collaborative ties at SPC, and PIs Lackmann, Etherton, and Parker have all previously participated in the SPC/NSSL Spring Experiment.

B. Proposed Work

1. Tropical Cyclone Inland Impacts (Lackmann, Aiyyer, and Etherton)

a. Definition of research problems

In a survey of 9 regional forecast offices conducted by the Raleigh, NC forecast office, 8 offices cite prediction of tropical cyclone (TC) winds and precipitation as top priorities for collaborative research. Specifically, the need for a climatological baseline for sustained wind and gusts with landfalling TCs, and improved algorithms for wind and gust prediction were listed by the Raleigh, Wakefield, Charleston, Greenville-Spartanburg, Wilmington, Peachtree

City, and Blacksburg forecast offices as high-priority forecasting challenges. Quantitative precipitation forecasting (QPF) with landfalling TCs is also a critical forecast parameter, and recent events such as Tropical Storm Hanna (2008) provided a challenging QPF situation. Inland flooding and severe damaging winds are two main sources of risk to life and property associated with landfalling tropical cyclones. While quantitative precipitation forecasting (QPF) has received substantially more attention in the past--and has been aided by improvements in numerical models--forecasting wind speed remains a major challenge.

Improved prediction of wind and precipitation with landfalling tropical cyclones will require a three-tiered approach. First, improvements in the representation of tropical cyclones in numerical weather prediction (NWP) models are required. Second, climatological observations of sustained winds and gusts for past TCs and algorithms designed to derive accurate predictions of these parameters from numerical model output are needed. Finally, improved precipitation forecasting for landfalling TCs will benefit from improved recognition and model representation of thermal boundaries during landfalling TCs, as well as a high-resolution probabilistic approach available from an ensemble prediction system.

i.) Improved Model Initial Conditions for Landfalling TCs: Background

A prerequisite for profitable use of numerical weather prediction (NWP) model output in forecasting of landfalling TCs is that the models provide a realistic representation of the track and intensity of the storm. However, major difficulties remain in the numerical prediction of TCs, particularly with the difficulties of current numerical models in predicting TC intensity (e.g., Elsberry 2005; Rogers et al. 2006). For the past two Atlantic hurricane seasons, PIs Lackmann and Etherton have worked with graduate students to develop and test a realtime NWP system, based on the Advanced Research version of the Weather Research and Forecasting model (WRF-ARW, Skamarock et al. 2007). The performance of this system benefits from the substantial computing resources of the Renaissance Computing Institute (RENCI) and efforts to utilize several features of WRF-ARW that are designed for improved TC representation (e.g., Davis et al. 2008). Significant computational power is required in order to run the model at grid lengths which allow explicit convection on the innermost (3km) model domain, while still allowing a domain size of sufficient size for proper representation of the TC. However, a significant weakness lies in the model initial conditions; that is one of the foci of this proposal. PI Etherton, with significant experience in the realm of data assimilation, will work with PI Lackmann and current graduate student Briana Gordon to continue ongoing efforts to optimize model initial conditions for cases of landfalling TCs. Use of retrospective cases within our realtime modeling framework, and coordination with regional NWSFOs that are running workstation versions of WRF will allow a transformative approach to TC prediction. Improved initial conditions, developed by PI Etherton at RENCI, will be distributed to those regional NWS offices wishing to utilize these in local workstation WRF forecasts. With improved TC representation in these localized models, profitable use of wind and gust algorithms, applied to local WRF output, can then be realized at regional offices.

ii.) Prediction of the Inland TC Wind Field: Background

Surface wind gusts are strongly modulated by the state of the planetary boundary layer, including thermal stratification and turbulent processes. The inherent stochasticity of the latter renders the problem of predictability extremely difficult even when high resolution numerical models are deployed. As a result, predictions of tropical cyclone wind speeds have been primarily determined using empirical techniques (e.g., Kaplan and DeMaria 1995; 2001). However, there are numerous gaps in our understanding of spatial and temporal distribution of sustained winds and wind gusts associated with landfalling tropical cyclones. Furthermore, due to variations in synoptic/mesoscale conditions, topography, storm track and storm morphology, empirical wind distribution models developed for one region are not universally applicable. These factors pose a significant impediment to operational forecasters while monitoring and issuing advisories during these catastrophic events. This calls for a development of a dynamical forecasting framework and training of forecast personnel to make optimum use of the same.

While past studies have examined the evolution of the tropical cyclone wind field after landfall (Wong et al. 2008; Bhowmik et al. 2005; and Kaplan and DeMaria 2001), the results from these studies have not been routinely used by NWS forecasters in operational prediction. The current methodology used by NWS field offices focuses on providing forecasts that are consistent with the official guidance from the NHC and with adjacent offices. The individual offices can make some adjustments to the official NHC forecast to account for local effects and to make the forecast appear more meteorologically sound, but this part of the process is typically subjective (Jonathan Blaes, NWS Raleigh, personal communication). The adjustments are often made without the benefit of good scientific or statistical guidance.

Forecasters now use a graphical editor known as the Graphical Forecaster Editor (GFE) included in the Interactive Forecast Preparation System (IFPS) to create high-resolution gridded forecasts of weather elements that are converted into text products, forecast graphics and gridded data (Ruth 2002; Glahn and Ruth 2003) as part of the National Digital Forecast Database (NDFD) http://www.nws.noaa.gov/ndfd).

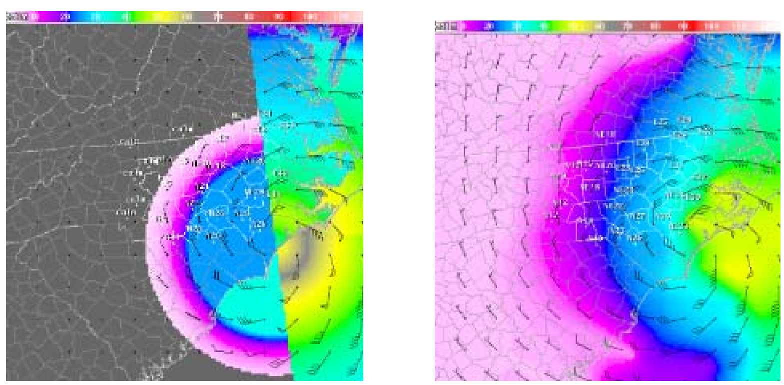


Figure 1. (a) Populated wind speed and wind direction forecast for Tropical Storm Hanna, shown in GFE, from NHC guidance issued at 09 UTC on Sept 4, 2008 valid at 09 UTC on Sept 6, 2008. Note the coarse nature of the data which is largely based on quadrants; and (b) Adjusted wind speed and wind direction forecast for Tropical Storm Hanna for the same time.

To ensure consistency with the official forecast from the National Hurricane Center, the process of creating wind and wind gust forecasts in GFE begins with populating wind grids with guidance from the NHC. Forecasters use a Smart Tool in GFE called the TCMWindTool to ingest and then downscale a tabular text forecast product (TCM) that contains tropical cyclone wind radii at 34 knot, 50 knot, and 64 knot thresholds. These radii are constructed by NHC forecasters to reflect the strongest wind expected in each quadrant [NE, SE, SW, and NW (centered on the storm center and relative to north)]. The wind grids are then constructed according to these radii and the projected path of the storm at 6 hour increments. The result is a wind forecast that is not always representative of the true atmosphere (Fig. 1). In order to produce a more realistic and accurate forecast, forecasters can use options in the TCMWindTool and other Smart Tools in GFE to make adjustments to the wind forecast grids. The Smart Tools allow forecasters to increase/decrease velocities, add/subtract values to the velocities, multiply/divide by factors, adjust the wind direction, smooth the speed and direction, and more.

The flexibility of the Smart Tools when combined with a limited scientific framework in a largely subjective process can result in wide ranging adjustments to the initial NHC guidance. When multiple offices in a given region are using their own subjective process, the result can be a poorly collaborated forecast as shown in Fig. 2.

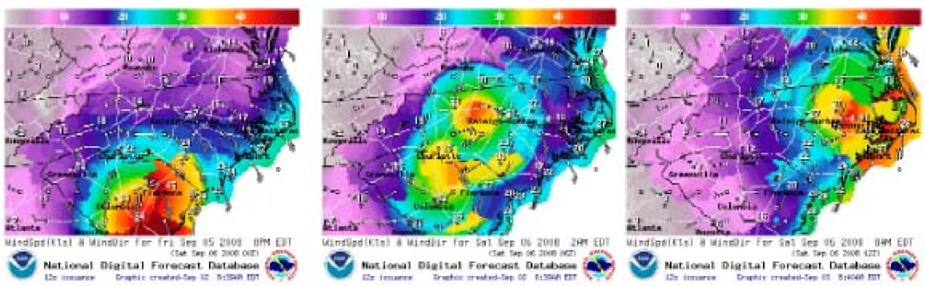


Figure 2. Wind speed and wind direction forecasts for Tropical Storm Hanna from the NDFD from various forecast issuances valid at (a) 00 UTC Sept 6, 2008; (b) 06 UTC Sept 6, 2008; and (c) 12 UTC Sept 6, 2008.

There is significant opportunity for improvement in the current paradigm of wind forecasting, as illustrated above. This can be achieved by combining results from past studies and new observations- and simulations-based analysis proposed herein. Powell et al. (1991) investigated the surface wind distribution across the Carolinas associated with Hurricane Hugo and compared the relative rapid decrease in sustained winds as the storm moved inland with a slow decrease in wind gust speeds that exceeded hurricane force in Charlotte, which is 330 km inland. In addition, Powell et al. (1991) investigated the ratio of maximum peak wind gusts to the maximum sustained (1-minute average) winds and produced a gust factor which was can be used to estimate wind gusts based on the mean wind. In the GFE framework, forecasters use the wind speed and direction forecast to produce the wind gust forecast. This is typically accomplished by multiplying the wind speed forecast by a percentage. Recent experience has shown that the determination of this percentage is often subjective and lacking a scientific foundation. Building upon the work of Powell et al. (1991) and others to incorporate gust factors into this process would greatly improve forecast consistency and accuracy.

This study derives its motivation from two primary considerations driven by the critical need for accurate wind forecasts and the current paradigm employed by operational forecasters:

- Accurate and timely forecasts of severe winds during tropical cyclone events is especially critical for users and decision makers charged with protecting life and property of residents and constituents. A poorly collaborated forecast as shown in Fig.

2 undermines the utility of the NDFD and results in decreased confidence in the forecast by emergency managers and decision makers.

- The current process of forecasting TC related inland winds is subjective, with limited conceptual guidance; and thus poses a significant challenge to individual National Weather Service (NWS) Weather Forecast Offices (WFOs).

iii.) Quantitative Precipitation & Ensemble Prediction of Landfalling TCs: Background

The QPF problem in the southeastern U.S. includes complexities associated with the terrain of the region, which can lead to orographic modification of precipitation amounts as well as playing a role in the formation and movement of boundaries, such as those accompanying cold-air damming (e.g., Srock and Bosart 2009). In the presence of even weak frontal boundaries, the wind and precipitation prediction problems can be related. On the cool side of such a boundary, enhanced isentropic lift and deep ascent can enhance rainfall totals (e.g., Atallah and Bosart 2003; Colle 2003; Atallah et al. 2007). An example of precipitation totals during tropical storm Hanna (2008) in North Carolina is shown in Fig. 3 (see http://www4.ncsu.edu/~nwsfo/storage/cases/20080906/ for a detailed summary of this event). While a boundary can result in locally heavy precipitation, the presence of stable air near the surface may reduce peak wind speeds there relative to what would otherwise occur. Figure 3 demonstrates that the strongest winds with Hanna were to the east of the zone of heaviest precipitation, consistent with the pattern expected in the presence of a quasi-stationary frontal boundary.

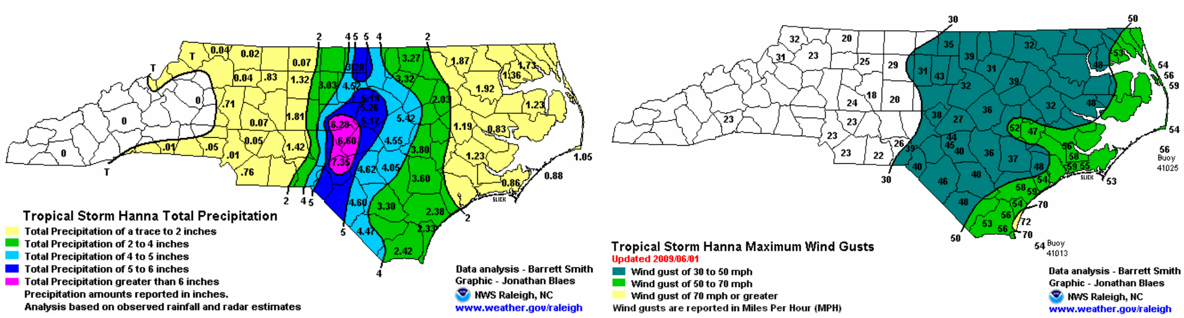


Figure 3. NWS Raleigh analysis of North Carolina storm total precipitation and wind gusts for tropical storm Hanna (2008).

While the studies cited above have clearly delineated many of the relevant physical processes during heavy TC precipitation, significant gaps remain: these studies have not directly explored how to improve numerical prediction of these events. An outcome of the proposed research is to provide a unique dataset with direct operational value for TC wind and precipitation prediction, while working directly with realtime modeling systems to both improve numerical prediction of landfalling storms and test algorithms of direct relevance to those using numerical model output from other sources. Experience with model configuration and process representation during cold-air damming events (e.g., Lackmann 2009) will help to identify optimum configurations of local models for prediction of TC-boundary interaction events. This aspect of the project will utilize the results of previous numerical experiments (e.g., Stanton 2004, Baker 2009) with cold-air damming to explore the optimization of boundary formation, maintenance, and movement.

Given the uncertainty inherent in prediction of precipitation, an ensemble approach is warranted. The use of an ensemble prediction systems in QPF is becoming more widespread in the meteorological community (e.g., Tracton *et al.,* 1998, Jones *et al.,* 2007; Eckel and Mass, 2005; Liu *et al.,* 2007; Xue *et al.*, 2007; Arnott *et al.*, 2007). Given that omission of a model convective parameterization scheme may be justified at model grid lengths of ~4km or smaller, an ensemble of such explicit convection model runs can be dubbed a Storm Scale Ensemble Forecast (SSEF). Within the region defined by collaborating NWS forecast offices, at least 10 different agencies are running high resolution modeling systems for realtime prediction. Taking advantage of the differences in model physics and initial conditions, a regional SSEF can be constructed, with ensemble products redistributed back to the different agencies, and used as guidance for heavy precipitation, high wind, or red-flag conditions forecasts.

b. TC Inland Impacts: Research objectives and plan of work

i.) Improved Model Initial Conditions for Landfalling TCs: Plan

The Renaissance Computing Institute (RENCI) at the University of North Carolina has the computational resources to run a Hurricane WRF ARW in real time. Such a system has been in place since 2008, and a hardware upgrade this fall will allow for parallel runs, an expanded domain, or both, in 2010 and beyond. This system took advantage of special modifications for tropical cyclone prediction, including use of a vortex-tracking moving nest capability with 27km, 9km and 3km grid domains. Preliminary results were very promising, but the experience also highlighted areas of needed improvement. The most significant of these were improving initial conditions, and better accounting of air-sea coupling (Davis et al. 2008).

The current version of our WRF-ARW based realtime TC prediction system run at RENCI utilizes Global Forecast System Data Assimilation System (GDAS) 0.5° data for initial and lateral boundary conditions. For the majority of Atlantic TCs during the 2008 and 2009 seasons, this system has proven reliable, especially for systems that are relatively weak at the time of initialization. However, the relatively coarse GFS data are not adequate for initialization for storms that are strong (e.g., Category 2 or greater) at the time of initialization. Clearly, the ability to accurately represent the landfall of strong TCs is needed for wind and precipitation prediction. Therefore, effort must be expended to improve model initial conditions sufficiently for useful landfall and post-landfall predictions.

An approach that PI Lackmann and Etherton have been using, in collaboration with graduate student Briana Gordon, is to obtain and utilize the GFDL initial vortex (Kurihara et al. 1993) to modify the GFS initial conditions. Recent work (Hart, 2008) has shown that the use of a GFS/GFDL merged field for initial conditions of 6km resolution MM5 forecasts produces different forecasts than using the GFS fields as initial conditions. Ms. Gordon has run several experiments using storms from the 2008 and 2009 seasons, and found that while the model better captures the initial intensity of the system with the use of the initial vortex, the benefit does not always persist in the model forecast cycle. Therefore, a new approach is needed. An alternative to the GFDL vortex is to use a new TC-bogus feature in version 3.1 of WRF ARW. Similar to MM5 (Low-Nam and Davis 2001; Wang and Frank 2000; Xiao et al. 2009), the input to the WRF bogus is a single time-period and single domain of analysis data, and variables describing the bogus TC location and strength. We propose to address the initial condition issue through experimentation with these different techniques. A more thorough understanding of the properties of the different bogus vortex strategies is required before identifying an optimum configuration for the realtime system.

During 2010-2012, we will continue to run WRF in real-time every 12 hours. Our intent is to run three forecasts every cycle. One forecast will be initialized with the GFS analysis valid at the synoptic time. The second forecast will use the tc.exe bogus scheme of WRF ARW, and the third run which uses a blend of the GFDL and GFS model analyses valid at the synoptic time (blending as per Hart, 2008). From this we will have a collection of forecasts from which to diagnose the issues regarding model initialization. Scientifically, we must understand how and why the different vortex initial conditions lead to differences in the model predictions. Our approach will be to utilize several past landfalling systems of varying intensity, including Hurricane Isabel (2003), Floyd (1999), and Hanna (2008) to test the new initial condition procedure.

During the summer of year 1, model experiments and continued testing of the various TC initial conditions will continue. Once satisfactory results have been obtained, the approach will be automated, and incorporated into the realtime prediction system during either the 2010 or 2011 Atlantic tropical seasons. Briana Gordon will complete her MS thesis during the summer or fall of 2010, and the modeling system results will be presented and submitted for publication in an AMS journal late in 2010.

ii.) Prediction of the Inland TC Wind Field: Plan

The overarching goal of this component of the study is to improve the currently used methodology for operational forecasts of wind speed and wind gust. This will be accomplished through a systematic analysis of observations and targeted numerical simulations. The proposed analysis tools encompass (i) climatological and statistical analysis; (ii) phenomenological case studies; and (iii) detailed verification of past forecasts. During year 1, when the initial conditions for the operational TC prediction system are being improved to adequately predict landfalling TC intensity, a climatological study, and subsequently, algorithm development will be underway. When ready, these algorithms will be used in conjunction with the NWP output for retrospective model case studies, and ultimately, for the realtime prediction system.

Hourly observed winds from all available measuring sites across North Carolina, South Carolina and Virginia will be used. The project will focus on a 13 year period from 1995 to 2008 when a preliminary analysis indicated 42 tropical cyclones impacted a portion of the study domain.

The specific objectives of this component of the proposed work are:

(i) To analyze all available observations during tropical cyclone events to produce a detailed climatology of inland wind and wind gusts. The climatological analysis will lead to a better understanding of the ranges of wind and wind gusts and historical context which should result in improved tropical cyclone wind forecasts.

(ii) To conduct a systematic verification analysis on NHC TCM forecasts and of local NWS WFO forecasts. This will be conducted for both gridded and point forecast products.

(iii) To build a statistical-dynamical model of winds and wind-gusts. This will be accomplished by combining the climatological observations-based analysis with specific high-resolution numerical simulations of selected cases. A physically motivated GFE smart tool will be developed for improved gust prediction.

(iv) To utilize the statistical-dynamical model in conjunction with both TPC forecasts and WRF-based NWP predictions for both retrospective, and, ultimately, real-time events.

If successful, the outcome of the study will lead to improved strategies for creating wind and wind gust forecasts using the GFE environment, and better utilization of operational NWP guidance. These strategies will be aimed at improving the scientific basis for the current subjective and mechanical forecast process.

iii. Quantitative Precipitation & Ensemble Prediction of Landfalling TCs: Plan

One goal of this work is to provide high resolution probabilistic forecast guidance. Preliminary work on probabilistic QPF for the Carolinas was done during the spring 2007, when PI Etherton and RENCI staff member Leesa Brieger constructed a 32-member ensemble of Weather Research and Forecasting (WRF, Skamarock et al. 1997; Michalakes et al, 1998) model simulations for the Carolinas. The focus of the experiment was the prediction of precipitation at 4km grid spacing in an area centered over the Carolinas (Figure 4). That ensemble consisted of 32 forecasts from the WRF model, each member having an outer (12-km) and inner (4-km) nest. We evaluated forecasts only on the inner domain; the 32 ensemble members were produced by having each member use one of 2 options for five different parameters: initialization time, PBL scheme, moist physics, soil physics, and cumulus scheme.

The goal of this work is to combine the high (~4km) resolution NWP from 10 agencies in the Carolinas to form a Storm Scale Ensemble Forecast, producing an ensemble similar to the experimental forecasts produced during the spring of 2007. All agencies will send surface fields (2-m temperature and dewpoint, 10-meter winds, and accumulated precipitation, etc.) to RENCI. From these surface fields, means, spreads, and probabilities (simple percentage of forecasts) will be produced for wind speed, precipitation, and red-flag condition forecasts. These products will then be sent back to the agencies. The current members of this SSEF include 8 runs produced at RENCI, and one run a piece from Savannah River National Laboratory and the National Weather Service Forecast Offices in Raleigh, NC, Greenville-Spartanbrug, SC, Columbia, SC, Wilmington, NC, Blacksburg, VA, and Baltimore-Washington, MD-DC. Note that later in 2009, RENCI hardware upgrades will allow for 16 RENCI ensemble members, as opposed to the current 8. Additionally, a few more agencies are nearly set to join the ensemble. With these new resources, we will have approximately 25 ensemble members. Lastly, with the commencement of HMT Southeast, the NOAA ESRL will be able to contribute members to this ensemble (Dr. Jankov, personal communication).

The operational centers provide their model output at whatever resolution (around 4km) and with whatever initialization time there are presently using, though all are on a similar domain. RENCI, having more computational resources, will start their ensemble members at different times – to broaden the diversity of the ensemble members. For the most part, RENCI will run WRF ARW, whereas the NWS WFOs will be running WRF NMM. As was learned in prior work, a diversity of ensemble members in terms of initial and boundary conditions, PBL scheme, moist physics, cumulus schemes, and soil schemes leads to a diversity of model forecasts. As such, RENCI will use those schemes that the operational centers are not using.

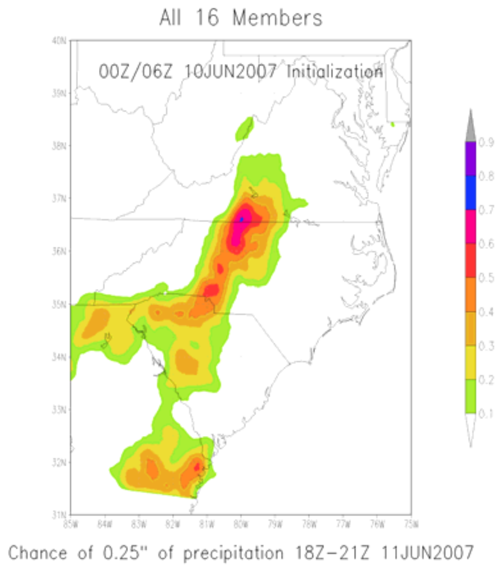


Figure 4. The inner domain for the WRF ensemble. The grid spacing of this domain is 4km.

In the first year of this project, the primary goal is the flow of model data from the operational and academic centers into RENCI, and then the flow of ensemble based forecasts back out of RENCI to those centers. To minimize bandwidth, only surface fields will be used. It is imperative that the ensemble forecast output be AWIPS ready. In year 1, PI Etherton will work with an NC State graduate student to establish the real time exchanges of model data between the participating agencies and RENCI, and produce forecasts listed below. In addition, in year 1 we will begin to evaluate the SSEF forecasts, evaluating both the QPF and the location of surface boundaries.

Forecasts will be compared to surface data. Surface data used in the comparison will be METAR observations, Stage-IV precipitation data, and the Real Time Mesoscale Analysis (RTMA). The National Center for Environmental Prediction (NCEP) Stage IV analysis uses the hourly/6-hourly analyses transmitted from the 12 River Forecast Centers (RFCs). The regional analyses done at the RFCs use the multi-sensor analysis algorithm (Fulton and Kondragunta, 2002) and manual quality control. The RTMA is produced by the National Centers for Environmental Prediction (NCEP), and consists of a set of gridded surface analyses, accompanied by an estimated error for each parameter. RTMA uses satellite, radar, rain gauges, ASOS, Mesonet, and other sensor data in the generation of these grids. The sensor data are interpolated to a 5 km CONUS grid, with analyses produced each hour. RTMA will be ideal for evaluation of hourly ensemble mean forecasts of temperature, dewpoint, and wind. If available, we look to use any special observations from the HMT Southeast program as part of our study.

In the second year, the model output will continue to be evaluated, and calibrated to improve forecast accuracy, by PI Etherton and the NC State graduate student. Various metrics will be used to do the evaluation, such as bias and mean-squared error of the ensemble mean, reliability diagrams, area under the ROC curve, and Talagrand diagrams. We will look to calibrate the ensemble QPF forecasts using the tools of bias correction, and perhaps Bayesian Model Averaging and Ensemble MOS (EMOS). In addition to improving/evaluating QPF forecasts, we will produce bias and MSE statistics for other surface parameters.

The proposed work should help operational hydrometeorological services, in providing high resolution forecast guidance that is presently unavailable from any other source. Our work will be transferred to forecast operations in a reasonable time frame, as we make the output data easy to ingest into the AWIPS systems used at NWS forecast offices. Once in AWIPS, SmartInit utilities will be developed to ingest forecast fields for use in GFE. Forecasters will then have the opportunity to compare and potentially populate the forecast grids with output from the ensemble. By making our output AWIPS ready and developing SmartInit routines, our results should transition to operations successfully and efficiently.

Our proposed work combines the many modeling efforts already ongoing in the Carolinas to produce a storm scale ensemble forecast. While a SSEF is relatively new, it has been done in research mode (notably, at HWT in Norman, Oklahoma), and thus the concept has reached a level of maturity suitable for operational uses. We are aware that there is the potential for a vast amount of data to be exchanged, and thus, we have limited our focus to the prediction of surface fields, where issues such as internet bandwidth and disk storage space are minimized.

RENCI is providing the disk storage space for the ensemble runs as well as providing between 8 and 16 members of the SSEF. We are also leveraging the existing NWP going on at various agencies in the Carolinas.

Expected Outcomes:

(i) Improved forecast tools and strategies: The results of the proposed work will improve strategies for creating wind and wind gust forecasts in the GFE environment. These strategies will be focused on improving the scientific basis for the current subjective and mechanical forecast process. The development of improved algorithms for applying these ideas in the GFE environment will stem directly from collaborative efforts.

(ii) Improved understanding of the evolution of the wind field: The proposed work will be guided by the working principle that, by incorporating all of the factors identified in the preceding discussions into a unified framework, a holistic conceptual model can be developed. With an improved understanding of these processes and some historical context, improved tropical cyclone wind forecasts can be made.

(iii) Access to improved NWP products for landfalling TCs: By improving the representation of TCs in model initial conditions, more realistic numerical predictions will allow forecasters to utilize NWP more reliably in the prediction of inland winds and rainfall.

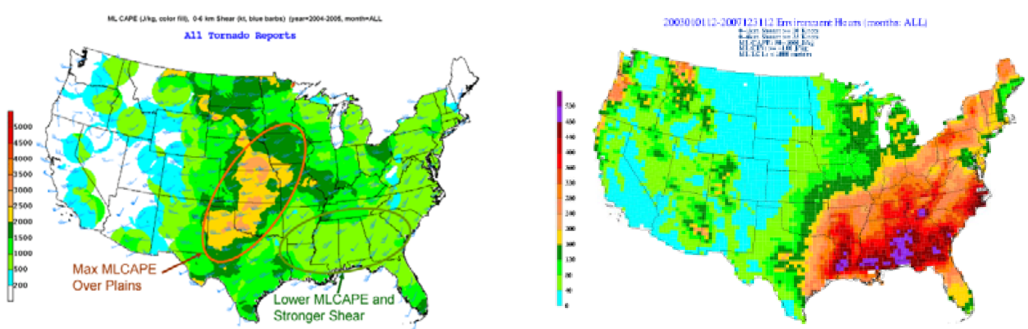
(iv) Improved utilization of NWP output in wind and precipitation prediction: Through work with the testbed NWP system, algorithms can be developed using both current and retrospective cases. Ensemble-based QPF grids will be made available in GFE for possible population of QPF forecast grids.

2. Severe weather in environments with marginal instability (Parker)

A final problem that is repeatedly mentioned by our regional partner forecast offices involves prediction, nowcasting, and warning for severe storms in environments with large vertical wind shear but small instability (i.e. CAPE). Such high-shear/low-CAPE (hereafter, "HSLC") severe storms may take the form of squall lines/bow echoes, which are common when lower tropospheric shear is large (e.g., Weisman 1993), and have been frequently observed during the cool season (Burke and Schultz 2004); or, alternatively, HSLC severe storms may take the form of "miniature" (also known as "low topped") supercells (e.g., Davies 1990, Kennedy et al. 1993). These HSLC outbreaks are often characterized by widespread severe wind reports, as well as some tornadoes. In particular, HSLC tornado days represent a very difficult forecasting challenge. Our operational partners note that such tornadoes are "difficult to identify on radar", and they often occur during the cool season "when many people assume that severe convective storms are highly unlikely." One office noted that this "taxes the warning system to its utmost" and another stated that they need researchers "to help find better techniques for the forecasters" in dealing with HSLC storms.

a. Definition of the problem

Regional significance. The HSLC problem is distinctly relevant in the southeastern US, where the mean tornado environment is characterized by CAPE values below 1000 J kg^{-1} (Fig. 5a). This is a small amount relative to that observed in the tornado environments of the Great Plains (i.e. the corridor from the Texas Panhandle through southeastern Nebraska in Figure 5a). The lower CAPE values are largely compensated by large vertical wind shear; tornado environments in the Southeast commonly exhibit 0-6 km bulk shear vector magnitudes (hereafter, "BSVM") of 18-25 m s^{-1}, which is stronger than the mean deep-layer BSVM found over the Great Plains (Fig. 5a). McCaul and Weisman (1996) have shown that the dynamic contribution from vertical wind shear can overcome the apparent drawbacks of limited buoyancy, such that HSLC supercells can have updraft speeds that are nearly as large as those of high-CAPE storms.



(a) (b)

Figure 5: Depiction of the mean environments for storms over the continental US. a) Mean mixed layer CAPE (MLCAPE, shaded, J kg^{-1}) and 0-6 km BSVM (barbs, kt) for all tornado reports in 2004 and 2005. b) Number of hours (totaled over the 5 year period 2003-2007) during which the local environment possessed low CAPE (1000 > MLCAPE > 50 J kg^{-1}), but was otherwise favorable for tornadoes, including large low-level vertical shear (0-1 km BSVM > 10 m s^{-1}), large deep-layer wind shear (0-6 km BSVM > 18 m s^{-1}), small convective inhibition (MLCIN > -100 J kg^{-1}), and low cloud base (MLLCL height < 1000 m). Images provided by Steve Weiss of the SPC, derived from a database described by Schneider et al (2006) and Schneider and Dean (2008).

The HSLC environment is also relevant to severe bow echoes/squall lines. Squall lines may produce severe winds via conventional mechanisms (as reviewed by Wakimoto 2001), but are also associated with embedded mesovortices (Trapp and Weisman 2003, Atkins et al 2004, 2005, Wheatley et al 2006), which enhance straight-line winds (Wakimoto et al 2006; Atkins and St. Laurent 2009) and also can lead to tornadoes (Przybylinski 1995; Funk et al. 1999; Atkins et al. 2004; Trapp et al. 2005). Both Weisman and Trapp (2003) and Atkins and St. Laurent (2009) have shown that the occurrence of embedded mesovortices increases as the environmental shear increases (as in HSLC regimes).

Current operational approaches and needs. In operational settings, forecasters tell us that they are generally unsure of how to *quantify* the degree to which shear will offset low CAPE on a given day. Helpful guidance is provided in the form of the Storm Prediction Center's supercell composite and significant tornado parameters ("SCP" and "STP", Thompson et al. 2003, 2004), both of which attempt to estimate the combined contributions of CAPE and vertical wind shear. However, it is unclear to what degree the SCP and STP are useful in anticipating bow echo/squall line tornadoes. Further delineation between the high-end and non-threatening HSLC days is needed because, as shown in Figure 6.1b, HSLC environments are extremely common in the Southeast (in excess of 80 hours per year in Georgia and the Carolinas). A handful of these HSLC hours each year are associated with landfalling tropical cyclones (e.g. McCaul 1991, 1993) when situational awareness is already high; but, a good deal more of the HSLC hours occur during the cool season and at night, when situational awareness is often lower. These HSLC periods are of definite concern; for example, Trapp et al. (2005) showed that bow echo/squall line tornadoes display a statistically significant tendency to occur during the late night/early morning hours, and Ashley et al (2008) found that a high frequency of tornado fatalities occur at night in the Southeast. Even if/when elevated HSLC situational awareness is attained, false alarms remain a problem because a non-trivial fraction of the cool season and nocturnal HSLC hours are non-severe or non-convective.

Because prediction of HSLC tornadoes has proven difficult, forecasters in the Southeast often rely on recognition of the "broken-S" reflectivity pattern that may be associated with squall line mesovortices and tornadoes (e.g., Lee and Jones 1998, McAvoy et al 2000, Lane and Moore 2006, all of which were authored by forecasters at NWS-Greer, SC). However, much like hook echoes in supercells (which have a high false alarm rate and low probability of detection for tornadoes; Forbes 1981), the visual recognition of the broken-S by itself is not a sufficient forecasting/warning tool. Not all squall line tornadoes are associated with this pattern, nor are all broken-S echoes associated with the same basic storm-scale processes (Grumm and Glazewski 2004). Because most of extant work on the broken-S pattern comprises case studies of observed tornadoes, it is not currently known how frequently the broken-S pattern is observed in *non*-tornadic cases, nor how often HSLC environments in the Southeast are instead associated with miniature supercells (both tornadic and non-tornadic).

b. Research Objectives and plan of work

Specific objectives. The long range goal of this effort is to improve forecasts and warnings for severe weather and to reduce false alarms in HSLC convective environments. The specific objectives of the proposed activity are: 1) to catalog and understand the spectrum of southeastern HSLC convective storms in terms of their most common radar signatures and their severe weather production; and, 2) to identify the most effective environmental parameters for operationally discriminating between high-end (i.e. widespread severe winds or tornadoes) HSLC cases and null cases (see below) in the Southeast.

Plan of work. We will use the following two-part approach in order to achieve our specific objectives. This research will be accomplished by an M.S.-level graduate student with the assistance and supervision of PI Parker.

The first year of the HSLC investigation will constitute a radar-based climatology. Cases will be identified for a multi-year period using the Storm Prediction Center (SPC) Severe Thunderstorm Events archive (http://www.spc.noaa.gov/exper/archive/events/). Any day with severe reports in the Southeast (meaning Georgia, the Carolinas, and Virginia) will be cataloged for further study. We will review the regional radar reflectivity and storm reports in order to assess whether each day included one coherent mode of severe weather production, or whether it constituted multiple "cases". Then, using archived hourly gridded RUC mesoanalysis data we will separate the cases based on their comparative values of environmental CAPE and shear. Thompson et al. (2003) found the RUC analysis soundings to be of suitable accuracy for characterizing the convective environment, with the limitation that they were somewhat too cool and moist near the surface on average. To mitigate this problem, we will therefore extract near-storm grid-point soundings for each case and augment them by using observed surface temperature and humidity, much in the manner used in the operational SPC mesoanalyses. Using the RUC data we will assign each case to one of four categories: high-shear/high-CAPE, high-shear/low-CAPE, low-shear/high-CAPE, and low-shear/low-CAPE, based on thresholds that arise naturally from the actual distributions of shear and CAPE in the cases (although the choices of 18 m s^{-1} and 1000 J kg^{-1} from Steve Weiss of SPC, e.g. Fig. 5, are reasonable first guesses). We will compare the overall frequency of events in the four shear/CAPE bins, as well as the types and numbers of severe weather reports associated with each. Finally, we will qualitatively review the single-site WSR-88D reflectivity and Doppler velocity data for each case in order to ascertain the predominant storm type, and to assess whether useful radar signatures (such as hook echoes, broken-S echoes, persistent mesocyclones) were present. *The specific aim of this part of the investigation is to improve situational awareness by identifying the chief commonalities and differences between severe storms in HSLC environments vs. other shear/CAPE regimes.*

The second year of the investigation will constitute a statistical analysis of the HSLC cases from year 1, including a comparison to a null database. The archived RUC analysis proximity soundings (as above) will be used to compute numerous parameters of potential operational use (e.g. CIN, LCL height, CAPE below 3 km, lower tropospheric shear, storm-relative helicity, SCP, STP, etc.). We will then generate a null dataset by identifying HSLC environments that are associated with non-severe convective storms. The creation of the null dataset will be accomplished by simultaneously processing the RUC analyses (to identify HSLC environments), regional composite radar data (to identify storm occurrence, e.g. reflectivities > 50 dBZ), and our database of severe weather reports (to confirm that a case was non-severe). The purpose of the null dataset is then to undertake a rigorous statistical comparison of the severe vs. non-severe HSLC storm days. *The specific aim of this part of the investigation is reduce false alarms by identifying recurring situations in which a HSLC environment is present but severe weather is not likely.*

Expected outcomes. We expect to provide a specific list of environmental parameters that forecasters ought to use to assess the severe potential of HSLC environments, as well as a specific list of recurring storm modes and radar signatures associated with different kinds of severe weather on HSLC days. We will work with regional NWS offices in order to identify optimal ways in which this new knowledge can be implemented into their forecasting and warning procedures. *These outcomes will be significant because of their potential to dramatically upgrade our operational capabilities in HSLC environments, which are quite common in the Southeast (Figure 5).* It is expected that results from this study of southeastern HSLC storms would also be generally applicable in other regions with HSLC episodes as well. Indeed, in developing this proposal we contacted Steve Weiss (Science and Operations Officer for SPC) who told us: "the collaborative work you are describing… sounds most interesting to us at the SPC, as we clearly face the same challenges that the WFO forecaster faces regarding the prototypical cool season severe weather environments… if you think that SPC participation in the proposed project might be helpful, we would be happy to play a secondary role." We plan to have regular communication with SPC throughout the proposed research, and to incorporate their datasets (e.g. Thompson et al. 2003, 2004, 2008 and Schneider et al. 2006, 2008) and expertise to the fullest extent possible.

C. Time Line

If funded, the proposed projects would be staggered in time, with the TC impact projects beginning during year 1, and the convective storms project beginning in year two. We anticipate that current graduate student Briana Gordon would continue ongoing work to develop an improved technique for initializing tropical cyclones in model initial conditions in summer and fall 2010. During fall of 2010, one additional student, supported partially with TA funds, would begin work on the inland winds problem.

In the second year, the realtime modeling system would be used to study inland wind and QPF problems by Briana Gordon and the inland wind student. By the fall of 2011, an additional student would begin work on the low-CAPE convection problem. It is anticipated that the TC inland impacts work would be completed by the end of year two, with the convection and coastal impacts work continuing until the end of year three.

During the final year of the project, we plan to host a regional workshop, involving all collaborative partners and others holding an interest in the project outcomes. In the past, such workshops have met with success, and have proven well worth the effort.

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