COMET Outreach Program
Final Report

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Project Title: Inland Flooding from Tropical Cyclones

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EXECUTIVE SUMMARY OF OPERATIONAL FORECASTING ADVANCES AS A RESULT OF THIS STUDY

Due to the inherent characteristics of tropical cyclones, heavy rain for a given location is typically assured provided that the storm's track is favorable; however physical mechanisms for exceptionally heavy rainfall such as that which occurred over inland North Carolina during Hurricane Floyd are not completely understood, which provides a great deal of challenges for forecasters. This study not only led to improved scientific understanding of tropical cyclone precipitation and inland flooding processes, but also addresses the goals of the COMET project from a forecaster's "need to know" perspective and the project's impact upon improving river flood warning and flash flood warning capabilities for central and eastern North Carolina.

The scientific results obtained from the physical processes portion of this project as summarized in Section 2 were exceedingly enlightening for forecasters. For some time forecasters have known that when tropical cyclones interact with mid latitude meteorological disturbances, the potential exists for enhanced rainfall greater than what would otherwise be expected; however the details as to why and the supporting conceptual models alerting forecasters to the potential of exceptionally heavy rain have been in part lacking.

This research has shown that enhanced rainfall producing hurricanes such as Hurricane Floyd interact with meteorological features on a variety of scales. Indeed, it was found that large scale meteorological features hundreds miles removed at 72 hours prior to landfall sets up the locally small scale environment for enhanced precipitation near the time of landfall.

Relative to the Carolinas, this research identified the influence of warm season cold air damming as one principal contributor for enhanced rainfall induced by tropical cyclones impacting the area. Moreover 12-24 hours prior to landfall, cold air damming over the inland Carolinas produces a low level wind shift. This in turn strengthens a near shore coastal front. This strong coastal front then becomes a major contributor for enhanced rainfall as the tropical cyclone approaches.

Near the time of the tropical cyclone's landfall, this research also found additional interactions between meteorological features and atmospheric processes augmenting rainfall. Principal among these were the interactions between the mid latitude upper level disturbance and the release of heat previously stored in water vapor from the tropical cyclone's ongoing rainfall. Indeed, this interaction was shown to turn the existing upper level winds toward a more inland direction, generating additional showers and thunderstorms that result in more inland rainfall than what might be expected simply due to the track of a tropical cyclone.

The research has allowed our collaboration to develop procedures for the National Weather Service's principal operational system, AWIPS (Advanced Weather Interactive Processing System). These procedures direct forecasters to evaluate the principal features and physical processes that have the potential for enhancing tropical cyclone induced rainfall across the inland sections of the Carolinas. While these features and processes occur at various scales and interact with each other in a number of ways, our forecast procedures guide meteorologists through a structured evaluation ensuring they are evaluating those features and processes that potentially can interact with tropical cyclones to enhance rainfall amounts over inland areas as did Hurricane Floyd.

During the 2005 hurricane season, the National Weather Service forecast office in Raleigh implemented into their operations our newly developed forecast procedures for evaluating the potential for enhanced rainfall associated with tropical cyclones impacting central North Carolina. Despite the record breaking number of tropical cyclones last season, there were only two storms, Hurricanes Cindy and Ophelia, impacting central North Carolina. Our procedures were combined with other forecast means to correctly determined that while some areas of North Carolina would experience heavy rainfall amounts, the impact on central North Carolina would not be great. Our limited rainfall projections were then collaborated with the Southeastern River Forecasting Center to correctly conclude that the impact of both storms would be minimal to the river water levels in central and eastern North Carolina.

In addition to the forecast improvements for addressing the issue of rainfall amounts and their potential to produce river flooding, this project has also resulted in improvements to the forecast office's flash-flood warning capabilities. This was accomplished by constructing a flash-flood "hot spot" climatology. In a given area, there are typically specific locations (e.g., near streams or in low lying areas), that are likely to quickly flood from heavy rain. By identifying locations ("hot spots") prone to flash flooding and then mapping their locations into AWIPS (NWS's principal operational system), forecasters at NWS Raleigh are now able to better maintain a higher degree of situational awareness so important to the timely issuance of flash flood warnings. Moreover, the flash flood "hot spots" along with information about their flooding characteristics and climatology are being merged with existing technologies such as Doppler radar data, stream gage data, and FFMP (Flash Flood Monitoring Program). As displayed on AWIPS, the flash flood hot spot data is combined with road maps, river and stream maps, Doppler radar rainfall estimates, and projected stream level rises which all improve the capability to anticipate flash flooding before it occurs.

These advances have also led to better communications, allowing forecasters to prompt county officials to closely monitor those specific locations when flash flooding is becoming a threat. These advances are also providing flash flood warnings that cite greater detail with respect to the location and characteristics of the flash flood threat as well as greater warning lead time in advance of the flash flooding. Indeed, the flood hot spot data has already been used in real time to issue flash flood warnings for Johnston, Guilford and Stanly counties. Forecasters at NWS Raleigh agree that the warnings for Guilford and Stanly counties would not have been issued in a timely fashion, if at all, without the benefit of the "hot spot" information. In the case of Stanly County, forecasters at NWS RAH had been closely monitoring AWIPS looking for indication that some hot spots might soon flood. Shortly after the first flash flood warning was issued, the county 911 Dispatch Office was called to ask if there had been any reports of flooding. When told there had been no reports, the forecaster requested that a deputy be sent to check on the hot spot location of most concern. Not long afterwards, the forecast office received a call from Stanly County 911 indicating that 4 people stranded in flood waters had been rescued from the hot spot location.

SECTION 1: SUMMARY OF PROJECT OBJECTIVES

The objectives of the project were on "precipitation climatology and inland flooding hot spots" and "process studies" as outlined in the proposal. The objectives of the "precipitation climatology" component includes a composite precipitation climatology of historical hurricanes and the identification of flood "hot spots", i.e., locations where inland flooding occurred frequently in the past. The main objective for the "process studies" component was to identify synoptic weather patterns that are typical for heavy precipitation storms and relatively dry storms, respectively. The accomplishments in these two components are summarized in the next section.

SECTION 2: PROJECT ACOMPLISHMENTS/FINDINGS

2.1 "Precipitation climatology"

2.1a) "Flood hot spot" climatology (see Appendix B for a detailed summary)

As of December 31, 2005, 479 flooding events which occurred across 31 counties comprising the Raleigh National Weather Service's Central Warning Area (CWA) have been studied. This work represents a joint effort by a team comprising North Carolina State University graduate students and NWS forecasters. The work included identifying flash-flood-prone areas, or "hot spots", in these counties and mapping them using ArcView GIS software. This was accomplished with the help of employees of the Raleigh NWS office by obtaining information on and locations of these areas from county emergency management officials. We have successfully mapped the locations of hot spots in roughly half of the thirty-one counties in the CWA. Although COMET funding ended on December 31, 2005, the work on identifying and categorizing additional flash flooding "hot spots" in these counties and mapping the "hot spots" using GIS is continuing.

In addition to mapping flooding "hot spots", we have been researching the dates and times of all flooding events in these counties from 1 January 1993 to 31 December 2003 through the use of the National Climatic Data Center's Storm Data Archive as well as other sources, such as some of the counties' websites and newspapers. After the dates and times for flooding events were found, weather and impact information about each flooding event was gathered. Based on the information collected, we have developed a database to store and sort all this information, which included parameters such as the type of weather event that produced the flooding, the extent of the flooding, the amount of rain that was associated with the event, pre-existing conditions, and noted major impacts. A graduate student is continuing to expand the database. The goal of this work is to produce a statistical relationship between the flooding and the weather patterns that produced each flooding event.

While we are continuing to obtain the locations of flash flooding hot spots in the rest of the counties, demonstration projects with a focus on Johnston, Guilford, and Stanly counties have already shown practical utility. The results from the demonstration project will be expanded to other counties once we have gathered all the information on them.

Our flooding "hot spot" database presently covers the thirty-one counties in the CWA and 479 flooding events. Of these, 119, or approximately 25 percent, appear to be associated with tropical events. Another 78, or about 16 percent, of the flooding events occurred between January and March, and were associated with mid-latitude cyclones as opposed to tropical or convective systems. Using Johnston County as an example, there were 31 flash flooding hot spots identified and 19 flooding events between 1993 and 2003. Five, or approximately 26 percent, were associated with a tropical system. Another four, or about 21 percent, were associated with winter storms. As more detailed information is obtained and analyzed, very specific trends between weather patterns, precipitation qualities, and the resulting flash flooding, will become apparent. Access to this information may ultimately lead to a better understanding and prediction of flash flooding events in North Carolina.

2.1b) Rainfall mapping

In order to study precipitation climatology, accurate and high resolution mappings of precipitation to specific regions or river basins are needed. Since only one graduate student can be supported by COMET funds, this component of the project was carried out in collaboration with two other NOAA projects, Collaborative Science and Technology Applied Research (CSTAR) and Climate and Weather Impacts on Society and the Environment (CWISE).

This period of research focused on three necessary steps to accomplish the larger objective summarized above. First, we needed to establish a methodology that would serve as the foundation of our geostatistical model. This included analyzing past work in geostatistics as it applies to precipitation mapping, proposing a collection of data sets to be used in the model, establishing a domain of study (31.5°N-37.5°N, 85°W-75°W), and drafting a detailed outline of the model steps. As suggested, our ground-truth data set, otherwise known as the primary variable, is the Daily Reported Precipitation (DRP) data from the National Climatic Data Center (NCDC), which was previously archived in-house for NC and SC as part of the CSTAR2 project. That in-house archive has been expanded this period to include the entire states of GA, TN, KY, WV, and VA, for the entire period of record, following a multi-step procedure described in past reports. Our auxiliary variables, in other words, the variables that are supplementing the primary variable to improve the accuracy of our spatial predictions, include Global Land One-kilometer Base Elevation (GLOBE) Digital Elevation Model (DEM) data (30 arc-second or approximately 1-km grid spacing) from the National Geophysical Data Center (NGDC), and output from the North American Regional Reanalysis (NARR) project. The NARR output offers several advantages, most importantly providing 32-km grid spacing of hundreds of variables over, eventually, a climatological period of record.

Second, we developed a suite of computer code to acquire, concatenate, convert, analyze, and perform calculations and other manipulations on the various data sets selected for the study. The developmental process included crafting new data sets, namely a slope data set and a "terrain-induced" vertical component of wind. The slope dataset is derived from the GLOBE DEM data. The vertical component of wind is derived from the horizontal surface winds outputted from the NARR project and is defined as the inner product of the components of slope with the corresponding horizontal wind components (e.g., Kyriakidis et al. 2001 and Alpert 1986). Studies including Kyriakidis et al. (2001) successfully used this wind component as a way to quantify orographic lifting. Also needed was the transformation of the geometric coordinates to a Cartesian coordinate system that satisfied equal-area assumptions. An advantage of these accomplishments is that they are facilitating our introduction of additional cases and can, in turn, have use in future research projects that aim to employ our mapping technique.

Finally, we tested various model steps with data from 14-16 September 1999, which included analyzing each data set for summary statistics (e.g., means, medians, and spatial patterns) as well as basic statistical properties (e.g., normality and stationarity), transforming the data sets as needed, and performing trend and residual modeling. Future work will continue to explore ways to optimize the steps of the model through testing and analysis and we intend to produce final precipitation maps with relevant meteorological and statistical interpretation. Much of this will be accomplished while introducing additional warm and cool season cases for analysis. The statistical components of this research are being carried out using the SAS and R environments.

The geostatistical model we proposed and are currently implementing relies on the separation of the gauge data set into a trend and residual component. The trend or drift component is determined first from comparisons of various multivariate linear regression models and the residual component is then derived from what remains once the trend is removed from the precipitation values. It is the residual component that we then interpolate, adding the trend to the interpolation for our final prediction. The interpolation technique is known as ordinary kriging (OK), and the entire geostatistical model is known in the literature as kriging with external drift (KED). The KED technique relies on a variance-covariance matrix derived from the spatial variability of the sampled data and produces predictions at unsampled locations as a linear combination of each sampled location multiplied by a weighting factor. The technique is unbiased and is known as the best predictor in that it minimizes the variance of the prediction error. The KED approach is superior to other popular interpolation techniques such as inverse distance weighting and Thiessen polygons because it introduces an explicit measurement of model uncertainty.

The trend modeling experiments we conducted on the rain-gauge data investigated the relationship between non-zero rain-gauge data and NARR horizontal surface wind data, elevation, local slope, and local vertical components of wind. It should be noted that through our exploratory analysis of the precipitation data set in our first case, a logarithmic transformation was required to normalize a positively skewed distribution. This transformation, among other issues, meant we first tested relationships between the auxiliary variables and gauge measurements of precipitation that were non-zero. Hurricane Floyd, which serves as our initial warm season case, produced precipitation predominately in the coastal plain of the Carolinas on 15 September 1999. Because of the location of precipitation relative to the terrain, we did not expect relationships between terrain characteristics and precipitation associated with orographic lift. Though statistical relationships between the lower terrain and precipitation were theorized and aided in our removal of the mean or trend of the gauge measurements, they have not yet been shown to be statistically significant. Statistically significant relationships between location x, location y, and the component of surface horizontal wind along the y-axis dominated our best regression model to date, collectively explaining 45% of the variance in the original data set. Resultant residuals are successfully reduced to random variations, exhibiting no remnant trends. Further, we are currently investigating regression models that include sites that recorded no precipitation (we must transform 0mm accumulation reports to 0.01mm accumulation reports before taking logarithms).

Residual modeling equates to a modeling of the small-scale variations, where as trend/drift modeling equates to the modeling of large-scale variations. It is important to remove as much of the variability in the data set to be interpolated as possible in order have a resultant data set that contains little or, ideally no, trend. Our best regression models to date have successfully accomplished this removal. We then evaluate the spatial variance of the residuals through the use of an estimated semivariogram: plots of variance between pairs of residuals as a function of distance. We fit semivariogram models to the semivariogram estimate and using multiple methods (e.g., by eye, using a weighted non-linear least squares technique, via maximum likelihood estimation, etc.) we produce a final variance-covariance matrix that produces our kriging predictions. Most semivariogram models are largely a function of the range of the data, or the distance at which spatial independence is reached and the sill of the data, or the variance between data pairs at distances equal to or greater than the range. Current results show this point of independence occurs at distances between 150 and 200km for the Hurricane Floyd case, which we would expect to vary based on the scale of meteorological features.

It is important to note that the process of producing kriging predictions is not limited to the precipitation data set. We have also performed this interpolation on the NARR variables included in our regression analysis, producing a "geostatistical model within the geostatistical model", so-to-speak. This is crucial for studying the relationships between these auxiliary variables and the gauge data set as regression analysis is not space dependent and thus requires a co-location of all variables. In cases where this co-location is not naturally present (as it is in this research), it must be created. Given the relatively low demand of this prediction as a result of NARR grid density and a large number of gauges, we have concluded from our analysis that removal of trend for our current case is not necessary. Therefore, the modeling of spatial variability (i.e., the production of a representative semivariogram for each NARR variable) used to perform kriging is based on the complete data set.

2.2 Process studies

Our process studies focus on the synoptic and mesoscale processes associated with various types of hurricane precipitation. Fifty-two stations across six climate regions of North Carolina were used for the Quantitative Precipitation Forecast (QPF) portion of this study. The six climate regions include the Northern Piedmont, Central Piedmont, Southern Piedmont, Northern Coastal Plain, Central Coastal Plain, and Southern Coastal Plain. Daily rain gauge data of twenty-eight storms dating back to 1953 was used for the precipitation analysis. Since there are no specifications on when rain gauge data should be collected, some of the data may have been collected in the early hours of the day, while other data may be collected in the evening. To account for this potential discrepancy, three-day rainfall totals were used in this study. These totals accounted for precipitation that occurred prior to, during, and after landfall. Precipitation can be enhanced due to interactions with synoptic or mesoscale features, occurring several hours preceding or after landfall of the tropical cyclone, so this is another advantage of using three-day rainfall totals.

The three-day precipitation totals from 52 stations across the six climate regions were arithmetically averaged, for all twenty-eight tropical cyclones. This number became the benchmark to classify storms as heavy or light rainfall events. If a storm received greater precipitation then the average number it was considered a heavy rainfall event. There were 14 storms in each the heavy and light rainfall categories. ARCGIS was used to create krigged analysis of precipitation. Krigging is a statistical technique, which enhanced the accuracy of the analysis. Precipitation maps with track overlays were created for both the heavy and light rainfall groups. These maps illustrated that the tropical cyclones classified as heavier events tended to spread higher precipitation totals to inland North Carolina, and tracked further inland as compared to the light precipitation events. However, there were several storms in the heavy precipitation category that tracked along the coastline, while there were also light storms that tracked through central North Carolina. This precipitation analysis showed that although most of the heavy storms tracked further inland than the light storms, other mechanisms must be at work to enhance the precipitation from tropical cyclones.

The next step was to examine the similarities in synoptic/dynamic features among the storms in each group. This was done on four length scales (Planetary, Synoptic, Meso-α and Meso-β) with different time scales for each length scale. The Planetary and Synoptic scales account for data seventy-two to thirty-six hours prior to landfall, the Meso-α scale begins 36 hours prior to landfall and the Meso-β scale only incorporates data up to 12 hours prior to landfall. This study was completed using both 2.5 by 2.5 degree coarse resolution NCEP (National Center for Environmental Prediction) data as well as 36 km high-resolution data from the NARR (North American Regional Reanalysis) dataset. The planetary scale involved examining 250 mb geopotential heights from 3 days prior to the day of landfall. This showed that the heavy events had a large negative anomaly over northwest North America and a positive anomaly over northeast North America. This starkly contrasted with the 250 mb geopotential height anomaly for the light events, where a positive anomaly existed over both northwest North America and northeast North America. The large negative anomaly over northwest North America, along with a positive anomaly over northeast North America, for the heavy events both prior to landfall, correspond with a strong upper level trough over northwestern North America for the same time period. This is expected to enhance precipitation for the landfalling tropical cyclone by providing a larger scale region predisposed to higher relative humidity as a precursor to landfall. Meteorologists have previously discussed the significance a trough may play in the enhancement or destruction of a tropical cyclone; however there has not been considerable research on how an upper level trough existing days prior to landfall enhances precipitation.

Synoptic scale analysis includes examining upper and lower level potential vorticity (PV) features. Large PV values are expected at low levels due to the tropical cyclone producing precipitation resulting in latent heating, which, in turn, enhances PV; however large PV values at upper levels could positively influence precipitation enhancement. A negatively tilted trough of high PV values was present in many of the cases that exhibited heavy rainfall. The trough of significant upper level (500-250 mb) PV could act to create a favorable mass divergence aloft, in turn enhancing upward vertical motion, increased relative humidity and subsequently precipitation. Cross sections of PV were created to exhibit the connection between the lower level PV of the tropical cyclone and the upper level PV due to a synoptic scale feature.

The next step of the analysis involved examining the magnitude and direction of the moisture flux and the convergence at the 925-850 mb layer at the Meso-α scale. The results show that the storms that produced the highest precipitation tended to have a high magnitude of moisture flux, with high rates of convergence and moisture flux vectors that are aligned with the storm. The heaviest rainfall storms also had a strong northerly/northeasterly component over the Appalachian region. The light precipitation events had much weaker signals of these variables. The third portion of the synoptic analysis involved examining the advection of equivalent potential temperature on the 310 K isentropic surface. This showed that for the heavy rainfall events, as the storms approached the coastline, the air parcels associated with the tropical cyclone were being advected towards lower pressure on the 310 K surface by the isallobaric wind component thus enhancing precipitation, and connecting the tropical cyclone to the upper level preexisting synoptic features. The isallobaric wind component is the result of the approaching upper level trough and large PV center.

The 90-level Stratospheric Non-Hydrostatic Mesoscale Atmospheric Simulation System (NHMASS) numerical model was run to complete the synoptic, Meso-α and Meso-β scale analyses of this study. The model was run on a heavy and light rainfall event, Hurricane Floyd and Tropical Storm Arthur, respectively. The synoptic scale analysis was performed using a 36 km grid scale run 72 hours prior to landfall, while the Meso-α scale will focus on central and eastern United States with an 18 km grid beginning 36 hours prior to landfall. The Meso-β scale domain was centered on the mid-Atlantic coast and Appalachians with a grid scale of 6 km and begin about 12 hours prior to landfall. Running the NHMASS model led to the creation of a paradigm describing heavy rainfall events up to 72 hours prior to landfall, utilizing data from all four time scales.

2.3 RELATED ACCOMPLISHMENTS

2.3a *Unfunded related* University accomplishments

The precipitation mapping project described in 2.1b was a result of collaboration between COMET, CSTAR and CWISE. All three projects share the common need for high-resolution, high accuracy precipitation maps for the Carolinas. Although not supported by COMET, the COMET team met with the CSTAR and CWISE research teams on a weekly basis to exchange information and discuss each project's needs.

One of the COMET PIs (Mike Kaplan) and a COMET student (Meredith Croke) made presentations in August 2004 at NWS Raleigh Forecast Office to share some preliminary results from the COMET project. Also, Dr. Kaplan presented a seminar to NWS Raleigh forecasters highlighting the mesoscale mechanisms for extreme rainfall production during the landfall of Hurricane Floyd. Jamie Wirth presented his flood hot spot work to the NWS Raleigh Office on May 31, 2005.

On June 1st 2005, Meredith Croke presented a poster at Tropical Cyclone Media Day held by Congressman Etheridge of North Carolina. Her poster provided an overview of her physical process studies work. Also during this past summer 2005 as part of the NWS Raleigh's extensive seasonal familiarization preparations for the 2005 tropical cyclone season, Meredith presented her final results on the physical processes studies to NWS operational forecasters from Raleigh, Air Weather Service meteorologists from nearby bases, local media meteorologists, and meteorologists from the state of North Carolina. Then on October 6th 2005 at the CSTAR Regional Workshop, Meredith once again presented the final results from her physical processes research. This presentation was modified to emphasize the operational applications aspects of her findings. Forecasters from seven different NWS offices were attendance as well as representatives from NOAA HQ and NWS Eastern Region HQ.

2.3b *Unfunded related Forecast Office accomplishments*

NWS forecasters at the Raleigh Forecast Office have been actively engaged in NCSU graduate and undergraduate education. As a result of the COMET project, Kermit Keeter from NWS Raleigh WFO served on the graduate student thesis advising committee for both Meredith Croke and Jamie Wirth (both students are partially funded).

Doug Schneider and Kermit Keeter from the NWS Raleigh WFO worked with graduate student Meredith Croke to produce an AWIPS (Advanced Weather Interactive Processing System) procedure. These procedures will guide forecasters through a structured evaluation of meteorological features and physical processes which potentially can interact with tropical cyclones to enhance rainfall amounts. The Raleigh NWS and the Southeastern River Forecasting Center will then use the results from this evaluation to aid in their decision of issuing river flood watches and river flood warnings.

Kermit Keeter from the NWS Raleigh WFO presented at the CSTAR Regional Workshop on October 6th 2005, the design of the AWIPS procedures used to evaluate the potential for enhanced rainfall from tropical cyclones interacting with mid latitude meteorological features (PowerPoint files of CSTAR workshop presentation can be found at http://www.meas.ncsu.edu/nws/www/workshops/).

SECTION 3: BENEFITS AND LESSONS LEARNED OPERATIONAL PARTNER PERSPECTIVE

From the NWS perspective, there were significant unexpected benefits and lessons learned from this collaborative effort. The physical process studies revealed the connectivity between large scale and small scale meteorological features and physical processes. Moreover, the understanding that the large scale environment from 72 hours prior sets up the mesoscale environment for enhanced heavy rainfall over central North Carolina around the time of landfall taught our forecasters that there is added value in looking far upstream well in advance of the tropical cyclone's landfall. Prior to the studies findings, our operational practices did not include this large scale upstream monitoring.

This project also assisted us greatly in better fulfilling our role in the collaboration of river flood warnings with the Southeastern River Forecast Center. With the forecast procedures developed from this research, we in the NWS RAH forecast office now have better tools to ensure that the River Forecast Centers in their river water level projections are accounting for the likelihood of enhanced rainfall inland beyond that which would be expected due to the inherent characteristics of a tropical cyclone and its associated track.

The project's work in identifying flash flood hot spots resulted in a valuable partnership with the USGS where stream water level gauges were placed along Buffalo Creek – a flash flood prone urban creek in Greensboro, North Carolina. These gauges have already proven to be very valuable in monitoring the potential for flash flooding along one of the most troublesome flash flood hot spots in the county warning area.

Finally, this project has taught us the value of approaching a critical forecast issue from a multiple scale approach. Relative to the need to issue accurate and timely river flood and flash flood warnings, this research has accounted for factors in the large planetary scale through the synoptic and mesoscale down to the microscale. Such an approach is needed in order to sufficiently address the degree of river and flash flooding associated with enhanced rainfall generated from the interaction of tropical cyclones with mid latitude systems.

SECTION 4: BENEFITS AND LESSONS LEARNED UNIVERSITY PARTNER PERSPECTIVE

This collaborative project has allowed the PIs and the students to directly participate in the inland flood forecasting process. This allowed the PIs and the students to have a good understanding of the "operational" aspects of inland flooding issue, and increased marketability after graduation. One of the students (Joshua Palmer) is currently employed by the National Weather Service Office in New Orleans region, coordinating inland flooding forecasting. Another student, Meredith Croke, has been hired by a TV Station to become a Broadcasting Meteorologist in Spokane, Washington State. These are clear benefits to our students.

SECTION 5: PRESENTATIONS AND PUBLICATIONS

One of the COMET funded students, Meredith Croke, gave a presentation at the American Meteorological Society "21st Conference on Weather Analysis and Forecasting/17th Conference on Numerical Weather Prediction" (the extended abstract of this presentation can be found in Appendix A).

Additional presentations are summarized in Section 2.3a and 2.3b.

Two journal papers are currently being developed based on the thesis of the student.

SECTION 6: SUMMARY OF UNIVERSITY/OPERATIONAL PARTNER INTERACTIONS AND ROLES

The unique design of this project allowed both the university and the NWS operational partner to take a leading role on a specific component of the project. The "processes studies" are led by the university, and the implementation of findings from the process studies is arranged by the NWS operational partner. On the other hand, the flood "hot spot" survey component is led by the NWS operational partner, with participation by a university graduate student. Scientific issues arisen from the "hot spot" survey are then addressed by the university scientists, in collaboration with the NWS partner.

Appendix A: Extended Abstract: 2005 AMS Conference on Weather Analysis and Forecasting

EXAMINING PLANETARY, SYNOPTIC, AND MESOSCALE FEATURES THAT ENHANCE PRECIPITATION ASSOCIATED WITH TROPICAL CYCLONES MAKING LANDFALL OVER NORTH CAROLINA

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1. INTRODUCTION AND BACKGROUND

Forecasting heavy rain associated with a landfalling tropical cyclone (TC) is a difficult task that can be made even more complicated when external features exist that may enhance the precipitation preceding or during landfall. The damage of inland freshwater floods can often exceed the coastal damage of these life-threatening storms (Rappaport 2000). In the United States, inland flooding is the predominant cause of deaths associated with TCs (Elsberry 2002). The most recent example of this was during Hurricane Floyd (1999) when inland floods claimed 50 lives in the United States. Another 1400 people were saved from Floyd's floodwaters, thanks to a massive rescue mission (Rappaport 2000; J. Cline, Raleigh, North Carolina National Weather Service (NWS) Forecast Office, 1999, personal communication). Rainfall totals of over 46 cm (18 in.) were reported at several locations in eastern North Carolina (Cline 2003), with many locations exceeding 100-year flood levels (Elsberry 2002).

Previous studies have found that potential vorticity (PV) provides a useful dynamical framework for studying the influence of upper-tropospheric trough interactions on TCs (Molinari et al. 1998). There are two main advantages of using PV: it is quasi-conserved for adiabatic, frictionless motion, and it directly relates dynamics and adiabatic heating. These conservative properties allow PV to be used as a tracer for adiabatic features (Molinari et al. 1998).

Upper-level troughs are often associated with increased wind shear, which would serve to weaken the TC. However, the PV anomaly and enhanced upper-level divergence may be strong enough to mitigate the negative influence of the high vertical wind shear (Hanley et al. 2001). Ultimately, determining if the trough will serve to enhance or weaken the precipitation associated with the TC, is dependent on the location and strength of the environmental features the TC is approaching.

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2. MOTIVATION AND HYPOTHESIS

North Carolina's geographic location makes it a prime target for TCs that recurve in the Atlantic Ocean, near the U.S. Forecasting precipitation totals from landfalling TCs is made even more complicated by their interactions with midlatitude systems. It is believed that a paradigm can be created to determine the potential of enhanced precipitation due to the interaction of the TC with other meteorological features as early as 72-hours prior to landfall. This paradigm would give forecasters an indication of the potential for an enhanced precipitation event. Features may exist at different temporal and spatial scales (i.e. planetary, synoptic, meso-α and meso-β) and intensify as landfall is approached (Orlanski 1975). Determining the multi-scale features that enhance precipitation during a TC could give forecasters greater lead-time and skill in determining the potential for an enhanced rain event.

3. METHODOLOGY

This research consisted of three parts. The first part is a statistical analysis of TC induced precipitation amounts to show the intrinsic features of the TC are not well correlated to the intensity of precipitation. The second is a climatology of 28 TCs that made landfall or tracked along the immediate coastline of North Carolina. The third part is a numerical simulation of two TCs that influenced North Carolina, Hurricane Floyd (1999) and Tropical Storm (TS) Arthur (1996), which were heavy and light precipitation events respectively.

3.1 Statistical Analysis

A 28-storm dataset (Table 1) of TCs that made landfall or tracked along the North Carolina coast between 1953 and 2003 was constructed. Figure 1 shows the fifty-three rain gauge stations obtained from the National Climatic Data Center (NCDC) and used to divide the TCs into groups of 14 heavy and light precipitation events. The heavy and light groups were determined by calculating the 3-day daily station mean rainfall total. This mean was 15.36 mm. The 3-day period was used since there is currently no standard time to collect rain gauge data. Using a 3-day period allowed for the majority of precipitation that was associated with the TC to be accounted for in this study. If a storm caused precipitation totals greater than the mean amount of 15.36 mm, it was considered a relatively heavy rain producer. Concurrently, if the 3-day daily station average rainfall was less then 15.36 mm, the storm was considered a relatively light rain event. A statistical analysis was performed to account for the variance of precipitation and to verify that there were no intrinsic features (i.e. storm intensity, translation speed) within the 28-storm dataset that accounted for the precipitation.

3.2 Climatological Study

The purpose of the climatological study was to determine the planetary and synoptic scale features associated with relatively heavy or light precipitation events in the past. The planetary scale analysis was performed using 2.5^{o}X2.5^{o} grid data from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis 1 Data. The synoptic and mesoscale features were examined using the North American Regional Reanalysis (NARR) 32-km dataset. NARR data is currently available from 1979-2003, therefore only the 12 TCs that occurred during this period were examined for this portion of the study. The 12 TCs occurring since 1979 are composed of six heavy and six light events represented in bold in Table 1.

Tropical Cyclone Name	Landfall Date	Approximate Landfall Time (UTC)	Precipitation Category	Daily Station Average Precipitation (mm)
Hurricane Isabel	9/18/2004	1700	Heavy	18.27
Hurricane Floyd	9/16/1999	0630	Heavy	50.86
T.S. Dennis 99	9/4/1999	2100	Heavy	22.68
Hurricane Bonnie	8/27/1998	0400	Light	14.85
Hurricane Fran	9/6/1996	0300	Heavy	36.79
Hurricane Bertha	7/12/1996	1200	Light	15.22
T.S. Arthur	6/20/1996	0000	Light	3.64
Hurricane Emily	8/31/1993	2100	Light	0.17
Hurricane Charley	8/17/1986	1400	Light	5.01
Hurricane Gloria	9/27/1985	0530	Light	10.85
Hurricane Diana	9/13/1984	0700	Heavy	15.86
T.S. Dennis	8/20/1981	0300	Heavy	16.40
Hurricane Ginger	9/30/1971	2000	Heavy	18.13
T.S. Doria	8/27/1971	1800	Light	13.64
T.S. #4	8/17/1970	1200	Light	3.22
Hurricane Gladys	10/20/1968	No Landfall	Heavy	21.91
T.S. Doria 67	9/12/1967	1200	Light	0.68
Hurricane Isbell	10/16/1964	1200	Heavy	16.84
Hurricane Alma	8/28/1962	No Landfall	Light	4.63
T.S. #6	9/14/1961	0600	Light	3.45
Hurricane Donna	9/12/1960	0300	Heavy	22.87
Hurricane Helene	9/27/1958	No Landfall	Light	4.90
Hurricane Ione	9/19/1955	0600	Heavy	18.48
Hurricane Diane	8/17/1955	1200	Heavy	24.83
Hurricane Connie	8/12/1955	1200	Heavy	19.98
Hurricane Hazel	10/15/1954	1200	Heavy	35.00
Hurricane Carol	8/31/1954	No Landfall	Light	4.32
Hurricane Barbara	8/14/1953	0000	Light	6.54

Table 1. 28 Tropical cyclones that made landfall or tracked along coastal North Carolina from 1953-2003. Precipitation totals greater than 15.36mm were considered relatively heavy events. Names in bold were storms used for the NARR composite analysis.

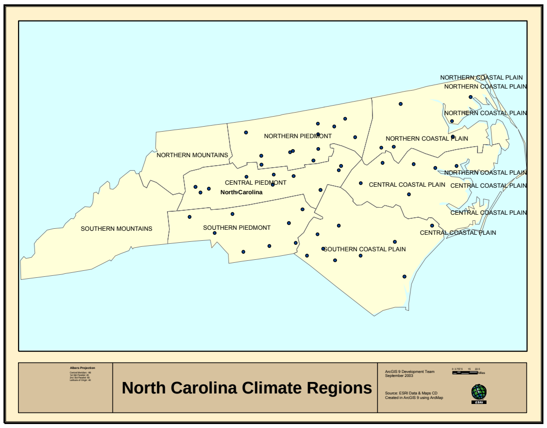

FIG. 1. Climate regions of North Carolina with 52 rain gauge stations used in the study (indicated by dots).

3.3. Numerical Simulation

The modeling section served to test the agreement between the climatological study and the two case studies. The two case studies, Hurricane Floyd (1999) and Tropical Storm Arthur (1996) represent a heavy and light rain event respectively. The numerical model makes it possible to examine features at small scales compared to the NARR Reanalysis data. Analyzing the meso-β scale features allows us to determine the consequences of upstream long period signals on short period circulation differences in the heavy versus light cases. The model chosen for this study is the Non-hydrostatic Mesoscale Atmospheric Simulation System (NHMASS) version 6.3 (MESO Inc. 1994). A one-way nested grid with initial coarse resolutions of 36 km and 18 km horizontal spacing and nested grid resolutions of 6 km and 2 km were performed for both Hurricane Floyd and Tropical Storm Arthur. All simulations used the 162X162 grid matrix with the domain center position shifted southeast as landfall approached. Turbulent Kinetic Energy (TKE) PBL physics (Therry and Lacarrerre 1983); mixed-phase moisture physics (Lin et al. 1983; Rutledge and Hobbs 1983) and the Kain-Fritsch cumulus parameterization scheme (Kain and Fritsch 1993) were used in all eight simulations. The model runs consisted of 90 vertical levels with staggered spacing, which allowed for higher resolution in the PBL and lower stratosphere. The upper boundary of the model was set to 10 hPa.

4. RESULTS

4.1 Precipitation Analysis

The precipitation analysis of the climatological portion of this research used data from 52 rain gauge stations across six climate regions (Northern, Central and Southern Piedmont and Northern, Central and Southern Coastal Plain) of North Carolina. After separating the storms into heavy and light rainfall groups as discussed in the methodology, various statistical analyses were performed to ensure the TC intrinsic features played no significant role regarding whether the TCs produced relatively heavy or light precipitation amounts.

The correlation coefficient (R^2 value) is equal to the percent of the total variance of the predictor to predictant, where the predictor is the various intrinsic features of the TC and the predictant is the precipitation value. The intrinsic features examined include translation speed, maximum storm intensity, landfall intensity and characteristics of landfall. Characteristics of landfall include i) direct landfall over NC. ii) a track along the coast of NC. iii) landfall over Florida (FL) with a second landfall over NC. iv) landfall over FL then tracking along the coast of NC. The results of the correlation between the TC intrinsic features and rainfall are shown in Table 2. Note that the correlation coefficient for each intrinsic features was relatively low. The strongest correlation existed between maximum storm intensity and precipitation, however less than 25% of the total variance associated with precipitation is accounted for by the maximum storm intensity. The above statistics allowed us to conclude, for this study, that the TCs intrinsic features did not have a significant impact on the precipitation that occurred over North Carolina.

Tropical Cyclone Intrinsic Properties	Correlation Coefficient (R^2)
Translation Speed	-0.068
Maximum Storm Intensity	0.234
Landfall Intensity	0.154
Characteristics of Landfall	0.061

Table 2. Correlation coefficients for each intrinsic property related to precipitation due to the 28 TCs used in this study.

4.2 Climatological Study

4.2.1 28-Storm Planetary Scale Analysis

There are major differences between the 250 hPa geopotential height composite anomalies at 72-hours prior to landfall for the heavy versus light precipitation producing TCs. A distinct positive height anomaly indicating a ridge over eastern North America (NA) and a negative anomaly indicating a trough developing over western NA exists in the heavy events. The light events are dominated by two positive anomalies over western and eastern NA and a weak negative anomaly over the Midwest (Fig. 2). Also significant is the negative anomaly located over the Southern Plains in the heavy events. This negative anomaly continues to be present through 24-hours prior to landfall, while a positive anomaly exists for the light events in the same location.

4.2.2 12-Storm Synoptic to Mesoscale Analysis

Composite analyses of upper-level (250-500 hPa), and lower-level (700-850 hPa) PV structures were completed for six heavy and light precipitation events using the NARR data. The upper-level PV pattern began signifying a possible enhanced rain event approximately 36-hours prior to landfall. A trough of strong PV (0.9-1.0 PVU) exists at 36-hours prior to landfall west of the Ohio River Valley (not shown). By 24-hours prior to landfall the difference in PV between the heavy and light events becomes statistically significant at the 95% confidence interval with higher values of PV forming over the Ohio River Valley in the heavy events compared to the light events (Fig. 3). The upper-level PV associated with a negatively tilted upper-tropospheric trough of geopotential heights (not shown) over the Ohio River Valley continues to strengthen during the 24-hours prior to landfall. This region of positive PV couples with the TC to aid in the creation of a favorable mass divergence aloft which may result in the formation of a secondary mesoscale convective system (MCS) that can lead to enhanced precipitation.

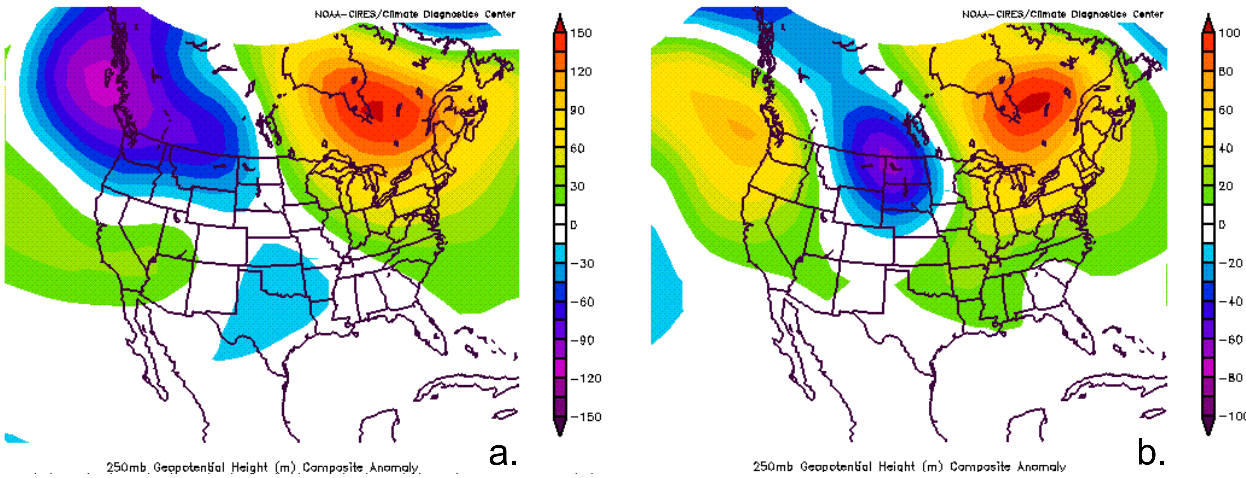

FIG. 2. 250 hPa composites of geopotential height anomalies (m) of (a) 14 heavy and (b) light precipitation events at 72-hours prior to landfall in NC.

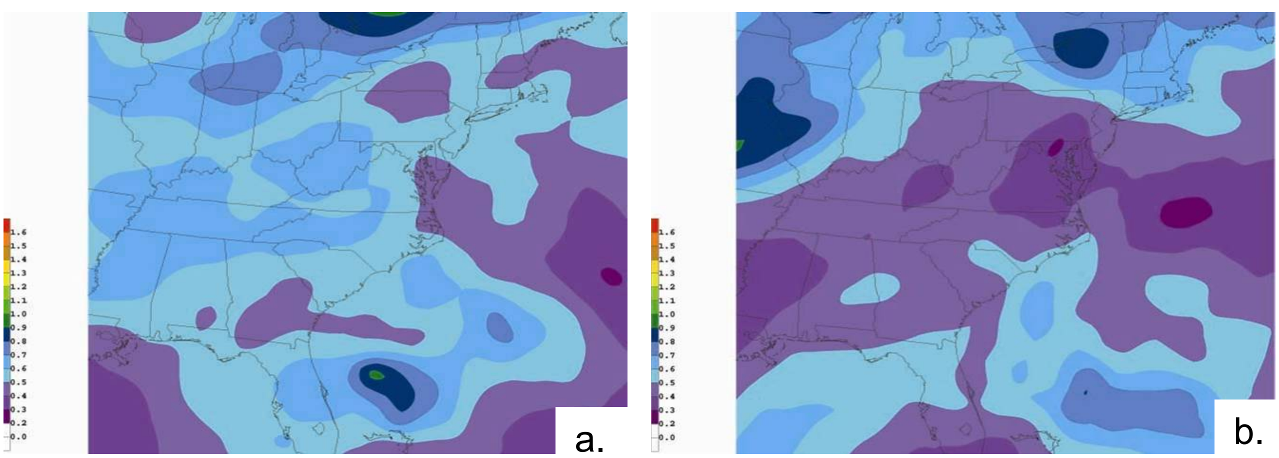

FIG. 3. Composite of 250-500 hPa potential vorticity (PVU) for (a) 6 heavy and (b) light precipitation events at 24-hours prior to landfall in NC. Significantly higher PV over eastern U.S. associated with heavy events.

To investigate the transport of moisture prior to and during landfall of the TCs, the 925-850 hPa layer moisture flux, moisture flux vectors and convergence was calculated. The moisture flux convergence is a useful quantity for forecasters to determine the potential for intensified precipitation because it is proportional to the precipitation rate. The heavy precipitation events exhibited an onshore moisture flux from 48-hours prior to landfall through landfall, while the light events experienced an offshore flux of moisture (Fig.4.) As landfall approached the moisture flux vectors for the heavy events intensified and were directed onshore due to the presence of a trough, indicating a higher likelihood of precipitation. Conversely, the moisture flux vectors for the light events appeared to be influenced by a ridge, which aided to direct the moisture offshore. The onshore versus offshore direction of the moisture flux vectors is a useful quantitative method of determining the potential of enhanced precipitation during a landfalling TC. The mesoscale features that were examined for this study included low-level isotherms, winds, mean sea level pressure and frontogenesis from 18-hours prior to landfall. The heavy composites exhibit a ridge of high pressure that brings cool air southward.

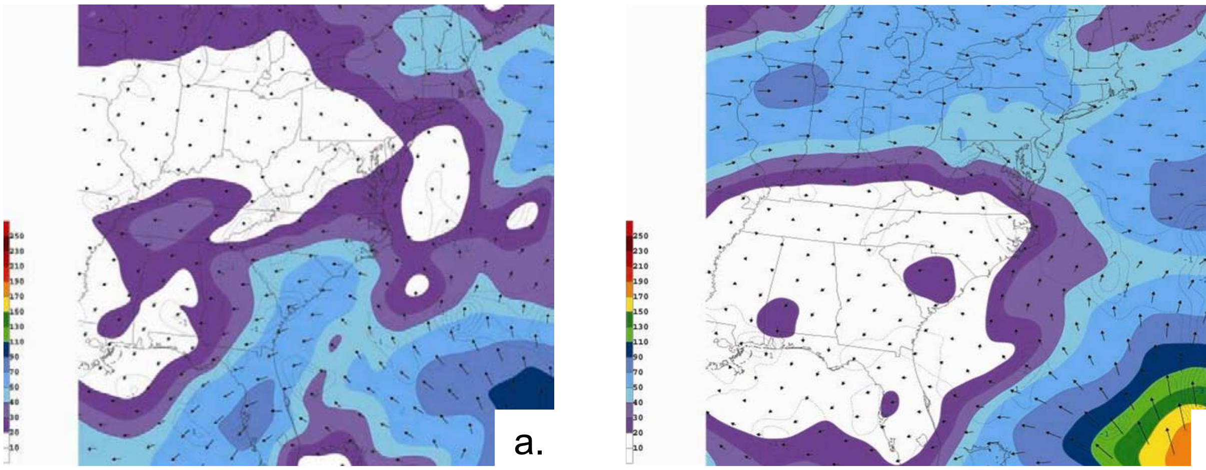

FIG. 4. Moisture flux vectors (x10-4 m s^{-1} black arrows), moisture flux (x 10-4 m s^{-1} shaded) and moisture flux convergence (contours, $gkg^{-1}ms^{-1}$) for (a) heavy and (b) light precipitation events at 48-hours prior to landfall in NC.

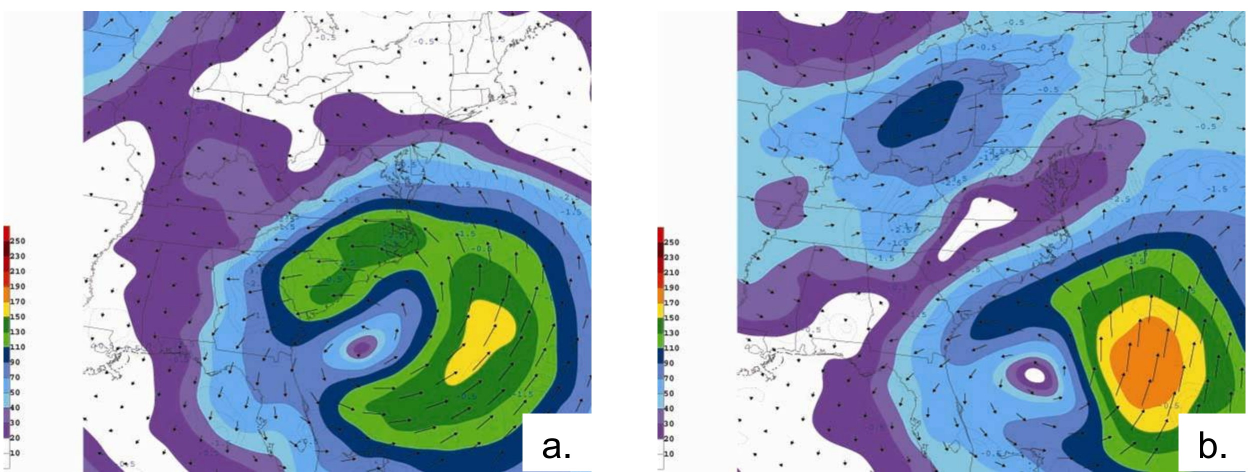

FIG. 5. As in Fig. 4 except for 12-hours prior to landfall in NC.

This in turn strengthens the zone of surface convergence and moderate frontogenesis that is found east of the cool air (Fig. 6). Throughout the following 18-hours, the cool air over North Carolina, zone of convergence and frontogenesis continued to strengthen in the heavy events. In the light events there is very little notable frontogenesis and subsequently weak surface convergence and virtually no temperature gradient that forms during the entire 18-hour period prior to landfall. Figure 7 exhibits the strengthening of frontogenesis for the heavy events as landfall is approached.

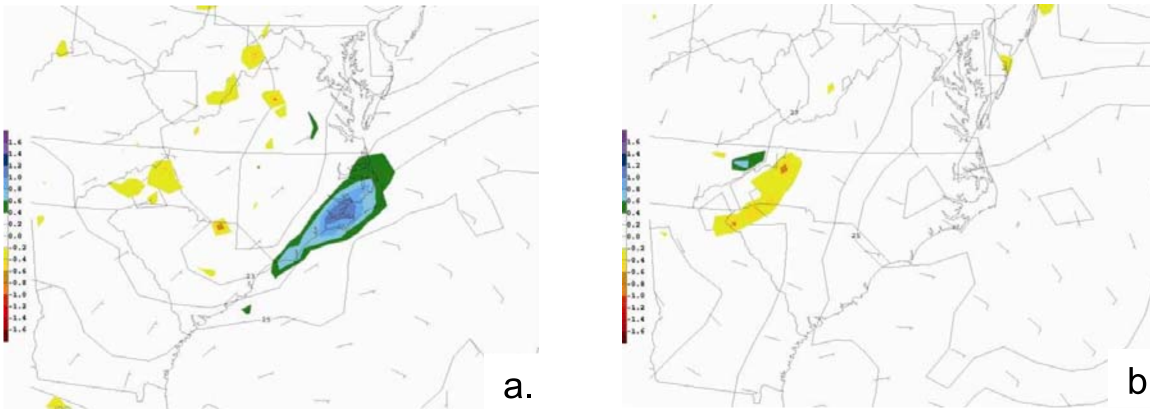

FIG. 6. Composite analysis of 1000 hPa frontogenesis (color fill, °C 100km^{-1} 3hr^{-1}), temperature (contours, °C) and wind barbs (ms^{-1}) for 6 (a) heavy and (b) light precipitation events at 18-hours prior to landfall.

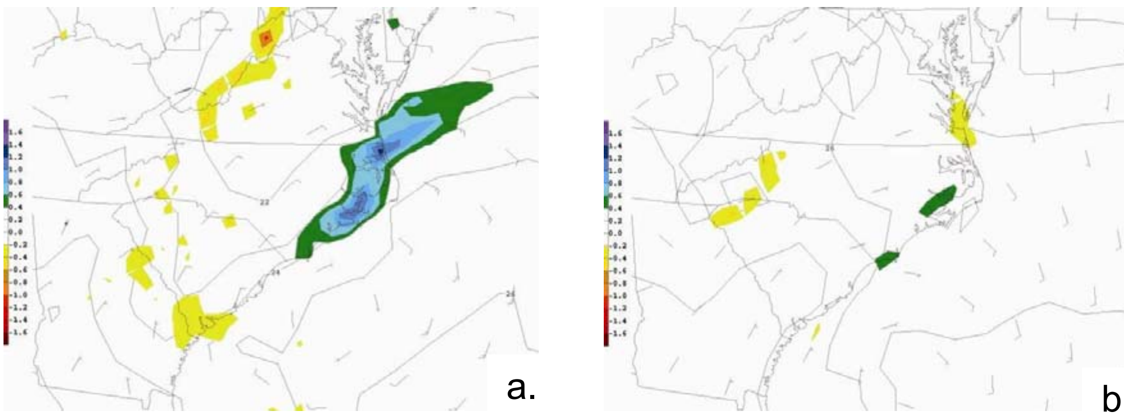

FIG. 7. As in Fig. 6 except for 6 hours prior to landfall.

4.3 Modeling Study

Simulations of Hurricane Floyd and Tropical Storm Arthur were performed using the NHMASS model to check the agreement between the results of the climatological study and the individual case studies. The modeling portion also served to further investigate the mesoscale environment the TCs were entering prior to and at landfall. The model analysis agrees with the climatological results presented in section 5.1, further indicating the importance of an upper-level (250 hPa) trough over the Southern Plains, presence of high PV values (500-250 hPa), and well aligned onshore moisture flux vectors (925-850 hPa) for the production of enhanced rainfall. Preliminary results indicate that, for the heavy events, the large-scale environment from 72-hours prior to landfall sets up the mesoscale environment that is favorable for enhanced precipitation. The preexisting planetary scale environment is conducive to the formation of a region of cool air (Fig. 8) moving southward into North Carolina as well as a coastal front. Figure 9 is a model analysis of frontogenesis, indicating high levels of frontogenesis along coastal North Carolina.

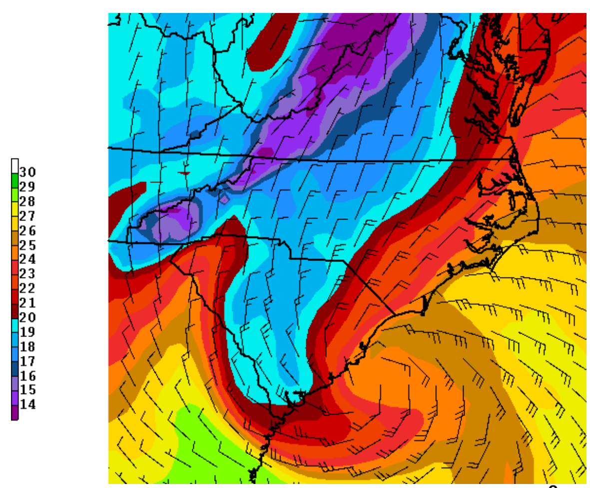

Fig. 8. NHMASS model 1000 hPa temperature (°C) and wind (ms^{-1})for Hurricane Floyd, 3-hours prior to landfall (0300 UTC 99/09/16).

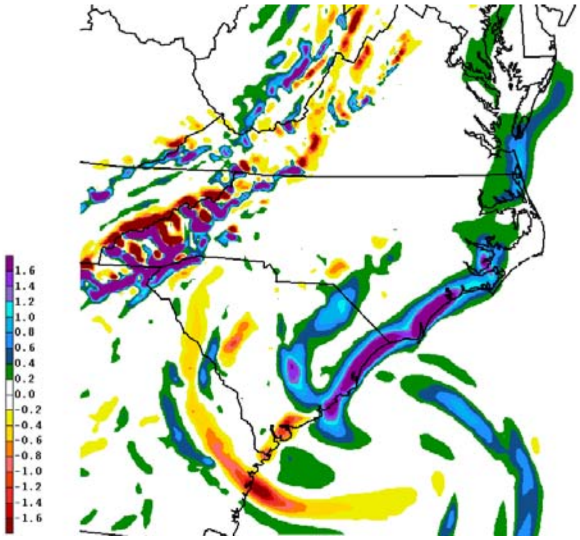

Fig. 9 NHMASS model 1000 hPa frontogenesis (^{o}C100km^{-1}3hr^{-1}) 3-hours prior to landfall of Hurricane Floyd (0300 UTC 99/09/16).

The accelerations within the right entrance region of the polar jet located to the north of Hurricane Floyd creates an environment favorable for upward motions and surface pressure falls near the coastal front. Any additional acceleration aloft due to latent heating induced pressure rises will turn the winds to the left due to the strong southerly flow ahead of the trough (Fig. 10). This wind shift can enhance the outflow and divergence. The pressure falls adjacent to the inland pressure rises accompanying the region of cold air ahead of the trough strengthens the ascent over the coastal front. As the tropical air is lifted above the coastal front under the diverging flow aloft, latent heating intensifies the accelerating outflow aloft, strengthening the jet right entrance region and strengthening the downstream upper ridge ahead of the upstream trough. As the upper ridge builds above the coastal front, the upstream trough interacts with it to produce secondary regions of geostrophic wind imbalance aloft. The regions of geostrophic wind imbalance builds the ascending flow south and west of the coastal front triggering precipitation farther west as the trough moves northwards. Figure 10 indicates the high levels of upper-level divergence (250 hPa) and the sharp left turn in the winds. The abundant moisture feed into these thermally direct circulations, allows a moist neutral environment to develop that is favorable for widespread mesoscale convective system formation. The enhanced rainfall due to the MCS can be seen in figs 11 and 12, the 3-hour precipitation and the accumulated precipitation, respectively.

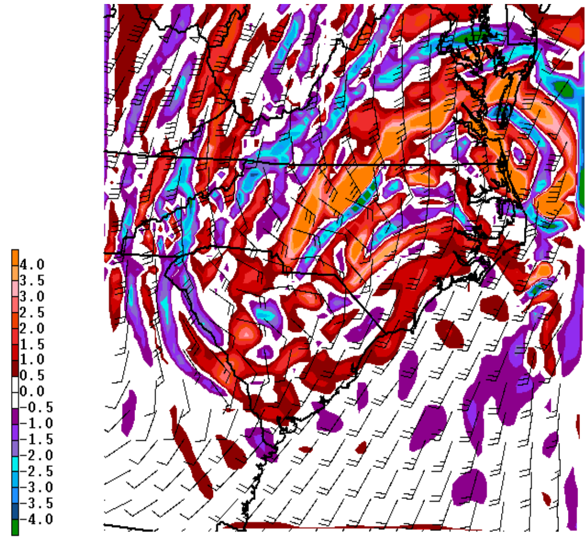

Fig. 10 NHMASS model 250 hPa divergence (s^{-1}*10^{-4}) and winds (ms^{-1}) 2-hours after landfall (0800 UTC 99/09/16),

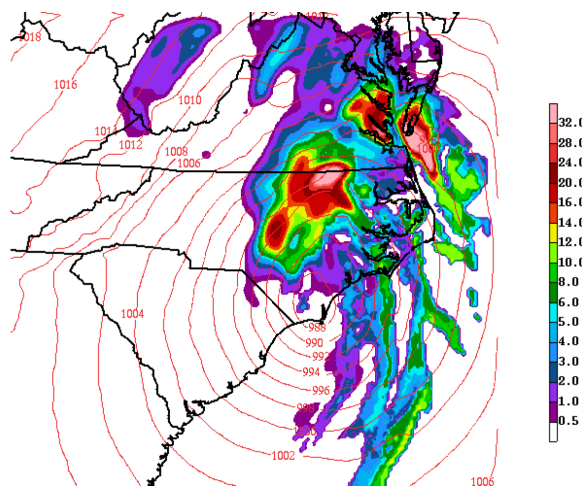

Fig. 11 NHMASS model precipitation (mm) and mslp (hPa) 7-hours after landfall (1300 UTC 99/09/16)

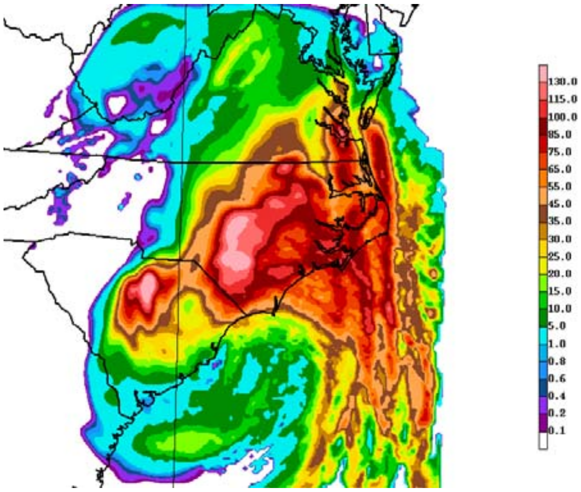

Fig. 12 NHMASS model accumulated precipitation (mm) from 0300 UTC 99/09/16–1300 UTC 99/06/16.

5. SUMMARY AND CONCLUSIONS

This study shows that features on multiple spatial and temporal scales can enhance rainfall associated with TCs making landfall or tracking along the coast of North Carolina. At 72-hours prior to landfall a forecaster can concentrate on the planetary scale signal of 250 hPa geopotential height. A forecaster can look for a trough over western NA and a ridge over northeastern NA, with a weak trough beginning to develop west of the southeast coast of the U.S. (over the Southern Plains). At 36-hours prior to landfall the forecaster can begin examining the upper-level (500-250 hPa) environmental PV. The heavy precipitation events typically exhibit higher values of PV across the southeast. A forecaster can pay close attention to a trough of negatively tilted upper-level PV penetrating southeastward through the Ohio River Valley. Such a trough can interact with the lower-level (850-700 hPa) PV associated with the TC serving to create a favorable mass divergence aloft, producing a secondary MCS, and thus enhancing precipitation.

Further evidence signifying the potential for a heavy rain event can be obtained by examining the moisture flux convergence, magnitude of moisture flux and the moisture flux vectors (925-850 hPa). The moisture flux is proportional to precipitation rate, so a forecaster can examine the intensity and direction of the moisture flux to determine the likelihood of heavy precipitation. Heavy rainfall events typically have onshore moisture flux vectors from 48-hours prior to landfall, which increases in magnitude as landfall is approached. This is significantly different from the composite analysis of the light events, in which strong south-southeast winds dominated the flow. This wind directs the moisture flux vectors offshore, and acts to prevent the formation of a moist environment prior to landfall of the TC. Beginning 18-hours prior to landfall the forecaster can look for signs of the ridge associated with the heavy events bringing cool air southward into North Carolina and the formation of low-level frontogenesis. The heavy events examined in this study had significantly higher values of frontogenesis from 18-hours prior to landfall through landfall, compared to the light events.

6. FUTURE WORK

This work will be presented to the National Weather Service (NWS) Raleigh as part of their tropical cyclone seasonal familiarization activities. An advanced weather interactive processing system (AWIPS) procedure will be developed for use by the NWS Raleigh office. This procedure will guide forecasters through a structured evaluation of meteorological features which potentially can interact with TCs to enhance rainfall amounts. The Raleigh NWS and the Southeastern River Forecasting Center can then use this evaluation to aid in the decision of issuing river flood watches and warnings.

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Appendix B: COMET Inland Flooding Project Summary: Inland Flooding "Hot Spots"

PURPOSE:

The purpose of this component of the project was to gather information on the characteristics of local, inland flooding, caused by both tropical and extra-tropical weather that affects central North Carolina. The area of focus for this study was the 31 counties comprising the Central Warning Area (CWA) serviced by the Raleigh National Weather Service Forecast Office (RAH). These are the counties for which the RAH office is responsible for monitoring and issuing forecast products, including warnings.

The main goals for this aspect of the project were to identify local areas which are generally more prone to flooding, referred to as "hot spots", describe and map those locations, and gather pertinent information about these sites and their flooding histories. Such information included past flooding events, frequency of flooding, recent trends in flooding frequency or severity, stream flow data if a stream gage was located near the site, and meteorological data surrounding flooding events at each hot spot. This information was sought after with the goal of providing local forecasters with beneficial insight about these flood prone locations that could lead to a better understanding of where flooding is most likely to occur and the conditions under which such locales tend to flood. This would allow the forecasters to issue flood warnings with greater lead-times and with greater detail as to the locations under the greatest threat, both of which provide a more beneficial service to the public.

PROCEDURE AND RESULTS:

The first step for this project was to identify the flooding hot spots for each county in the CWA. NCSU graduate students worked with the forecasters at the RAH office to devise a plan as to how to go about identifying the hot spots. We decided that the best way was to contact the Emergency Management Office for each county and arrange to meet with the emergency managers, who have a great deal of insight and experience dealing with flooding in their respective counties. When meeting with the emergency managers, they would point out on maps where they routinely have trouble with flooding. They would provide any information they could as to the severity of the flooding, the frequency, and how much of a threat flooding at a particular location posed to life or property. Aside from identifying all the locations where flooding has been a problem in the past, the emergency managers also indicated which few spots are the most problematic or pose the greatest threat to life or property so that we could prioritize our efforts by gathering additional information on the most significant hot spots first. On several occasions, the RAH staff and NCSU graduate students were taken to visit and document these most significant sites first hand, which added a greater understanding and appreciation for these hot spots.

Once a visit was complete and a set of hot spots was identified for a certain county, we would then begin the process of mapping those locations using geographical information system (GIS) software such as ArcView3.X and ArcMap9.1. This was done at the RAH office with the purpose of being able to import the mapped hot spots into the Flash Flood Monitoring Program (FFMP), which the National Weather Service uses to monitor local streams for flooding. This program allows the forecasters to track how local streams are responding to precipitation events and gives them guidance for issuing flood watches and warnings. The FFMP, however, provides guidance for the various rivers, tributaries, and streams in each county with little detail as to where along those reaches flooding is most likely. By having the locations of the more flood prone areas available to view along with the FFMP's guidance, forecasters can focus their efforts and observations on the areas that are known to have a greater potential for flooding. This doesn't mean that the forecasters will only focus on those areas as flooding can arise anywhere, but this does allow them see the areas that are more likely to be a problem. This can lead to flood warnings with not only greater lead-times, but with greater detail as to what locations in particular the public should be cautious of. Providing greater detail in the flood statements was achieved by adding a description of the location of each hot spot as they were mapped. Along with the descriptions on the map, descriptions of the sites were also added to a text file that is used by the forecasters to generate the flood watches and warnings that are distributed to the public.

Figure 1 shows the 31 counties comprising the RAH CWA. Figure 2 shows a closer view with the locations of all the hot spots that have been identified and mapped thus far. The grey outlined areas in Figure 2 show the city boundaries in those counties for which mapping of the hot spots has been completed. Of the 115 hot spots identified thus far, 36 (or approximately 31%) lie within urban areas. Since these areas are generally the most populated and developed, flooding often poses a greater threat to life and property in these areas as opposed to more rural areas. Furthermore, some areas have a considerable amount of development outside the city boundary, so it is possible that even a greater percentage of hot spots pose this increased threat. It should be noted though, that just because a site is identified as being more prone to flooding than surrounding areas, it doesn't mean that the severity of the flooding is always, if ever, enough to be a threat to life or property. This is where the acquisition of additional

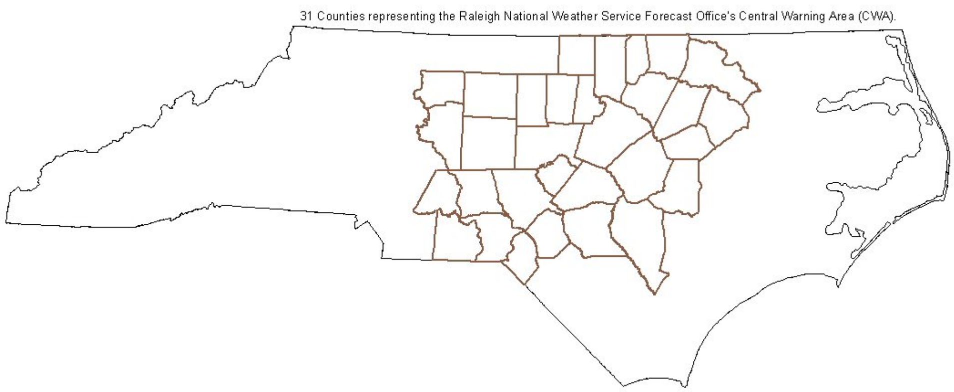

Figure 1. 31 central Carolina counties included in the "hot spots" study.

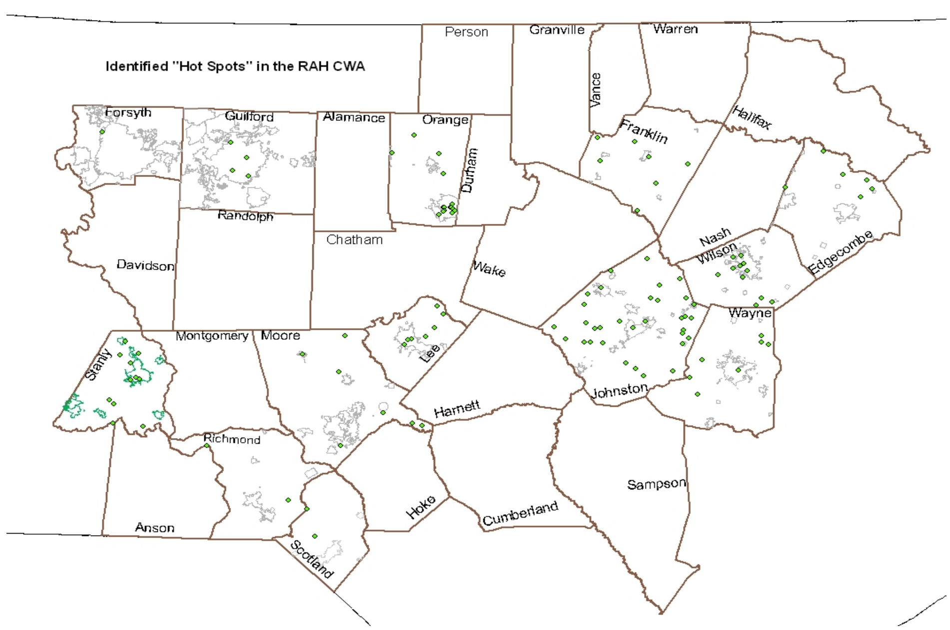

Figure 2 - The dots represent "hot spots" that have been mapped thus far. The grey boundaries show the city boundaries for the counties in which the "hot spot" mapping has been completed.

information on the hot spots, such as having the emergency managers indicate which locations pose the most significant or frequent threat, is of benefit. This way, the forecasters have an idea of not only all the areas that are more susceptible to flooding, but those that pose the greatest risk as well. Figure 3 shows an example of the description as well as the latitude and longitude coordinates associated with each hot spot located on the map in Figure 2. It is these descriptions that can be viewed by forecasters and added, in slightly more detail, to their flood warnings.

As can be seen in Figure 2, 13 of the 31 counties have been visited and have had hot spots mapped. Unfortunately, the logistics of coordinating a visit with the county emergency managers and personnel, ourselves, and the forecasters that may accompany me, has proven to be quite cumbersome. Efforts are still underway, however, to continue this work and finish mapping the rest of the counties in the CWA. Completion of the hot spot mapping is not necessary to show the benefit of such work though, as the identification of even a few sites can prove to be beneficial to forecasters when identifying areas under threat of flooding and issuing warnings to the public.

62	Point	Tanner Rd at Compass Cr	35.99	-77.77	Edgecombe
63	Point	Ethridge Farm Rd near Fishing Cr	36.11	-77.63	Edgecombe
64	Point	Bethlehem Ch Rd at Maple Swp	36.03	-77.56	Edgecombe
65	Point	Bats Chapel Rd & Hwy 258	35.95	-77.5	Edgecombe
66	Point	Cutchin Farm Rd near Deep Cr	35.98	-77.45	Edgecombe
67	Point	Dickens Rd. low lying areas	36.01	-77.47	Edgecombe
68	Point	S.Buffalo & Ryan Crs. in S. Grnsboro	36.02	-79.8	Guilford
69	Point	Horsepen Cr. near Old Battleground Rd	36.14	-79.86	Guilford
70	Point	S. Buffalo Cr.-Pinecroft Rd. to Merritt Dr.	36.08	-79.86	Guilford
71	Point	N. Buffalo Cr. in cen. Grnsboro	36.09	-79.8	Guilford
72	Point	Fox Cr. at E. River Rd. and Rt.56	36.1	-78.29	Franklin
73	Point	Big Peachtree Cr. at Stallings Mill Rd.	36.07	-78.14	Franklin
74	Point	Mutt Winstead Rd. near Tar R.	36.01	-78.26	Franklin
75	Point	Bennett Perry Rd. near Perry's Pond	35.91	-78.33	Franklin
76	Point	US-1A and Cedar Cr.	36.08	-78.47	Franklin
77	Point	Green Hill Rd. at Middle & McGee Crs.	36.16	-78.48	Franklin
78	Point	Lynch Cr. at Dyking Rd	36.15	-78.34	Franklin
79	Point	Mill & Grassy Crs. in N-NW Win-Sal.	36.17	-80.34	Franklin
80	Point	Hwy 177 west to NC Speedway	34.94	-79.63	Richmond
81	Point	Grassy Island Rd. near Pee Dee R.	35.12	-79.94	Richmond
82	Point	Gum Swamp Cr. & Dam	34.91	-79.56	Scotland
83	Point	Richmond Mill Lake Dam	34.82	-79.53	Scotland

Figure 3 - Attribute table associated with GIS map of hot spots in Figure 2.

The next step in this project was to begin gathering information on the flooding histories for the sites, particularly the most significant hot spots. First, we searched through the National Climatic Data Center's (NCDC) online Storm Events Database for flooding events in the counties where hot spots had been already mapped. The database consisted of any severe weather reports that were made for a particular county from 1993 to the present. We searched for only those reports consisting of a flooding event. Unfortunately, official storm reports did not focus on including flooding reports prior to 1993. Storm event reports prior to that time mainly listed wind and precipitation events and only mentioned flooding if it was a high-impact, widespread event. Therefore, storm event reports before 1993 provided no additional events for any particular hot spot. We also searched the county government websites as some had records of weather-related damages that occurred in that county. We then stored all the records of flooding events in a spreadsheet file that included information such as date of the event, type of flooding (river or flash), the body of water experiencing flooding, the local area affected, and whatever summaries of the event we could retrieve from the Storm Events Database. This was just a way to easily access information for the various flooding events that have occurred in counties being studied. Figure 4 shows a screen capture of this spreadsheet for the flooding events reported in Guilford County.

Event Date	County	EventType	Flood Type	Flooding Body	Flooding Locales	Even tDetail
9704282120	Guilford	ML Cyc.	Flash		Southeast Portion of Co.	Bridge flooded in SE portion along with flooding on secondary roads.
9609031900	Guilford	Thdr Strm	Flash		High Point	5 inches in a short period.
9607251216	Guilford	Thdr Strm	Flash		Greensboro, High Point	5 inches fell from multiple, near stationary thunderstorms. Streets and underpasses flooded, several cars abandonded.
9408181630	Guilford	Thdr Strm	Flash		Greensboro: numerous roads	1.23 inches fell in 33 min.
0407172115	Guilford	Frnt Pass	Flash	S. and N. Buffalo Creeks, E. Deep Fork River,and others	Greensboro: I-40 at Exit 68; Terrace, Industrial Village, Tower Rds.; W. Friendly Ave near N. Chimney Rock Rd; Ashley Creek Apts. at Maplewood Lane; Latham Park near Wendover Ave.	Flooding caused closings of I-40 at exit 68, parts of Terrance Rd, Industrial Village Rd, and Tower Rd. Numerous cars abandonded along I-40 with door-handle to roof- high water in some areas. Several vehicles stuck in water along West Friendly Ave. near Chimney Rock Rd. South Buffalo Creek flooded near mall. Ashley Creek Apts. evacuated.
0409080930	Guilford	H Frances	Flash	Numerous Including S. Buffalo Cr. and Deep River,	Holden Rd. and High Point Rd., Ashley Creek Apts., Harvey Rd, Stanly Rd, East Woodlyn Way off of Hilltop Rd.	Ashley Creek Apts. evacuated. Vehicles stuck in water at Holden and High Point Rds. Vehicular water rescues at Harvy and Stanly Rds. 6 inches of water over bridge on East Woodlyn Way.
0409272310	Guilford	H Jeane	Flash	Horsepen Cr., Brush Cr., E. Fork Deep River	Battleground Ave., Airport Rd and I-40 from P-T Airport to Forsyth County.	Flooding occurred at stated locations.
0412100330	Guilford	ML Cyc.	Flash	N. Buffalo Cr	Wendover Ave.	Flooding at location.
0309230200	Guilford	Frnt Pass	Flash	S. & N. Buffalo Cr	Greensboro: Near Ashley Creek Apts. and Latham Park.	Flooding of Buffalo Cr. Damaged about 40 apts. near Four Seasons Mall. Homes near Latham Park flooded with as much at 3 ft. of water.
0308311430	Guilford	Thdr Strm	Flash	Several including tributary of Big Alamance Creek	Greensboro: Several roads including bridge on Abernathy Rd.	Several roads flooded and bridge on Abernathy Rd. submerged.
0308171930	Guilford	Frnt Pass	Flash	Horsepen Cr., S. Buffalo Cr, and others	Greensboro: Numerous roads near Piedmont Triad Airport, namely New Garden, High Point, and Bryant Rds.	
0308041945	Guilford	Frnt Pass	Flash	Climax Cr.	Climax	Several homes and roads flooded as Climax Cr. Overflowed banks.
0307131858	Guilford	Frnt Pass	Flash	Horsepen Cr.	5 mi. south of Summerfield: Battleground Rd. and New Gordon Rd. closed.	
0304101218	Guilford	ML Cyc.	River	Several Creeks	Countywide	Persistant rain and thunder storms caused several creeks to overflow banks and flood roads. Basement flooding in some residences.
0303200627	Guilford	ML Cyc.	River	Numerous Creeks	Countywide	Persistant rain for about 12 hours resulted in 2-4 inches of rain over wide area. Numerous creeks overflowed banks. Numerous roads flooded and closed.
0302221200	Guilford	ML Cyc.	Flash		Western Portion	Several roads flooded.
0209181355	Guilford	Frnt Pass	Flash	Muddy Creek or Uwharrie River	High Point: Surret Dr.	Several cars flooded.
0107041826	Guilford	Frnt Pass	Flash	N. Buffalo Cr. + Several others	Greensboro: Wendover Ave. covered	3 inches of rain in short period. Several creeks flooded, one of which submerged Wendover Ave. Several people rescued from flooded cars. Flooding receeded quickly.
0009142310	Guilford	Frnt Pass	Flash		Oak Ridge in west Greensboro	Numerous roads flooded w/ some covered by as much as 6 inches of water.
0009011858	Guilford	Thdr Strm	Flash	S. Buffalo Cr	Greensboro: Highways, Ashley Creek Apts.	2-3 ft. of flooding on some highways. Roof caved in on Wal-Mart (Wendover Ave.). Ashley Creek Apts. Evacuated
0008280300	Guilford	Frnt Pass	Flash		Greensboro	Water up to houses in some residential areas. Some flooding on side streets.
0008270300	Guilford	Thdr Strm	Flash		Southeast of Greensboro	Highwater on roads.
0006191400	Guilford	Thdr Strm	Flash		Greensboro	Approx. 5 in. of rain fell in ~1 hr. Cars stranded as 8 in. (reportedly) of water covered roads. 2-3 ft. of flooding damaged 16 homes.

Figure 4 - Screen capture of flood event data collected from NCDC Storm Events Database for Guilford County, NC

This, however, only provided data for the flooding events for the whole county, not at selected hot spots. Therefore, my next step was to separate the events by hot spot, if the Storm Events summary provided enough detail to mention a certain hot spot location. Often, only a general area was mentioned in the flood report and we had to reference various county maps to determine if any of the hot spots were within that area and likely flooded during the event. To further determine if a certain hot spot flooded during an event in which the flood record did not explicitly mention the location of a hot spot, we acquired stream gage data from nearby gage stations. This data was obtained from the United States Geologic Survey (USGS) stream gage data archive. The data acquired included various gage height and stream discharge data, especially the maximum values for the dates on which a flooding event occurred. If the stream gage data was relatively close to a hot spot location, trends in stream gage data from events when a hot spot was know to flood was compared to the data from event dates when it was uncertain whether a certain hot spot actually flooded or not. This way, it could be determined with a good amount of confidence whether that hot spot flooded during a particular reported event. Figure 4 shows a screen capture of an Excel sheet used to store some of this USGS stream gage data for several events during which two different hot spots in Guilford County, NC flooded or were suspected of flooding. The two hot spots were South Buffalo Creek near the Ashley Creek Apartment Complex and North Buffalo Creek at Latham Park. Figure 5 shows values for stream gage data including the maximum stream height on the day of the flooding event as well as the previous day and the maximum stream discharge for the same times. The South Buffalo Creek hot spot has one nearby stream gage while the North Buffalo Creek hot spot has two nearby stream gages, one upstream and one downstream.

S. Buff. At Ashley Cr. Apts	Event Date YYMMDDTTTT (est)	Stream	Gage Location	Gage Height Max (ft)	Prior Day Gage Ht Max (ft)	Stream Discharge Max (ft^3/s)	Prior Day Discharge Max (ft^3/s)
	0407172115	S. Buffalo Cr.	02094659 SBPN7 Pamona	**13.84**	0.69	**3000**	2
Known	0409080930	S. Buffalo Cr.	02094659 SBPN7 Pamona	**11.55**	2.4	**2440**	102
and	0309230200	S. Buffalo Cr.	02094659 SBPN7 Pamona	**15.45**	4.36	**3350**	434
Suspected	0308171930	S. Buffalo Cr.	02094659 SBPN7 Pamona	**7.34**	2.03	**1300**	62
Events	0304101218	S. Buffalo Cr.	02094659 SBPN7 Pamona	**8.66**	4.37	**1670**	436
	0303200627	S. Buffalo Cr.	02094659 SBPN7 Pamona	**10.88**	1.18	**2270**	9
	0009142310	S. Buffalo Cr.	02094659 SBPN7 Pamona	**14.01**	3.1	**1070**	190
	0009011858	S. Buffalo Cr.	02094659 SBPN7 Pamona	**10.78**	3.26	**930**	215
N. Buff. at	0412100330	N. Buffalo Cr.	02095271 NBUN7 Church St.	**13.99**	4.89	**2000**	178
Latham Park	0412100330	N. Buffalo Cr.	02095181 NBWN7 Westover Terrace	**11.16**	2.71	**851**	129
	0407172115	N. Buffalo Cr.	02095271 NBUN7 Church St.	**11.91**	2.25	**1390**	4.5
Known	0407172115	N. Buffalo Cr.	02095181 NBWN7 Westover Terrace	**12**	1.17	**754**	1.6
and	0309230200	N. Buffalo Cr.	02095271 NBUN7 Church St.	**17.81**	7.79	**3090**	520
Suspected	0309230200	N. Buffalo Cr.	02095181 NBWN7 Westover Terrace	**14.07**	4.65	**963**	465
Events	0304101218	N. Buffalo Cr.	02095271 NBUN7 Church St.	**12.79**	8.53	**1640**	645
	0304101218	N. Buffalo Cr.	02095181 NBWN7 Westover Terrace	**9.73**	4.48	**977**	490
	0303200627	N. Buffalo Cr.	02095271 NBUN7 Church St.	**14.23**	3.25	**2080**	69
	0303200627	N. Buffalo Cr.	02095181 NBWN7 Westover Terrace	**10.91**	1.88	**928**	9.2
	0107041826	N. Buffalo Cr.	02095271 NBUN7 Church St.	**14.55**	2.02	**1450**	7.5
	0107041826	N. Buffalo Cr.	02095181 NBWN7 Westover Terrace	**11.71**	1.22	**2220**	3.5
	0008280300	N. Buffalo Cr.	02095271 NBUN7 Church St.	**12.62**	5.75	**586**	2.16
	0008280300	N. Buffalo Cr.	02095181 NBWN7 Westover Terrace	**10.52**	1.53	**1870**	11
	0006191400	N. Buffalo Cr.	02095271 NBUN7 Church St.	**15.65**	7.95	**578**	350
	0006191400	N. Buffalo Cr.	02095181 NBWN7 Westover Terrace	**12.27**	5.41	**2390**	612

Figure 5 - Example of USGS stream data collected from gages near two hot spots for flooding events at each hot spot. The alternating light and dark records separate events.

Once the dates of flooding events for a particular hot spot were determined, the next step was to gather meteorological information for the events at each site. Initially, we tried to determine the general synoptic environment surrounding each event for a particular hot spot. We chose the same two hot spots as mentioned above to begin my meteorological analysis. We used online data resources such as the Plymouth State University's weather data archive, which stores various, detailed meteorological analysis data as well as satellite imagery, and the NCDC's NEXRAD National Mosaic Reflectivity Image archive. It is this initial data with which we were able to categorize the events for these two hot spots. In general, the events were categorized as tropical, mid-latitude cyclone, frontal passage, or convective thunderstorm based on the general synoptic conditions that surrounded the event. These categories may be updated or changed for a particular event as more detailed model and hand analysis of recently acquired Rapid Update Cycle (RUC) model data and surface observation data are analyzed.

The culmination of all the data gathered thus far is shown in Figure 6, which displays information gathered for the South Buffalo Creek hot spot including the dates of flooding events at this site, the general weather pattern associated with the flooding events, and details on the event itself such as locations affected and an event summary.

Event Date	County	EventType	Flood Type	Flooding Body	Flooding Locales	Event Detail
0407172115	Guilford	Frnt Pass	Flash	S. and N. Buffalo Creeks, E. Deep Fork River,and others	Greensboro: I-40 at Exit 68; Terrace, Industrial Village, Tower Rds.; W. Friendly Ave near N. Chimney Rock Rd; Ashley Creek Apts. at Maplewood Lane; Latham Park near Wendover Ave.	Flooding caused closings of I-40 at exit 68, parts of Terrance Rd, Industrial Village Rd, and Tower Rd. Numerous cars abandonded along I-40 with door-handle to roof- high water in some areas. Several vehicles stuck in water along West Friendly Ave. near Chimney Rock Rd. South Buffalo Creek flooded near mall. Ashley Creek Apts. evacuated.
0409080930	Guilford	H Frances	Flash	Numerous Including S. Buffalo Cr. and Deep River,	Holden Rd. and High Point Rd., Ashley Creek Apts., Harvey Rd, Stanly Rd, East Woodlyn Way off of Hilltop Rd.	Ashley Creek Apts. evacuated. Vehicles stuck in water at Holden and High Point Rds. Vehicular water rescues at Harvy and Stanly Rds. 6 inches of water over bridge on East Woodlyn Way.
0309230200	Guilford	Frnt Pass	Flash	S. & N. Buffalo Cr	Greensboro: Near Ashley Creek Apts. and Latham Park.	Flooding of Buffalo Cr. Damaged about 40 apts. near Four Seasons Mall. Homes near Latham Park flooded with as much at 3 ft. of water.
0308171930	Guilford	Frnt Pass	Flash	Horsepen Cr., S. Buffalo Cr, and others	Greensboro: Numerous roads near Piedmont Triad Airport, namely New Garden, High Point, and Bryant Rds.	
0304101218	Guilford	ML Cyc.	River	Several Creeks	Countywide	Persistant rain and thunder storms caused several creeks to overflow banks and flood roads. Basement flooding in some residences.
0303200627	Guilford	ML Cyc.	River	Numerous Creeks	Countywide	Persistant rain for about 12 hours resulted in 2-4 inches of rain over wide area. Numerous creeks overflowed banks. Numerous roads flooded and closed.
0009011858	Guilford	Thdr Strm	Flash	S. Buffalo Cr	Greensboro: Highways, Ashley Creek Apts.	2-3 ft. of flooding on some highways. Roof caved in on Wal-Mart (Wendover Ave.). Ashley Creek Apts. Evacuated
0009142310	Guilford	Frnt Pass	Flash	Various	Oak Ridge in west Greensboro and other areas.	Numerous roads flooded w/ some covered by as much as 6 inches of water.

Figure 6 - Event summary for South Buffalo Creek near the Ashley Creek Apartments.

This data can be used to obtain an understanding of the weather patterns that commonly result in flooding at a certain hot spot, trends in the frequency of recent flooding, and most importantly, the location of the hot spot itself along with the surrounding area that can be affected by flooding. Figure 7 shows how this data can be used to see if any trends are visible in the recent record. It shows a graph of the number of floods per year at the South Buffalo Creek hot spot from 1993 through 2004. It should be noted that striped bars represent events for which no sufficient data has been found to accurately determine whether flooding occurred at this particular hot spot, but for which flooding in the general area of the hot spot was recorded.

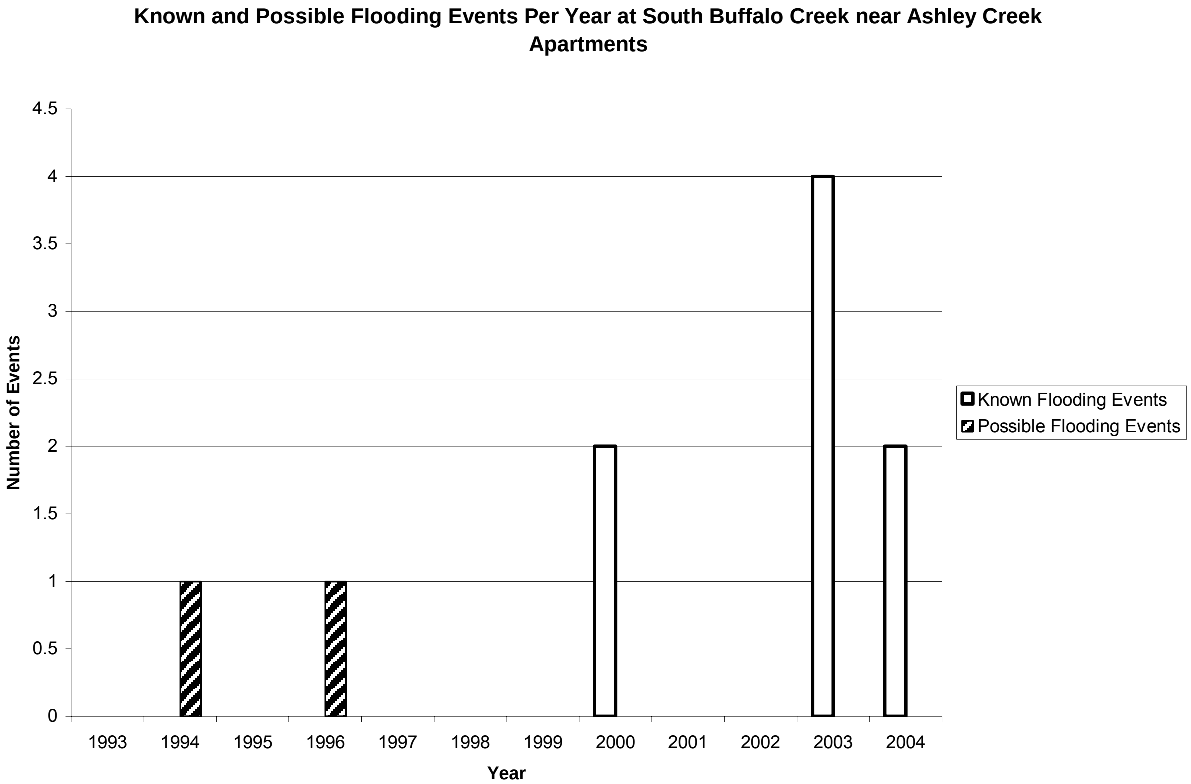

Figure 7 - Flooding Events at S. Buffalo Creek Hot Spot

As can be seen, there are too few events to determine a statistically significant trend in the frequency of flooding. However, the slight trend of increased flooding events at this location since 2000 is still somewhat valid and of use to forecasters. The reason that this trend is possibly valid despite the lack of cases is that this is a site that was visited with the local emergency managers from Guilford County. On the visit to this area of South Buffalo Creek near the Ashley Creek Apartment complex we were able to talk to local business owners and residents about their experiences with flooding in this area. We found that those interviewed reported an increase in the flooding activity and severity in the past decade, approximately. They cited the city's (Greensboro) cessation of dredging parts of the local streams as well as nearby development of roads and housing, especially upstream of this hot spot, as possible explanations for increased flooding activity. This may be useful to forecasters because a site at which flooding is influence by such factors may be more likely to flood with heavy rain beginning up stream as opposed to right near the site or it may respond more quickly to heavy rain than surrounding areas. This is an example of how the acquisition of data and information associated with hot spots, including visits to the sites, can be a possible benefit to forecasters when monitoring the threat of inland flooding.

PROOF OF CONCEPT:

The goal of this project was to provide forecasters with information on the characteristics of local flood-prone hot spots that would then lead to an improvement in their flood warning statements. On July 17, 2004, such a goal was met through the efforts of this project. During the hours just before midnight on July 17, a line of heavy rain producing thunderstorms began moving east across North Carolina and approached Guilford County and the city of Greensboro. Hot spots in Guilford County were some of the first identified and mapped, which proved to be of vital importance to forecasters at the Raleigh National Weather Service Forecast Office (RAH). They began issuing flood-warning statements for Guilford County, especially Greensboro, shortly after 11:00 pm EDT. The warning statements issued contained references to two of the more problematic hot spots identified in Guilford County, both of which are located in Greensboro. These spots were South Buffalo Creek near the Ashley Creek Apartment complex and North Buffalo Creek at Latham Park. Shortly after midnight, local law enforcement officials reported flooding in Greensboro to the National Weather Service in Raleigh. Figure 8 shows an excerpt from a warning statement issued during this event.

THE NATIONAL WEATHER SERVICE IN RALEIGH HAS ISSUED A
* FLASH FLOOD WARNING FOR... GUILFORD COUNTY IN CENTRAL NORTH CAROLINA
* UNTIL 130 AM EDT SAT. JULY 17 2004
* AT 1203 AM EDT LOCAL LAW ENFORCEMENT OFFICIALS REPORTED FLASH FLOODING IN GREENSBORO AND ALONG BUFFALO CREEK.

VERY HEAVY RAINFALL ACROSS WEST GREENSBORO WILL CAUSE SOUTH BUFFALO CREEK TO THREATEN NUMEROUS APARTMENTS IN THE ASHLEY CREEK AREA. PORTIONS OF INTERSTATE 40 REMAINED CLOSED FROM FLOODING. LOCATIONS FROM MERRITT DRIVE TO HOLDEN ROAD...PINECROFT ROAD AND HIGHWAY 29 WILL EXPERIENCE FLOODING.

FURTHER DOWNSTREAM WATER WILL CONTINUE TO RISE IN AND AROUND LATHAM PARK THREATENING SEVERAL HOMES ALONG LATHAM ROAD. ROADS ALONG THE CREEK FROM WESTOVER TERRACE TO ELM STREET COULD ALSO BECOME THREATENED BY FLOOD WATERS. INTERSTATE 40 IS COMPLETELY CLOSED FROM GALLIMORE DAIRY ROAD TO HIGHWAY 68

Figure 8 - Flood Warning Statement issued by Raleigh NWS Forecast Office on July 17, 2004.

A post-storm report cited that forecasters at the RAH forecast office were able to coordinate with Guilford County emergency officials and warn them of likely flooding along North and South Buffalo Creeks approximately an hour before flooding began to affect houses and apartments. Two of the locations affected by flooding were the Ashley Creek Apartment complex and several homes along Latham Park. The early warnings of the forecasters along with the specific identification of several of the most flood prone areas allowed emergency officials to reach these locations and begin evacuations before the flooding of the homes and apartments began. This case demonstrates how increased knowledge of these flooding hot spots allows forecasters to issue more detailed warnings with a greater lead-time, which in turn, provides the public with a greater chance to avoid the dangers of floods.

CONCLUSION/FUTURE WORK:

The goal of this aspect of the project was to provide local National Weather Service forecasters with information that would help in their task of forecasting and issuing warnings for inland flooding, both from tropical and extra-tropical events. To achieve this, locations that are more prone to flooding, referred to as "hot spots", were identified with the help of county emergency managers. The hot spots were then mapped using GIS software and were input into the Raleigh National Weather Service Forecast Office's (RAH) Flash Flood Monitoring Program (FFMP), along with descriptions of the hot spot locations. This allows forecasters to focus on monitoring the areas where flooding is more likely to occur or become significant. Thus far, 13 of the 31 counties in the RAH forecast office's Central Warning Area (CWA) have been mapped. Unfortunately, the very limited funding from COMET program ($41,000 over 12 months) was only sufficient to complete the demonstration project reported above. If additional resources are available, we can extend the work to reach our goal of mapping all 31 counties in Central North Carolina and then expend our study to East and West North Carolina.

Once the hot spots were identified, additional information including data on past flooding events and meteorological conditions associated with those events was gathered. The initial focus has been on the most significant of the hot spots that pose the greatest threat of flooding. This information could then be analyzed to see if any trends in recent flooding history or in the meteorological conditions for the events could be seen, which may aid forecasters in their flood monitoring and warning issuance. The mapping and identification of the hot spots has already proved to be a benefit to forecasters as seen in the July 17, 2004 case involving two hot spots in Greensboro, Guilford County.

With additional resources, much more work can be done to add to the scope and depth of this study, such as, identification and mapping of hot spots in the remaining counties in the CWA, getting a more detailed understanding of the meteorological conditions that result in local inland flooding, and a more in-depth analysis of select events. These analyses would focus on studying not only the synoptic conditions surrounding an event, but mesoscale conditions as well. This would be done using Rapid Update Cycle (RUC) model analyses as well as hand-analyzed surface observations. Furthermore, to provide forecasters with more concise and accurate information as to what conditions will likely trigger flooding at a particular site, hydrologic modeling of select events at certain hot spots would be performed. These sites would consist of the fore-mentioned hot spots in Greensboro, Guilford County; South Buffalo Creek near the Ashley Creek Apartment complex and North Buffalo Creek at Latham Park. The first goal is to, using GIS data, meteorological and hydrological data for past events, and the U. S. Army Corps of Engineer's Hydrologic Modeling System, accurately replicate flooding events at those sites. If successful, the next goal is to conduct sensitivity experiments testing various meteorological conditions, such as rainfall rate and amount, as well as various hydrologic conditions, such as soil moisture and initial stream height. This will hopefully add more detail and more certainty as to what conditions are most likely to trigger flooding at a location and what conditions are less likely to do so.

Due to funding limitations, these tasks are being performed on only two sites so that the work can be taken to completion and analyzed for its value and functionality to local forecasters before efforts are made to perform such work on a larger scope. Success in this ongoing work will add to the forecaster's understanding of the dynamics responsible for inland flooding, especially at the most flood prone areas. This will allow them to improve the accuracy, detail, and lead-times of flood watch and warning statements, thus providing a greater service to the public.