Scientific Progress Report on

Improving Understanding and Prediction of Warm Season Precipitation Systems in the Southeastern and Mid-Atlantic Regions

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- Mr. Billy Booth

Collaborative Offices of the National Weather Service:
- Raleigh, North Carolina
- Wilmington, North Carolina
- Morehead City, North Carolina
- Blacksburg, Virginia
- Sterling, Virginia
- Wakefield, Virginia
- Greer, South Carolina
- Charleston, South Carolina
- Columbia, South Carolina
- Peachtree City, Georgia

A. Overview and Plan of Work

There are five proposed research topics to be addressed over the 3-year funding period: (i) warm-season cold-air damming (CAD) and wedge-front convection, (ii) coastal flooding with landfalling tropical cyclones, (iii) tropical cyclone quantitative precipitation forecasting (QPF), boundary interactions, and modeling, (iv) tornadoes accompanying landfalling tropical cyclones (TCs), and (v) mesoscale convective systems (MCSs) crossing the Appalachian Mountains. It is not possible to address all of these areas simultaneously. Topics (i) and (ii) are in the second year, and work on topics (iii), (iv), and (v) has begun within the last reporting period.

B. Personnel

Two new graduate students have joined the NCSU CSTAR project team: Matt Morin and Casey Letkewicz; Matt is working on the TC tornado problem, and Casey studying MCSs crossing the Appalachians. Two other graduate students, Adam Baker and Qianhong Tang, continue their CSTAR research, on wedge front convection and inland flooding, respectively. Partial support was provided for graduate student Billy Booth in May, 2008. Billy has since graduated and has completed his thesis project on sea-breeze convection.

The three faculty PIs are focused on mentoring graduate student research projects, preparing journal articles, and reviewing collaborative materials.

C. Research Activity, 1 May – 31 October 2008

i.) Wedge-front convection (Baker and Lackmann)

a.) Background and objectives

Some of the material presented below is repeated from the previous progress report, but was retained for background. The occurrence of convection near the periphery of the CAD cold-dome, along the so-called "wedge front", has been recognized as an important forecasting challenge in the southeastern U.S. In the summer, upright convection can form in the convergence zone at the periphery of the more stable CAD cold dome. The result of the more stable CAD air mass surrounded by convergence near the wedge front is the so-called "ring of fire" precipitation pattern (Fig. 1.1a). Figure 1.1b demonstrates the difficulty that operational numerical models can have in predicting this precipitation pattern, in part due to their inability to accurately predict CAD erosion.

In the spring and fall, severe storms may form in the convergent, sheared environment found near the edge of the cold dome, and the Peachtree City, Columbia, and Charleston SC offices have all cited this phenomenon as an important forecasting concern. A better understanding of the character of the boundary layer on both sides of the wedge front is needed, along with improved understanding of how convection is altered by the presence of the CAD boundary.

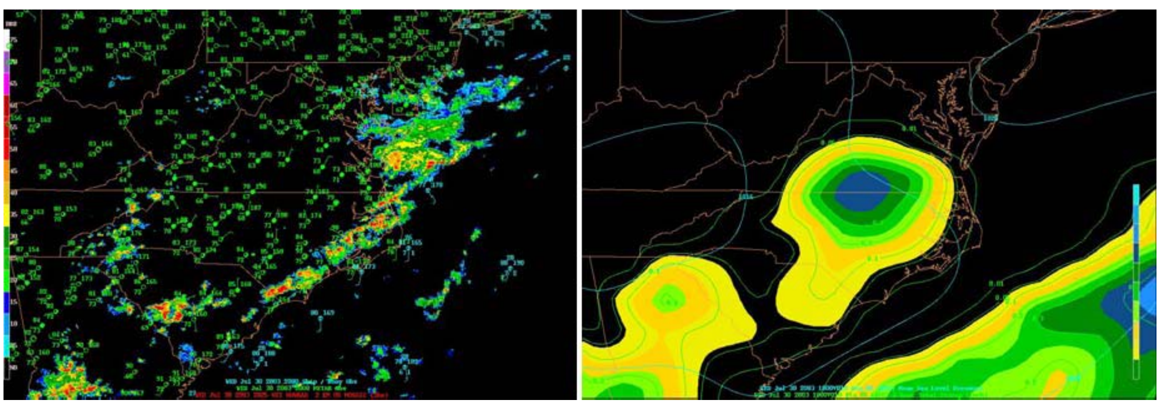

Fig. 1.1. (a) Surface observations and 2-km composite radar mosaic valid 20 UTC 30 July 2003, and (b) NAM model 18-h sea level pressure and 6-h quantitative precipitation forecast valid 00 UTC 31 July 2003.

The primary objectives for this component of the project are (i) to distinguish the synoptic- and mesoscale environments for CAD events with and without severe peripheral convection, and (ii) for convectively active events, better understand the effect of the wedge front on the convective environment.

b.) Research progress

1.) Climatology

A wedge-front convection climatology was assembled in order to contrast convective and non-convective CAD events, refine scientific questions for convective events, and provided context for case studies. The event database described in the previous report was built around data from two earlier climatological studies of CAD. It was found that only around 10% of CAD days are characterized by wedge-front convection. Manual analyses helped to define the proximity of convection relative to the thermal gradient near the front. Of the active wedge-front convection days, occurrence peaked in the spring, but events were noted in the summer and fall as well. A recent November event, which featured severe weather in North Carolina on 15 November 2008, reminds us that these events can occur during any time of year. The diurnal timing shows a peak in the afternoon hours for the onset of wedge-front convection. When cloud cover persists within the interior of the CAD cold dome, differential daytime heating can enhance local thermally driven circulations. As expected, CAD events in which significant moisture and instability were present in the ambient air mass were necessary for wedge-front convection. There were several events that appear to be characterized by elevated convection; some of these cases had much smaller ambient instability.

Archived storm reports from the Storm Prediction Center revealed that 5 out of 16 wedge-front convection events included some severe convection (approximately one third of the events). Of the 5 severe events, 3 were associated with relatively strong CAD cold domes, as measured by the temperature difference between the dome interior and ambient environment.

2.) Case study

In order to isolate the role of the front in an actual wedge-front convection event, numerical simulations of the 20 March 2003 case were undertaken. A control simulation was able to accurately reproduce the CAD event and trigger convection near the wedge front (Fig. 1.2a). An experimental simulation in which the mountains were removed was compared to the control in order to quantify differences in instability, shear, and lift in the vicinity of the observed wedge front. In this run, the region of convective triggering was displaced towards the coast relative to the control run (Fig. 1.2b).

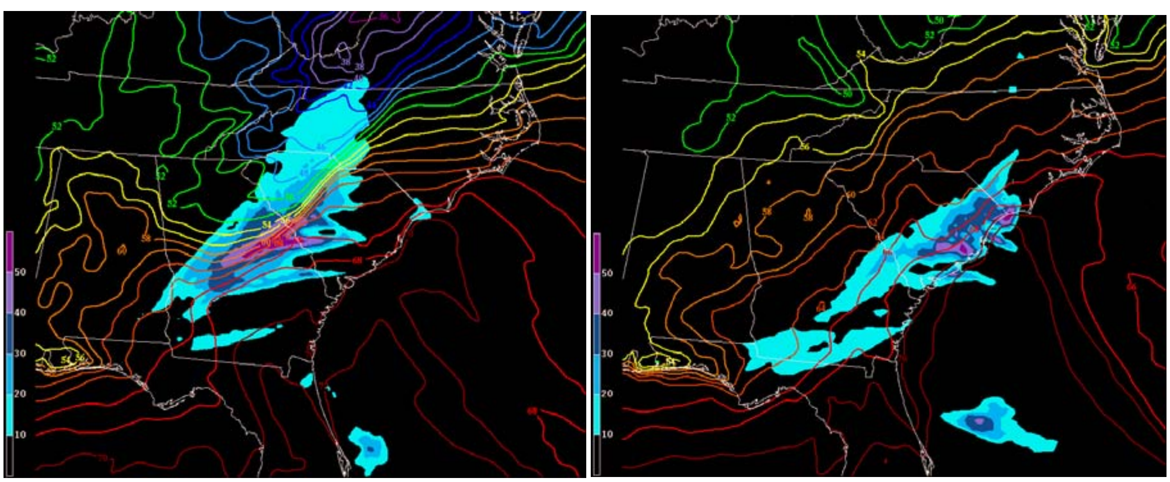

Fig. 1.2. Total convective precipitation (mm, interval 10 mm) and 2-m temperature (˚F) at 12 UTC 20 March 2003 (hour 54) for (a) control and (b) experimental run.

The runs were initially performed with 20 km grid-spacing, and then later run with 12-km grid-spacing (since 1 Nov. 07 to 30 April 2008 reporting period). These simulations utilized the Kain-Fritsch convective parameterization scheme and RUC land-surface model.

The absence of the CAD cold dome in the Carolinas and Georgia in the experimental simulation is evident in plots of 2-m potential temperature (Fig. 1.3). Differences in the convective environment between the two runs confirm that the control run, with the presence of a stable cold dome, is more stable throughout the lower troposphere, including coastal regions of Georgia and South Carolina (Fig. 1.4). While the presence of CAD may limit instability, a large positive difference in wind shear (helicity) is also observed, again consistent with the presence versus absence of the cold dome (Fig. 1.4). While some of the shear increase coincides with very stable air, the helicity difference field over northern and central Georgia overlaps with unstable air in areas where convection was observed, and where it was triggered in the control simulation (Fig. 1.2).

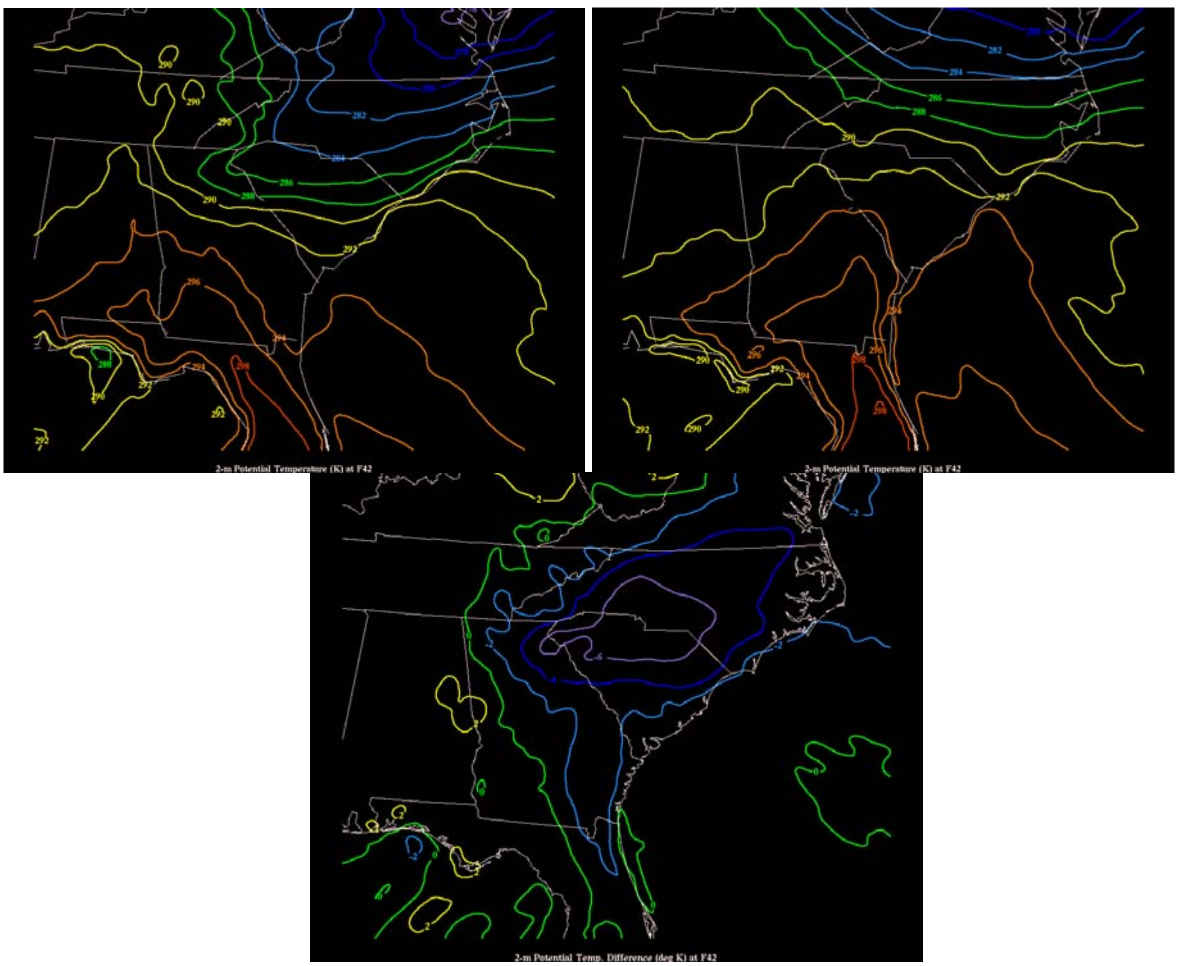

Fig. 1.3. 2-m potential temperature (K) at 00 UTC 20 March 2003 (hour 42 of the simulation) for (a) control run, (b) experimental (no mountain) run, and (c) difference between the runs, control minus experiment.

In addition to altering shear and instability, another potentially important role for the wedge front and cold dome is to provide a lifting mechanism to trigger convection. Either near-surface convergence in the immediate vicinity of the wedge front, or isentropic lift as moist southerly or southeasterly flow overrides the cold dome could serve to initiate convection. Comparison of vertical motion and convergence between the control and experimental simulations reveals that the wedge front indeed provides a significant lifting mechanism (Fig. 1.5). In addition, both runs show convergence and ascent along the coastline (most likely frictional convergence); however the area of strongest ascent and convergence is located near the wedge front in the control simulation.

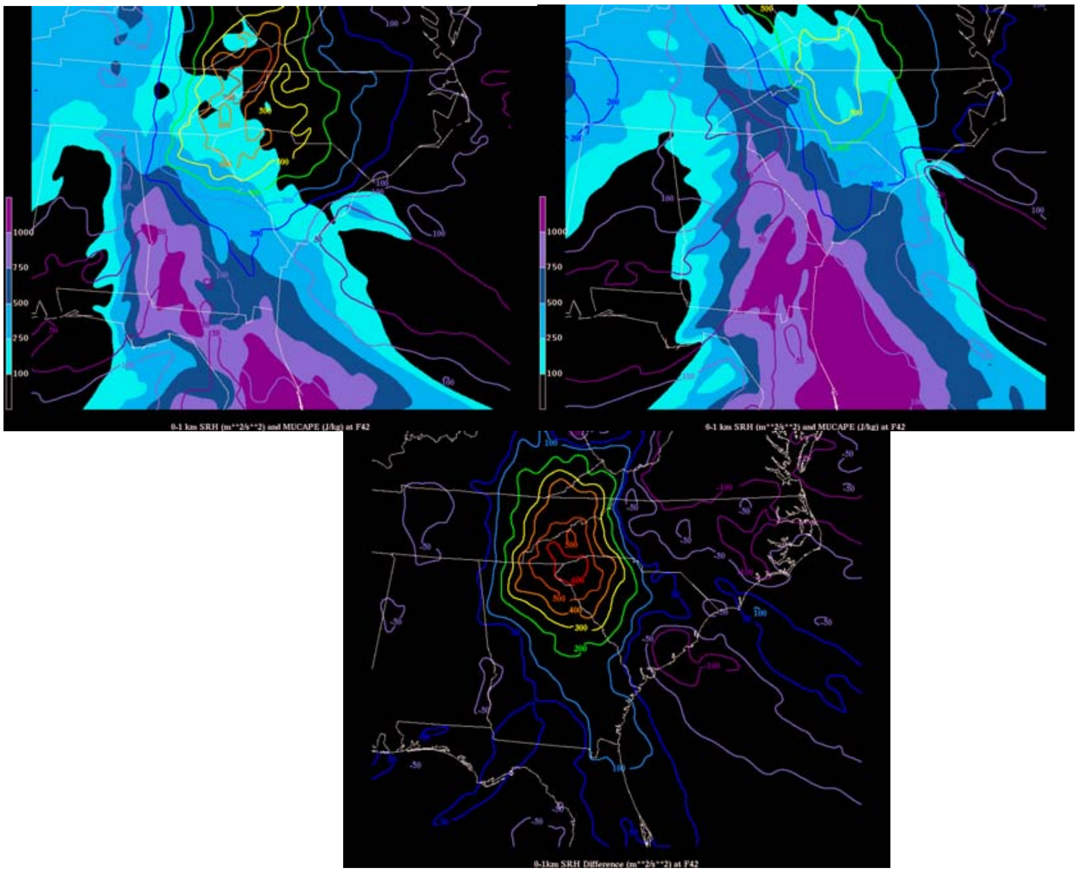

Fig. 1.4. Most-unstable convective available potential energy (MUCAPE, J/kg, shaded) and 0-1 km storm-relative helicity (m^2/s^2, contoured) at 00 UTC 20 March 2003 (hour 42) for (a) control and (b) experimental run. The light blue shading is at least 100 J/kg, dark blue is at least 500 J/kg, and the darker purple is at least 1000 J/kg. (c) is the difference in 0-1 km SRH between the runs.

In general, the comparisons between the control and experimental simulations confirm that the cold dome acts to stabilize the lower-tropospheric environment, which works against convection. However, the presence of the wedge front serves as a lifting mechanism, and the increased low-level shear found in this region contributes favorably to the convective environment.

3.) Conclusions and next steps

In order to more fully explore the wedge-front convection parameter space, two additional events have been examined and will be used for further model experiments. The 11 May 2002 case had relatively high moisture and instability with a strong CAD cold dome, and severe convection, whereas the 2 March 2002 case had contrastingly low moisture and instability in place with a strong CAD cold dome. Control and experimental simulations of these events will further define the role of the wedge front on the convective environment in a variety of CAD scenarios.

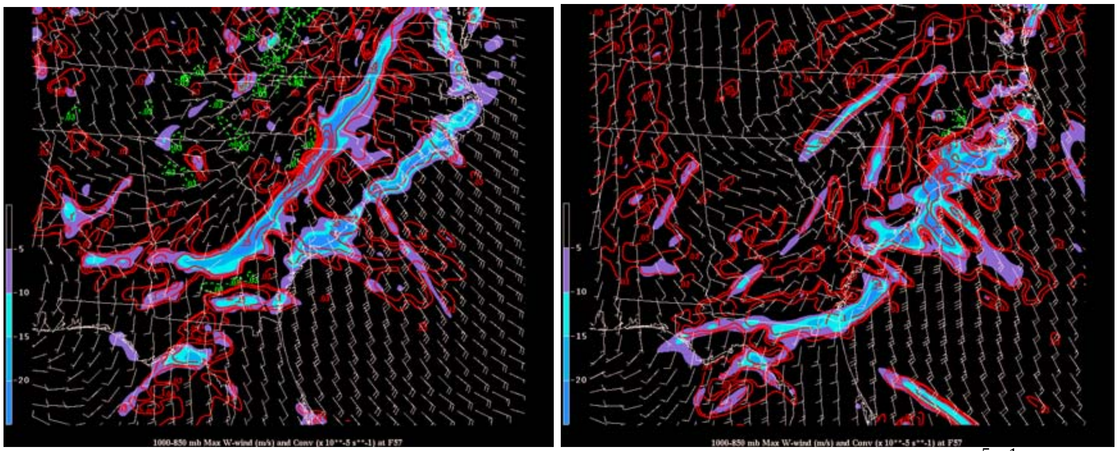

Fig. 1.5. 1000-850 hPa maximum vertical velocity (m/s), 10-m convergence (x $10^{-5}s^{-1}$), and 10-m wind barbs (kt) at 15 UTC 20 March 2003 (hour 57 of the simulation) for (a) control and (b) experimental run. Ascent is shown in the red contours, descent in the dashed green contours, and convergence is indicated by shading.

Based on the research completed to date, the main findings are as follows:

- Wedge-front convection is much less common than CAD, with only about 10% of CAD days exhibiting wedge-front convection. These events were most common in the late spring months, and during the afternoon hours.
- Model simulations with and without CAD exhibit similar moisture and stability environments, but changes in shear and lower-tropospheric lift differ greatly in the vicinity of the observed wedge front between the simulations.
- The biggest impacts of the CAD cold dome are with the triggering of convective development (specifically the location of convergence and effect on convective initiation) and with the shear environment.

Several additional scientific questions have arisen from the analysis. These include:

- To what extent does the helicity-rich air from within the wedge-frontal zone become incorporated into convective updrafts (e.g., Fig. 1.6)? What environmental or storm-scale processes regulate the ability of storms to draw on the potential rotation?
- Is the diurnal signal observed in wedge-front convection simply due to fluctuations in stability, or is there a diurnal modulation of the thermally driven frontal circulation that alters the convective environment?
- To what extent is the enhanced shear near the wedge front in thermal wind balance (balanced with the horizontal thermal gradient) versus ageostrophic shear across the CAD inversion?
- What is the maximum grid length at which an operational forecast model could be run to explicitly capture wedge-front convection? Or, is a relatively coarse simulation with parameterized convection adequate to predict such events?

- Can meaningful relations be identified between the strength of a CAD event and the character of wedge-front convection?

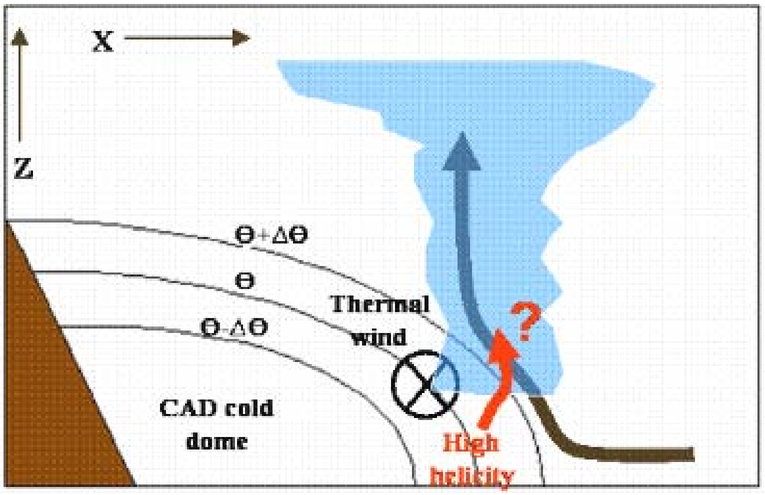

Fig. 1.6. Idealized schematic of a convective storm in the vicinity of a CAD wedge front.

c.) Sharing and collaborative activities

On 13 May 2008, graduate students Adam Baker, Christian Cassell, and Casey Letkewicz presented research results in the Raleigh forecast office. Since that time, the presentations were updated, and as of this writing the presenters are scheduled to record their presentations using software provided by RAH. Adam Baker recorded his presentation on 21 November 2008; the recorded presentations will soon be posted to the NWS-NCSU collaborative web page.

Additionally, Adam Baker has been in communication with NWS forecaster Trisha Palmer at the Peachtree, GA office (FFC) concerning results to date. Trisha's input has been valuable in shaping the project to date.

ii.) Coastal flooding research (Tang and Xie)

The first phase of the "Inland Flood Forecasting" component of CSTAR is mainly focusing on porting a watershed model to the "Tar-Pamlico Watershed". The model of choice is the USDA AGNPS model as it is a tested model in other watersheds and also contains a water quality component which can be used to study the ecological impacts of inland flooding. To port the model for the Tar Pamlico watershed, ground water, soil, land use and meteorological data must be collected and configured for the model.

During the past six months, one of the research foci was the hydrological processes associated with inland flooding from landfalling hurricanes. The efforts include: 1) the continuation of the work on distributed hydrological model of AGNPS with a focus on ground water recharges during landfall tropical cyclones in the Tar Pamlico River Basin; and 2) the numerical simulation of precipitation from landfalling hurricanes using the

Weather Research and Forecasting (WRF) model. On the hydrological aspect, we have attempted to answer questions such as:

1) how do tropical cyclone interact with coastal watershed?
2) Why some of tropical cyclones caused more flooding than others although the storm features and characteristics are similar?
3) What role does soil moisture content play in the flooding?
4) How fast are the reactions of the peak discharge occur after rainfall in the Tar Pamlico river basin?

Hurricane Floyd produced large amounts of precipitation, on top of that, soil moisture content and ground water level were both very high before the arrival of Hurricane Floyd due to the previous landfall of Hurricane Dennis. According to historical groundwater records, groundwater level at station N22Y1 at lower Tar Pamlico near the outlet of the watershed (Fig. 2.1) is merely 0.05 meters below the surface on Sept. 10, 1999. This is just 5 days before Hurricane Floyd's landfall at 0630 UTC on Sept. 16, 1999. In other words, at the outlet of Tar Pamlico River Basin before Hurricane Floyd landfall, the ground water recharge in the runoff almost reached the surface. Thus, any additional precipitation after Dennis would likely cause flooding. We will test this hypothesis in the next 6 month research period.

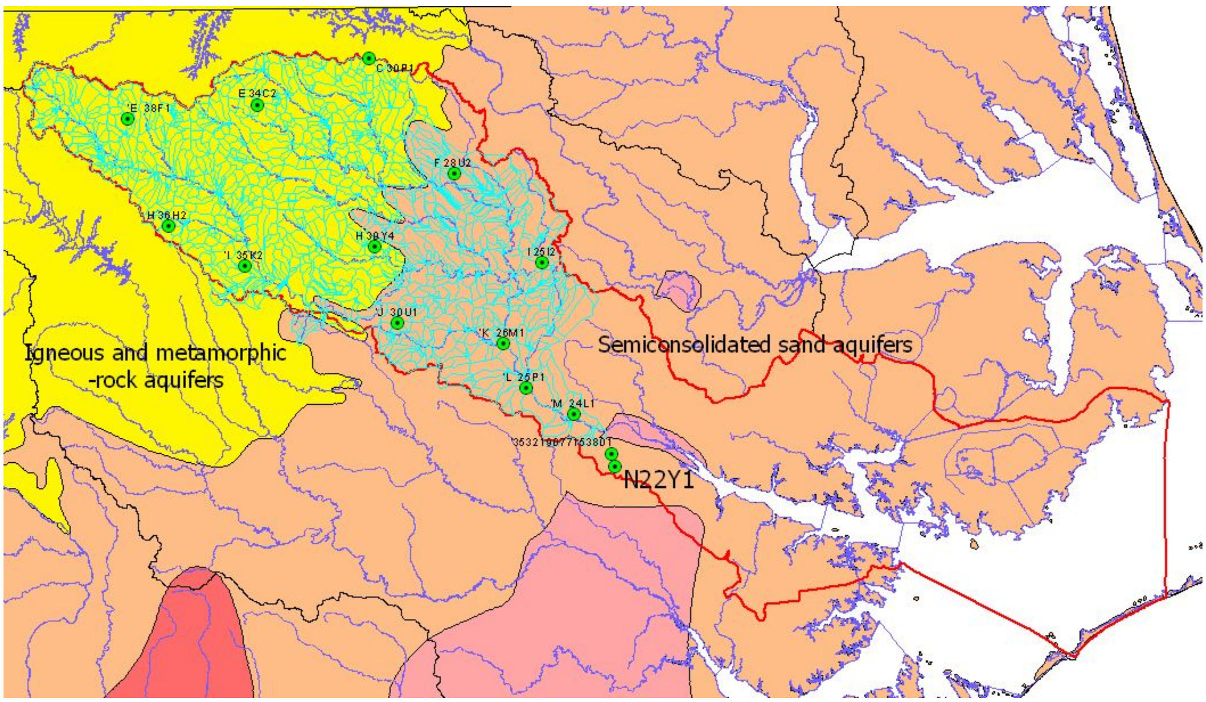

Fig. 2.1. Groundwater Stations in Tar Pamlico River Basin (Station data from State Climate Office)

iii.) Tropical cyclone QPF and modeling (Tang and Xie)

Ms. Tang has also begun to work on the simulation of precipitation from landfalling hurricanes using the Weather Research and Forecasting (WRF) model. The goal is to eventually be able to simulate the precipitation from historical hurricanes which affected the Carolinas under three scenarios: 1) selected hurricane cases; 2) same as 1) but the hurricane will be removed or reduced; and 3) the background flow will be removed or reduced. The precipitation under each scenario will be used to drive the hydrological model. The resulting inland flood levels (or stream flow amount from each case) will be compared to quantify the contribution from the storm and the background flow and the nonlinear interaction between them to the inland flooding process.

During the reporting period, the student has completed an online WRF training course and attended onsite WRF training at NCAR. The student is able to operate the model for control runs with initializations and boundary conditions from global and regional reanalysis. The next step is to simulate the precipitation from additional historical hurricanes and work on the separation of the storm field from the environmental field.

In addition to hydrological modeling, the team also provided model forecasts of the storm surge during the passage of Hurricane Hanna, and provided the model results to participating NWS offices.

iv.) MCS interactions with the Appalachian Mountains (Letkewicz and Parker)

Project status: The publication Parker and Ahijevych (2007) represented the culmination of our preliminary work that led up to this grant. Parker and Ahijevych (2007) documented the frequencies and typical properties of MCSs in the eastern U.S., including those approaching the Appalachian Mountains from the west. Of particular relevance to this present study, Parker and Ahijevych showed that roughly 14 MCSs per year cross the Appalachians from west to east; Keighton et al. (2007) noted that these are often implicated in widespread severe weather in the lee of the mountains.

Since then, M.S. student Casey Letkewicz has been working on understanding the environmental differences that discriminate between MCSs that do vs. do not cross the Appalachians. Casey has actively interacted with NOAA/NWS personnel, including several conference calls with Steve Keighton (NWS-Blacksburg) as well as a recent presentation at the NWS-Raleigh office. Her current results were also presented at the 24th AMS Conference on Severe Storms in October 2008, where she received the co-award for best student poster. She plans to defend her M.S. thesis in late spring 2009. Casey began her project in August 2007 and has been funded by the CSTAR grant since May 2008.

CSTAR scientific outcomes: Letkewicz's project began with a study of observed cases. A random sampling of 20 crossing and 20 noncrossing cases were chosen from the Keighton et al. (2007) database of MCSs in the Appalachian region. Representative upstream and downstream soundings were then analyzed for each case. Statistical tests suggest that the downstream environment east of the mountains is essential in determining whether crossing will occur. Specifically, crossers were associated with higher amounts of downstream conditional instability (i.e. CAPE), less downstream vertical wind shear, and a weaker downstream mean wind. The greater downstream instability was not a particularly surprising result. However, given the widely held belief that vertical wind shear is essential to the organization of convection (e.g. Weisman and Klemp 1982), the favorability of lesser downstream mean wind and vertical shear were somewhat unexpected. Our current working hypotheses are that a) because an MCS's cold pool is weakened by traversing the mountain range (e.g. Frame and Markowski 2006), a weaker vertical wind shear is more nearly in balance with the outflow on the lee side of the barrier, promoting deeper lifting according to the theory of Rotunno et al. (1988); and, b) a weaker mean wind entails a weaker prevailing downslope flow in the lee of the barrier, and therefore less lee suppression of the convection.

Of course, a greater vertical wind shear and a larger mean wind go hand-in-hand, so the observations alone cannot satisfactorily separate these possible effects. Therefore, we have subsequently designed numerical simulations that attempt to isolate the impacts of the mean wind and vertical shear, and to assess their relative impacts. This work is currently ongoing. We are using both the observed profiles of wind and idealized profiles, and are performing tests of the simulated sensitivity to changes in the mean wind and vertical wind shear. Preliminary results from an experiment in which the mean wind (but not the vertical shear) was modified reveal several interesting behaviors (Fig. 4.1). First, the addition of terrain to the simulation (cf. Figs. 4.1a,b) disrupted the MCS, with a period of weakening as it interacted with the mountain barrier (located at x=0 km). When the mean wind was increased, the interaction with terrain became even more disruptive (Fig. 4.1c), with a pronounced period of convective suppression (from approximately 3.5-5 h; Fig. 4.1c). Once the gust front was farther east, convection eventually became reestablished. A unique behavior emerged in our simulation with decreased mean wind. The initial MCS was again disrupted near the peak of the mountain barrier (Fig. 4.1d); however, new storms developed to the east of the barrier (x=100 km, t=4 h; Fig. 4.1d) in a zone of weak upslope flow. Although we cannot yet say how general this phenomenon is, we have observed such development on radar in North Carolina on a number of occasions.

Analysis of the governing dynamics in these simulations, and other sensitivity tests (new runs are being completed almost every day), is ongoing. We are also performing simulations with terrain but without a triggered MCS, in order to understand the basic influence of the wind profile on the local slope flows and orogenic gravity waves. The long-range goal of the simulations is to help us understand which of the environmental parameters from the observational study are the most physically relevant to a correct forecast of an MCS crossing/non-crossing.

v. Tornadoes in landfalling tropical cyclones (Morin and Parker)

Project status: The publication Baker et al. (2008) represented the culmination of our preliminary work that led up to this grant. Baker et al. (2008) documented the mesoscale environment and the evolution of embedded cells during the landfall of Hurricane Ivan (2004). As supercells over the Gulf of Mexico approached the coast during Ivan's landfall, rapid increases in mid-level vorticity and vertically integrated liquid (VIL) occurred. Based on compiled severe weather reports, these increases in storm intensity appear often to have immediately preceded tornadogenesis. The local environment for supercells in Ivan's interior was evaluated through the use of operational and research soundings. Via a comparison to Hurricane Jeanne (2004), the results suggested that the conventionally assessed ingredients for midlatitude continental supercells and tornadoes can be readily applied to discriminate among TC tornado episodes. Adam Baker completed this work as an undergraduate while funded from a different source. He continues as an M.S. student on the CSTAR grant, but is now working on the wedge-front convection problem with Dr. Lackmann.

New M.S. student Matt Morin has recently begun work using the WRF model to study potentially tornadic supercells embedded within the rainbands of a simulated hurricane. His first simulations have just been completed in the past week or so, and we are currently iterating toward a final model configuration and experimental design. Matt met with the personnel at NWS-Raleigh recently, and we plan for him to continue interacting regularly with Scott Sharp (NWS-Raleigh), who is an expert in TC-tornado warning procedures. Matt has been funded by the CSTAR grant since joining the M.S. program in August 2008.

CSTAR scientific outcomes: None yet. Morin has just begun work on the project. Based upon our initial meetings with Scott Sharp and other NWS forecasters, we are targeting the problem of relating observed radar signatures to actual physical processes within the embedded supercells. The long-range goal is a fuller understanding of what is happening on the storm scale when particular radar signatures occur (e.g. the velocity enhancement signature, "VES", of Schneider and Sharp, 2007).

Other work on warm season QPF

Project status: M.S. student Billy Booth studied the climatology of convective storms in the coastal Carolinas, with particular emphasis on the role of the sea breeze front in organizing storms. Billy successfully defended his M.S. thesis in June 2008. He was originally funded under the NOAA Cooperative Program for Climate & Weather Impacts on Society and the Environment (CWISE). Because his project was clearly relevant to regional warm season precipitation, Billy was funded by the CSTAR grant during his final month at NCSU, after his CWISE support had expired. A journal article reporting on Billy's work is currently in preparation for *Wea. Forecasting*.

CSTAR scientific outcomes: A radar climatology of the frequency of convection for the region around Charleston, South Carolina (CHS) was conducted to improve the understanding of the timing and location of summertime convective activity. The frequency of radar echoes ≥ 40 dBZ was strongly sensitive to the low level wind direction (Fig. 5.1). Several possible explanations emerged. First, the low–level moisture and overall instability are strongly linked to the prevailing flow direction, with southwesterly flow providing the most favorable environment for storms, and the highest storm frequencies. Secondly, we hypothesized that the sea breeze front (SBF) played a major role in initiating and organizing deep moist convection. A SBF was at least possible (land temperature exceeded ocean temperature) on most of the days in the study. To determine when a *strong* SBF passage occurred at CHS, a sea breeze detection index was computed using the wind, temperature, and dewpoint shifts in the CHS surface observations. Much as in previous studies, the strongest SBFs occurred with offshore 925 hPa flow. Onshore flow typically had weaker SBFs that were not the primary focus for convective development. Although the spatial distribution of storms changed somewhat, the strength of the SBF passage at CHS did not appear to be important in determining the overall frequencies of convection. Prior work (based largely on studies in Florida) has suggested that a combination of offshore flow and onshore shear should be most favorable for SBF lifting. However, storms near CHS did not occur most frequently in that scenario, suggesting that the majority of convection in South Carolina was likely governed by other factors, especially instability.

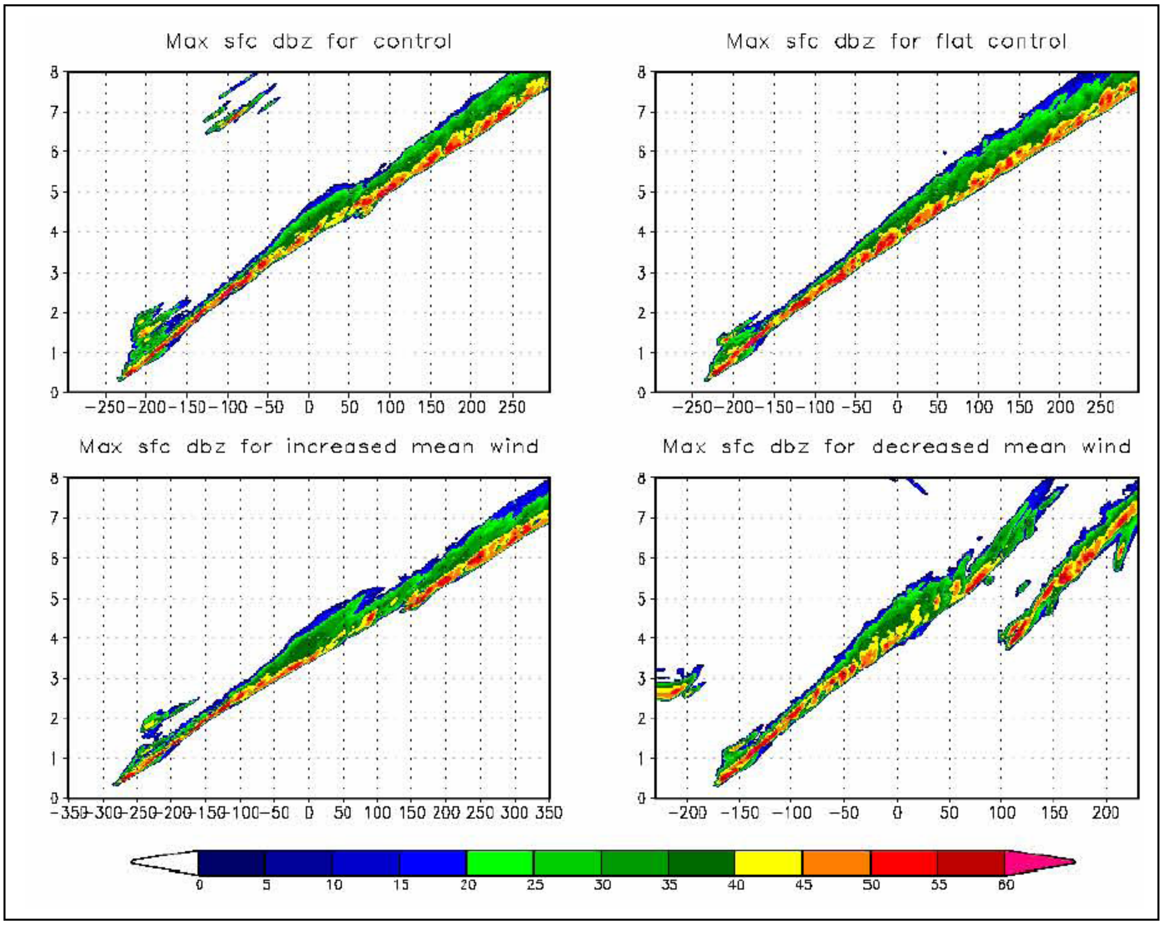

Fig. 4.1: Hovmoller diagrams of maximum surface simulated reflectivity for the control, flat control, increased mean wind, and decreased mean wind simulations. Time in hours is the y-axis, and distance from the mountain peak (at x=0) in km is the x-axis.

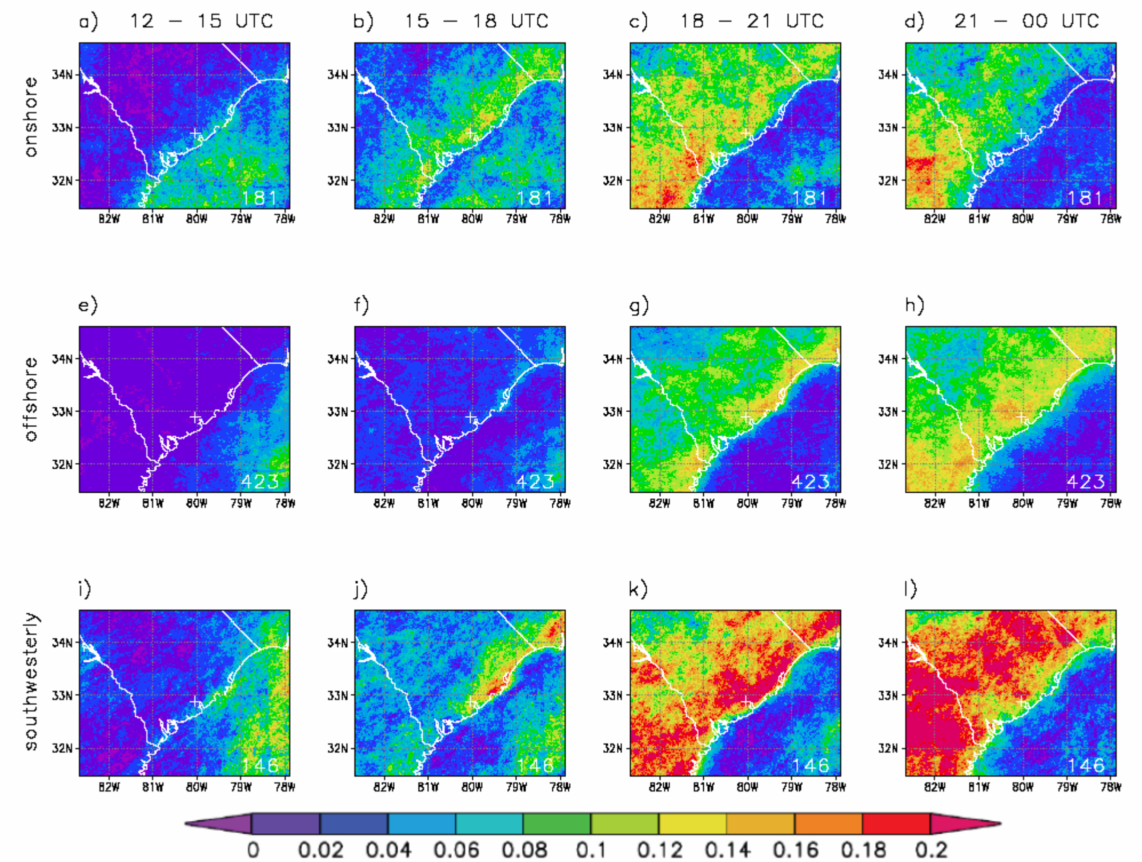

Fig. 5.1: 3 hour progressions of the frequency of convection for onshore, offshore, and southwesterly alongshore low-level flow directions. The number of days in each category is plotted in the lower right of each panel.

D. Other Collaborative Activities

Discussions with NWS personnel led to the scheduling of a "research sharing" presentation which took place at NWSFO RAH on 13 May 2008. This report is now posted online, and includes a 50-minute presentation by Adam Baker of the CSTAR wedge-front results. Several forecasters in attendance provided useful input and suggestions for future work. Another research sharing meeting was held on August 27th in which Jeff Waldstreicher from NWS ERH SSD attended. We plan to schedule additional updates of this type every 3-6 months, and we are currently using the Articulate software package to record and share these presentations.

CSTAR graduate student Matt Morin visited the Raleigh NWS office for a few hours in late August to meet with some of the forecasters and discuss his project informally. Matt was back at the Raleigh NWS office for several hours on Saturday, September 6th to shadow forecasters during the passage of Tropical Storm Hanna over NWS Raleigh's forecast area. Matt was invited to witness firsthand the operational aspect of the tropical cyclone related tornado forecast/warning issue that he is investigating in the CSTAR grant.

Several weather events involving CSTAR related forecast issues were discussed on the NCSU-NWS CSTAR listserver. The listserver allows forecasters and investigators to identify, discuss, and collaborate on these forecast issues in real time.

While not directly related to the CSTAR project, forecasters and CSTAR investigators continue to participate in the Northwest Flow Snowfall Discussion Group which is a "spin-off" of the regional CSTAR group with its primary focus being the specific regional forecast problem of northwest flow snowfall in the Appalachian Mountains.

NWS Raleigh held an open house on October 16, 2008, and this event was attended by more than 50 NCSU meteorology students. In addition to demonstrations of the WES and AWIPS software, there was a discussion of NWS-NCSU collaborative activities.

Ongoing discussion continues with NWS forecaster Trisha Palmer (NWSFO FFC), who has recently visited Southern Region Headquarters. Her input and encouragement have been very helpful in designing the project. Furthermore, we have shared the presentation mentioned above, which she presented during a recent visit to Southern Region HQ.

As mentioned in the personnel section, a small amount of support is being provided to graduate student Billy Booth, who is nearing completion of research on the sea breeze. Here a very brief summary of this work is provided. A radar-based climatology of convective storms was created for the region of Charleston, South Carolina. The aim of this study is to understand the timing and location of summertime convective activity, especially storms that are initiated by the sea breeze front (SBF). Overall, the results show that the strength the SBF is not typically the most important factor in determining the locations and frequencies of convection. Instead it is the prevailing flow direction, and it's associated thermodynamic environment, that appears to be the most important consideration. In particular, on days with southwesterly flow convection was widespread over South Carolina owing to the advection of unstable air from the Gulf of Mexico. On days with offshore flow, CIN was higher than average and the inland progress of the SBF was slowed, leading to later storm development, fewer overall storms, and to storm frequencies that were maximized along the coast. On days with onshore flow, CIN was lower than average and the SBF progressed well inland, leading to earlier initiation of storms, and a maximum in storminess that spread farther inland.

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