Primary Meteorological Aspects of Hurricanes Controlling Coastal & Inland Impacts

Steve Lyons
The Weather Channel

Despite continued widespread use of the Saffir-Simpson scale by government forecasters, Emergency Managers and much of the media to convey potential dangers from a hurricane, maximum wind speed at one spot at one moment in time does NOT usually reflect the magnitude of dangerous impacts a hurricane or tropical storm can bring to the coast and inland. The spatial distribution of strong winds and the duration of them will be addressed and contrasted with a localized wind maximum. How the size of hurricane and tropical storm winds contribute to coastal and inland impacts will be discussed and limitations of the "total kinetic energy" index of a hurricane will be outlined. Finally tropical cyclone motion, both speed and angle of attach to the coast, will be addressed relative to the magnitude of coastal and inland impacts.

Toward a U.S. Climatology of Coastal and Inland Tropical Cyclone Winds

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Over the past several years, attempts have been made to assess the relative frequency of coastal and inland counties that experience either hurricane or tropical storm force winds from a landfalling tropical cyclone. This is traditionally done by overlaying the historical track data for the Atlantic basin and implementing a symmetrical 50 km buffer around the storm to identify those counties which are influenced by the storm. This presentation will focus on a new analysis technique which employs a climatological average of the storm size during the lifecycle of the storm. The storm-size averages were determined for North Atlantic basin tropical storms and hurricanes using wind radii from the Extended Best Track dataset. The analysis methods used result in a more natural asymmetric buffer around the cyclone, which is also dependent upon storm strength. Climatological maps of the inland penetration of tropical cyclone winds based on tropical storms strength and Saffir-Simpson categories will be shown and discussed. *[Corresponding author address: Michael.Kruk@noaa.gov]*

Fatalities from wind-related tree failures during tropical cyclones in the U.S., 1995-2007

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Fallen trees and limbs are a significant hazard to human health and life during severe weather. Legal liability of tree owners for damages caused by fallen trees has been rising in the United States. The federal database Storm Data was searched for deaths due to tropical cyclones and the circumstances of the death was examined. There were 57 deaths from fallen trees caused by 15 tropical cyclones during 1995-2007, (not including deaths from Hurricane Katrina in Louisiana and Mississippi). This was 31% of all tropical cyclone deaths. Two-thirds of the deaths were male, the median age was 45 years (range 3-87 years), and deaths occurred in nearly equal numbers to people in homes (frame houses and mobile homes), in vehicles, or outdoors. The deaths occurred in 11 states from Texas to Vermont and all occurred within 200 miles of the coast. North Carolina had the most deaths with 14. Deaths occurred only in the months July through October, with a peak (58%) in September, corresponding with the tropical cyclone season in the North Atlantic. Trees are especially vulnerable to failures during the winds of tropical cyclones due to the duration winds, heavy rains that may weaken the soil strength, and the fact that deciduous trees are in full leaf during the tropical cyclone season. The risks from fallen trees described here emphasize the need to maintain trees in a healthy and structurally sound state so the risk from unhealthy or structurally unsound trees is minimized. A tree risk assessment and tree risk management program should be in place, especially in public areas such as along roads and in parks. *[Corresponding author address: tschmidl@kent.edu]*

Killer Trees: An Investigation of Tree-Related Fatalities due to High Winds associated with Tropical Cyclones since 1995

Eric Carpenter

NOAA/NWS WFO Jackson, Mississippi

On 29 August 2005, large and powerful Hurricane Katrina made landfall along the Central Gulf Coast, and then retained hurricane strength while moving northward across Central Mississippi. In the National Weather Service (NWS) Jackson, MS service area, there were 15 fatalities directly attributed to falling trees in the high winds that Katrina brought. This historic event was part of the inspiration behind an investigation into tree-related weather fatalities incurred across the nation since 1995.

In years prior to Hurricane Katrina, the author had perceived a greater frequency of tree-related weather casualties, including tragic stories of such incidents in seemingly benign weather conditions. In response to a reported increase in tree failures, the U.S. Department of Agriculture in 2003 published the first comprehensive guide for urban tree risk management, noting that the failure of limbs, or entire trees, is often predictable, detectable, and preventable. Furthermore, according to Bartlett Tree Research Laboratories in Charlotte, NC, many trees planted during the growth of suburbs after World War II are now approaching the end of their lives. The author also learned through recent correspondence with a landscape architect that clay soils in the Deep South can be harsh to the root systems of trees not planted properly, thus making them more susceptible to failure in high winds.

Initial findings from the investigation of Storm Data in 2006 indicated that weather-related tree casualties comprised about 12% of all weather-related fatalities during the period from 1995 through 2004. Outreach efforts by WFO Jackson have been made to mitigate weather-related tree danger risks in the ArkLaMiss region through call-to-action statements, information-sharing with the emergency management community, spotter training classes, and media interviews. Updates to the investigation incorporate Storm Data through 2008, with a focus on the effects of land-falling tropical cyclone winds. The results of these findings along with outreach plans will be presented. *[Corresponding author address: Eric.Carpenter@noaa.gov]*

Hurricane Ike in North Texas: Challenges at an Inland Weather Forecast Office

Jessica Schultz
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In the early morning of 13 September 2008, Hurricane Ike made landfall near Galveston, Texas. The storm traveled north during the day, bringing strong winds and heavy rainfall to parts of north Texas. Forecasting the event posed several challenges, especially with regard to the extent, magnitude, and duration of inland tropical storm- and hurricane-force winds. The Fort Worth/Dallas NWS Forecast Office used text statements, graphical Web pages, multimedia briefings, and telephone conversations to prepare emergency management officials, members of the media, and the general public for the anticipated hazardous weather. This presentation will document the challenges faced by an inland office impacted by a tropical cyclone. Community outreach and preparedness activities that were accomplished prior to Ike's passage over north Texas will also be presented. *[Corresponding author address: jessica.schultz@noaa.gov]*

A Comparison of the Inland Effects of Hurricanes Gustav and Ike across Arkansas

Lance Pyle
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Another active Atlantic tropical season was noted in 2008. A total of sixteen named tropical storms occurred during the 2008 season, eight of which achieved hurricane classification. Two of the hurricanes that made landfall at the U.S. coast, Gustav and Ike, produced substantial inland effects across much of Arkansas. Comparisons and contrasts between these two storms will be provided, along with comparisons with other tropical systems that have affected the state of Arkansas. *[Corresponding author address: lance.pyle@noaa.gov]*

Wind Damage in the Lower Ohio Valley from the Remnants of Hurricane Ike

Pat Spoden
NOAA/NWS WFO Paducah, Kentucky

On Sunday, September 14, 2008, the remnants of Hurricane Ike moved across the lower Ohio Valley. This system produced damaging wind gusts up to 68 kts over a widespread region. Although strong winds were anticipated, the actual wind gusts were 17 to 26 kts higher than those expected by forecasters.

A review of the event suggests that several factors played a role in the damaging wind storm: the dramatic change in forward motion of the storm center from 26 kts to 52 kts, the interaction of the remnants with an upper-level trough, and steep lapse rates in the lowest 100 mb of the atmosphere.

The impact of this system was quite large with an estimated cost of over $326 million just in the WFO Paducah county warning area. Numerous reports of damage and strong wind gusts were received at the National Weather Service that day. This presentation will review the path, intensity, and dynamics of the remnants of Hurricane Ike as it moved through the lower Ohio Valley along with ideas of how to forecast an event like this better in the future. *[Corresponding author address: pat.spoden@noaa.gov]*

Impacts of the 2008 Hurricane Ike windstorm in Ohio

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Hurricane Ike made landfall at Galveston, Texas, on 13 September 2008. It made the transition to an extra-tropical cyclone on 14 September as the circulation moved rapidly across the Ohio Valley and Great Lakes with wind gusts of 60-80 mph. This was the second most disruptive statewide windstorm in Ohio since 1913. The primary impacts of the storm were the result fallen trees and failures of electrical power. Private insured property losses of $553 million were the largest for a natural disaster in Ohio since the Xenia Tornado of 1974. It caused the largest electrical failure in Ohio history, with 2.5 million customers without power, about 18% of the state. Schools, businesses, and government offices were closed for one or more days. There were six deaths caused by the storm, four killed by trees, one drowned in a capsized boat, and one electrocuted. The American Red Cross opened 25 shelters and 86 feeding stations for displaced people. Hospitals used back-up generators to maintain operations after the storm and provided assistance to residents on home health care who lost electric power. Public water supply systems used generators to maintain operations but many issued 'boil alerts' or reduced water supply. Failure of several sewage treatment systems resulted in overflows into streams. Public health consequences of the storm were minimized by early warning from the NWS, good preplanning and preparedness at the county level, by moderate temperatures during the power failure, and the response of governments, the American Red Cross, charitable organizations, and private citizens. *[Corresponding author address: tschmidl@kent.edu]*

NHC's Tropical Cyclone Wind Speed Probability Products: Helping Users Make Decisions during Inland Tropical Cyclone Wind Events

Michael J. Brennan

NOAA/NWS/NCEP National Hurricane Center

The impact of inland high winds for landfalling tropical cyclones (TCs) will be discussed. The NHC tropical cyclone wind speed probability products, which are designed to assist users in decision making for TC wind events will be described in detail. These products are based on the NHC official forecast for a given TC as well as historical NHC forecast errors and climatological information on the TC wind field. Examples of the probability products and their use will be presented for historical inland wind cases, including Hugo (1989). Physical processes that determine the distribution of high winds in inland TCs will also be discussed. *[Corresponding author address: Michael.J.Brennan@noaa.gov]*

Employing Probabilities to Convey Forecast Uncertainty and Potential Impact through NWS Field Office Forecast Products

Dan Gregoria

NOAA/NWS WFO Miami, Florida

As tropical cyclone events unfold, decision-makers require a meteorologist's most likely wind speed forecast, along with an accompanying expression of uncertainty. Both are necessary to effectively manage preparations for life-threatening weather events. The inherent uncertainty in tropical cyclone forecasts reveals the limitation of deterministic-only wind speed forecasts such as those found within the legacy Zone Forecast Product and Coastal Waters Forecast issued by National Weather Service (NWS) Weather Forecast Offices (WFOs). To address this limitation, WFOs Miami (MFL) and Melbourne (MLB) have developed a means to consistently and coherently incorporate uncertainty information in these text products through the creative use of the National Hurricane Center's incremental wind speed probabilities. This paper will present a summary of this project and current status. Additionally, a brief description on the use of both deterministic and probabilistic data to create WFO scale Tropical Impact Graphics for the Wind, Inland Flooding, Coastal Flooding or Surge, and Tornado Hazards associated with Tropical Cyclones will be presented. This is part of an initiative led by the National Tropical Impact Graphics Team of which WFOs MFL and MLB are a crucial component. *[Corresponding author address: Dan.Gregoria@noaa.gov]*

Assessing hurricane risk for southern forests

Scott Goodrick and John Stanturf
US Forest Service

In the southeastern United States, forests are subject to a variety of damage-causing wind phenomena that range in scales from very localized (downbursts and tornados) to broad spatial scales (hurricanes). Incorporating the threat of wind damage into forest management plans requires tools capable of assessing risk across this range of scales. Our conceptual assessment approach involves breaking the risk down into components of event risk and resource vulnerability. Event risk can be simply stated as the probability of an event of a certain magnitude occurring in a given area and can be evaluated based on climatology. For wind related threats, resource vulnerability is determined by a complex function of forest stand and site characteristics. The GALES model is used to assess the potential for hurricane winds to damage managed stands of loblolly and longleaf pine (Pinus taeda and P. palustris) on a 20 year rotation. Based on the modeling results, recommended management strategies will be discussed that may mitigate the risk of hurricane damage. *[Corresponding author address: sgoodrick@fs.fed.us]*

Coastal and Inland Perception of Meteorological Threats from Hurricane Gustav

Jason C. Senkbeil
University of Alabama

Many coastal and inland residents may become confused by the discrepancies between expected tropical cyclone intensity and observed tropical cyclone intensity in the aftermath of a land-falling storm. Often the expected (forecasted) intensity outweighs the observed intensity or vice versa. Much of the explanation in observed damage discrepancy may be attributed to the individual's perceived storm track versus the actual storm track as it applies to their location. Furthermore, the individual may perceive one aspect of a land-falling tropical cyclone to be more hazardous than another at their location when in fact it is not. In this study, coastal and inland evacuees from the path of Hurricane Gustav were surveyed 48 - 20 hours prior to landfall to determine where they anticipated the storm to make landfall, and which meteorological variables would be the most hazardous at their residences. Three regions, Greater New Orleans, Houma, and Lafayette were represented most frequently as determined by zip code data collected from the surveys. In order to assess the discrepancies between perceived and actual storm track, we propose a Cry Wolf Index (CWI) as expressed by a Z score measuring perceived vs actual landfall distance in each region. For storm hazards, we established ratios which measured the importance of one type of storm hazard versus another within each region. Results indicate a personal landfall bias in the direction of each survey participant's home zip code. The greater New Orleans area displayed the highest mean CWI score at 3.3, followed by greater Lafayette at -1.4, and Houma at 0.9. Greater New Orleans residents were primarily concerned about storm surge while residents of Houma and Lafayette were more concerned about storm size, tornadoes, and heavy rain. The results from Hurricane Gustav provide valuable insight into the perceived threats of the public across the coastal to inland transition. Future research will focus on areas that are more or less frequently impacted by tropical systems. *[Corresponding author address: jcsenkbeil@bama.ua.edu]*

The Effects of Hurricane Frances on North and Central Georgia: Part I - Impacts

Robert Beasley and M. Sean Ryan
NOAA/NWS WFO Peachtree City, Georgia

Land falling tropical storms and hurricanes are no stranger to north and central Georgia. Almost annually the area feels at least some impact from such tropical systems, especially during the summer and early fall period from mid-August to early October. With the exception of 2006 and 2007, at least one tropical storm or hurricane impacted the region during the 5-year period of 2003-2008. Most of these systems tracked across the Gulf of Mexico before reaching Georgia. Depending on the exact track, intensity, and size of these systems, they often bring devastating high winds, flooding, and/or tornadoes causing millions in damages and occasionally injuries and loss of lives. The 2004 and 2005 tropical seasons were extraordinarily active. Three major hurricanes (Frances, Ivan, and Jeanne) tracked across north and central Georgia all within a 20-day time frame during September 2004. In 2005, two major hurricanes (Dennis and Katrina) and two tropical storms (Cindy and Tammy) impacted the region between July and October. In 2008, tropical storm Fay caused flash flooding and several tornadoes to north and central Georgia. Extensive damages were suffered as a result of each of these systems within the Peachtree City, GA (WFO FFC) forecast area.

Each of these tropical systems impacted different parts of the forecast area and in different ways. Hurricanes Ivan, Jeanne, and Dennis brought widespread, and in some cases, catastrophic flooding to many areas of North Georgia. Hurricane Katrina, along with tropical storms Cindy and Fay, brought numerous tornadoes to the area. A new daily and monthly record number of tornadoes for WFO FFC was set during Hurricane Katrina. But it was Hurricane Frances, which moved across the area September 6-7,2004, that brought the strongest and longest sustained period of tropical storm force winds to the region that had been observed since Hurricane Opal in October 1995. A three to four hour period of 40 to 50 mph winds accompanied an east-west oriented rain band through central and north Georgia around midnight on the 6th. Hundreds of trees and many power lines were downed in more than three dozen counties across north central, central, and east central Georgia. Many homes sustained significant damage. Resultant damages totaled nearly $30M. Consequently, 41 of the 96 counties within the WFO FFC forecast area received a disaster declaration from the Federal Emergency Management Agency (FEMA). *[Corresponding author address: Robert.Beasley@noaa.gov]*

The Effects of Hurricane Frances on North and Central Georgia: Part II - Meteorological Analysis

M. Sean Ryan and Robert Beasley
NOAA/NWS WFO Peachtree City, Georgia

The weakened remains of Hurricane Frances moved across Georgia beginning late on September 6 and continued through September 8, 2008. Remnants of tropical cyclones affect Georgia almost every year. Frances was unique in that the storm produced widespread wind damage across central and portions of northern Georgia. As Frances moved across north and central Georgia, wind gusts in excess of 50 mph were measured at several locations, with sustained winds in excess of 40 mph. The highest winds were concentrated in a single band of intense convection north of the center of circulation. The tropical storm force winds in this rain band were likely enhanced due to a significant pressure gradient that developed between the low pressure center of Frances and a strong 1026 mb surface high centered just off the coast of New England. This presentation examines several possible causes for the intense convective band and strong winds that accompanied Frances across north and central Georgia, including the strong pressure gradient and the effects of a possible "wedge front" associated with cold air damming prior to the arrival of Frances. *[Corresponding author address: Michael.S.Ryan@noaa.gov]*

Surface Observations of Landfalling Rainbands in Tropical Storm Hanna (2008)

Matthew D. Eastin
University of North Carolina at Charlotte

Tropical cyclone rainbands often produce severe winds, heavy precipitation, local flooding, and numerous weak tornadoes as they move onshore and inland, resulting in considerable property damage and multiple fatalities. Recent studies have suggested that the more severe rainbands are often located adjacent to mid- and low-level dry air intrusions, which promote the development of strong convective downdrafts and surface cold pools. Such cold pools are believed to play a significant role in not only rainband evolution, but also in the evolution and intensity of their parent tropical cyclone. Hence a better understanding of the kinematics, dynamics, and thermodynamics of tropical cyclone rainbands within landfalling rainbands would benefit forecasters and society.

The objective of this study is to document the mesoscale structure and evolution of several convective rainbands, and their surface cold pools, as they move onshore during the landfall of Tropical Storm Hanna (2008). The study uses data from a unique surface "mesonet" deployed between Myrtle Beach (SC) and Wilmington (NC) during the 2008 season. The mesonet consists of eight temporary surface weather stations and two standard ASOS sites. These data are combined with regional soundings, satellite, and WSR-88D radar data to document the structure and evolution of two landfalling convective rainbands adjacent to mid-level dry air intrusions. Preliminary results indicate that the passage of both rainbands over the mesonet produced significant wind gusts, wind shifts, and temperature decreases, implying the presence of surface cold pools. However, the strength of each cold pool was highly variable along each band and in time. A synopsis of the rainband and cold pool observations, as well as some speculation regarding their implications, will be presented at the conference. *[Corresponding author address: mdeastin@uncc.edu]*

Tropical Storm Erin Re-intensifies over Oklahoma

Patrick Burke
NOAA/NWS WFO Norman, Oklahoma

The remnants of Tropical Storm Erin underwent rapid intensification over central Oklahoma on the morning of August 19, 2007. Despite being located more than 500 miles inland, the cyclone developed seemingly warm core profiles of pressure, wind, and precipitation. Deep moist convection around the center increased in coverage and intensity, yielding measured rainfall rates between 2 and 3 inches per hour. Radar imagery depicted a well defined eye and spiral bands for several hours. The storm produced catastrophic damage and six flooding-related fatalities. There have been few examples of warm core cyclones developing or strengthening outside the tropics, and no known examples over land. We believe the events of 19 August, 2007, represent a yet undocumented means of warm core cyclone re-intensification. *[Corresponding author address: patrick.burke@noaa.gov]*

A Comparison of the Inland Impacts of Tropical Storm Fay (2008) and Hurricane Dora (1964)

Michael A. Jamski[1], Richard J. Lanier[1], Richard J. Verdi[2]
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Both Tropical Storm Fay and Hurricane Dora generated extreme inland rainfalls with similar tracks across northern Florida. Some of the similarities between the two systems were: moist maritime tropical air mass; landfalls along the Florida Northeast coast of Florida followed by an inland recurvature over the southeast United States; extremely slow movement over land; asymmetric pattern of rainfalls; extreme rainfalls in the Florida Big Bend and Suwannee River Basin; role of moisture flows from the Atlantic Ocean and Gulf of Mexico in the heavy rainfall production; widespread flooding; and an area of low rainfall in north central Florida near the storm centers. Some of the differences between the two systems were: Originating track across the Atlantic, phase of the El Niño/Southern Oscillation, wind strength, wind damage, storm surge and coastal flooding, greater number of flood-related deaths due to Fay; and absence of reported tornadoes during Dora.

This presentation will also address some of the forecasting challenges associated with Tropical Storm Fay and how similarities with Hurricane Dora aided the warning decision processes at the Weather Forecast Office in Tallahassee, Florida. Lessons learned will also be discussed. *[Corresponding author address: Michael A. Jamski, National Weather Service, Love Building, Florida State University, Tallahassee, FL 32306-4509; Mike.Jamski@noaa.gov]*

About CLIQR: A climatological aide to tropical cyclone rainfall forecasting

David Roth
NOAA/NWS Hydrometeorological Prediction Center

Tropical cyclone rainfall forecasting has historically seen significant challenges, both at the local and national level. In particular, old rules of thumb concerning tropical cyclone maxima forecasting have been hit or miss. Starting in 1999, and progressing in earnest in 2003, the Hydrometeorological Prediction Center has been developing an exhaustive storm-by-storm tropical cyclone rainfall climatology to help forecasters find suitable analogs to an ongoing event. Initial steps at developing a comprehensive set of web pages was not deemed user-friendly enough by users of the database. Thus, in 2008, a set of perl scripts and an in-house GUI were developed to help determine the best historical match to an ongoing tropical disturbance/tropical cyclone, using the CHGHUR/Tropical cyclone objective guidance messages as a guide for its initial input, which became available at HPC and online in July 2008. This output is also available on the HPC website during the hurricane season, on an experimental basis. The presentation will cover the databases which have been developed for use with these scripts, and future plans to help it become even more useful to end users. *[Corresponding author address: David.Roth@noaa.gov]*

Quantifying the contribution of tropical cyclones to extreme rainfall along the coastal southeastern United States

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Analysis of a unique satellite precipitation dataset coupled with an extensive database of storm tracks are used to develop a parameter called the ''millimeter-day (MD).'' MD analysis in 4 mini-basins near coastal southeastern United States reveals that September and October account for the largest number of extreme rainfall days (e.g. ''wet millimeter-days'' or MD > 0) during the 1998-2006 Atlantic hurricane seasons. Tropical cyclone (TC) days are more likely to produce ''wet millimeter days'' than non-TC days, and category 3-5 hurricane days (e.g., major hurricanes) produce the wet millimeter-days of largest magnitude. Major hurricanes produce the most extreme rainfall days, but tropical depression/storm days contribute most significantly to cumulative seasonal rainfall (8-17%, basin-dependent) due to frequency of occurrence. Thus, the influence of major hurricanes on rainfall may be most apparent in extreme daily events while weaker storms may be more critical for assessing trends in cumulative seasonal rainfall. *[Corresponding author address: marshgeo@uga.edu]*

A GIS-based analysis of the post-landfall shape properties of tropical cyclone rain fields

Dr. Corene Matyas
University of Florida, Dept. of Geography

The rainfall produced by tropical cyclones (TCs) can cause flooding both near to and hundreds of kilometers from the point of landfall. As convective rainfall may occur both near the storm center and at the periphery of the storm, identifying where heavy rainfall develops within the TC and tracking changes in the shapes of these regions may aid rainfall forecasts. This study performs a spatial analysis of radar reflectivity data to quantify the shapes and positions of convective rainfall regions within TCs making landfall within the U.S. during 1996-2007. A Geographic Information System (GIS) is first utilized to convert the radar data into polygons representing the rain fields. The GIS is then used to determine the locations of these centroids relative to the circulation centers of the TCs, and to calculate metrics that characterize the polygon shapes. These attributes are then related to environmental conditions such as vertical wind shear and relative humidity, storm intensity and motion, and interaction with topography. Determining the extent to which the physical environment affects the development of convection within landfalling TCs could help to identify areas that may receive heavy rainfall relative to the storm's track as it moves inland. *[Corresponding author address: matyas@ufl.edu]*

New Satellite-Derived Tools for Inland Rainfall Impacts from Tropical Cyclones

Sheldon Kusselson[1], Michael Turk[1], Limin Zhao[1], Stanley Kidder[2], John Forsythe[2], Andrew Jones[2], and Elizabeth E. Ebert[3]
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To improve the analysis and forecast of inland rainfall impacts from tropical cyclones, two satellite/remote sensing products are available. Operational blended Total Precipitable Water (TPW) products produced from polar orbiting microwave sensors, ground-based GPS and geostationary satellite sounders are available to use with other meteorological information to help improve the analysis and forecasts of heavy precipitation and flooding from landfalling tropical cyclones. Another product, Tropical Rainfall Potential (TRaP) has been generated operationally by NOAA/NESDIS since the mid-1980s and was improved upon earlier this decade with automation and the use of more reliable rain information from microwave sensors aboard polar-orbiting satellites. In the future, the process will be advanced by combining all single pass TRaPs generated within 3 hours of 00Z, 06Z, 12Z and 18Z to form a poor-man's ensemble, called e-TRaP. Experimental deterministic and probabilistic results will be shown from some recent United States landfalling tropical cyclones. Future improvements for the next decade will also be talked about. *[Corresponding author address: Sheldon.Kusselson@noaa.gov]*

Effects of Dry Air Ridging on Precipitation in Tropical Storm Hanna

Barrett Smith and Jonathan Blaes
NOAA/NWS WFO Raleigh, North Carolina

The distribution of precipitation associated with tropical cyclones remains a critical forecast problem. Heavy precipitation can lead to fresh water flooding which has been shown to be the greatest threat to human life associated with tropical cyclones. The distribution of heavy precipitation from land-falling tropical cyclones is dependent on several factors, including storm motion, intensity, areal extent, synoptic scale forcing, topographical characteristics, and boundaries. Of these factors, the combined role of topography and low-level boundaries can be uniquely significant to rainfall distribution over central North Carolina. Tropical Storm Hanna made landfall on just after midnight on September 6, 2008 and encountered a dry air ridge over the Mid-Atlantic States. It is hypothesized that precipitation falling into this dry air ridge created an in-situ stable layer through evaporative cooling and a resultant low-level boundary that enhanced precipitation. Simulations are conducted using the Weather Research and Forecasting (WRF) Model to test the response of rainfall location and amount to the presence and absence of the boundary. *[Corresponding author address: barrett.smith@noaa.gov]*

A Study of Predecessor Rainfall Events (PRE) in Advance of Tropical Cyclones

Michael L. Jurewicz, Sr.[1], Matthew Cote[2], Lance Bosart[2], and Daniel Keyser[2]
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PRE are defined as concentrated areas of heavy rainfall observed well downstream from landfalling tropical cyclones, or their extratropical remnants. Although the areas of precipitation associated with PRE are separate from the primary rainfall shields of tropical systems, they are indirectly linked to the existence of these tropical cyclones.

One of the primary foci of the meteorological community in recent years has been on adverse conditions directly associated with tropical cyclones. As a result, it can be easy for operational forecasters to divert their attention away from areas where PRE may form. Thus, PRE have been unexpected phenomena at times, particularly as far as rainfall magnitude is concerned. In some cases, PRE have produced tremendous rainfall, with accompanied severe flooding and loss of life. As a result, the main goals of this study are to raise awareness of PRE, establish a climatology of their occurrence, and provide useful forecasting tools to better anticipate their development.

Numerous data archives were investigated, in order to establish a relative frequency of PRE, whenever a tropical cyclone approached the U.S. coastline and/or made landfall. A database of PRE and their associated tropical cyclones was created, covering nine full Atlantic Basin tropical seasons, from 1998 through 2006.

Individual PRE from the above mentioned database were studied so that atmospheric elements common to their occurrence, as well as temporal and spatial distances from tropical cyclone centers, could be identified. Results to date indicate that locations which are downstream from the tropical cyclone itself, on the leading edge of a poleward advancing tropical moisture plume, and underneath the entrance region of an upper-tropospheric jet streak, are most susceptible to PRE development. Since PRE do not occur every time a tropical cyclone impacts the

United States, a number of null cases were analyzed as well. The most discriminating factors keyed on the position of the mean mid-tropospheric trough axis, and also the overall amplitude of the flow pattern north of the tropical system.

Possible future work includes an expansion of the database, both in time and areal extent. Also, investigating the role that tropical cyclones play in modulating jet strengths and conditioning the large-scale environment, to perhaps increase the likelihood of PRE formation. *[Corresponding author address: Michael.Jurewicz@noaa.gov]*

An Overview of Predecessor Heavy Rain Events Associated with Landfalling Tropical Cyclones

Lance F. Bosart and Thomas J. Galarneau, Jr.
University at Albany/SUNY

Predecessor heavy rain events (PREs), defined as rainstorms producing at least 100 mm in 24 h that occur well in advance of landfalling and recurving tropical cyclones (TCs), represent a significant forecast and scientific challenge. A previous climatological study identified 47 PREs associated with 21 TCs over the eastern part of the United States between 1998 and 2006. Roughly one third of all landfalling and recurving TCs in the eastern United States were associated with PREs. An important forecast challenge posed by PREs is the threat of significant inland flooding. The typical PRE occurs approximately ~1000 km in advance of the TC, leads the TC by ~36 h, and lasts for ~12 h.

The purpose of this presentation is to give an overview of PREs and the environmental factors that control their formation and evolution. This task will be accomplished by means of climatological, composite and case study analyses. Examples of noteworthy PREs associated with Erin (2007) and Ike (2008) that occurred over the upper Midwest, and from Texas to the western Great Lakes, respectively, will be used to illustrate environmental conditions supportive of PREs. Likewise, environments not conducive to PRE formation, of which Hanna (2008) is an example, will also be illustrated. *[Corresponding author address: bosart@atmos.albany.edu]*

A Comparison of Significant Predecessor Rain Events Associated with Tropical Cyclone Rita (2005) and Tropical Cyclone Erin (2007)

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Predecessor rain events (PREs) are distinct mesoscale regions of heavy rainfall that develop approximately 1000 km poleward and eastward of landfalling and recurving tropical cyclones (TCs) and approximately 24–36 h before the passage of the main rain shield of the TC. PREs develop as a continuous poleward stream of deep, tropical moisture emanating from the TC encounters a region of atmospheric lifting to produce heavy, prolonged rainfall. PREs present a forecast challenge because they have the potential to cause significant inland flooding, given that they are usually characterized by large rainfall totals (>100 mm in 24 h).

While most PREs exhibit similar synoptic-scale characteristics (e.g., anomalously high precipitable water values, formation in an equatorward jet entrance region), these events can vary greatly in structure, intensity, and longevity. Two upper Midwest PREs, associated with TC Rita (2005) and TC Erin (2007), respectively, were exceptionally high-impact events, both persisting for over 36 h and producing widespread heavy rainfall totals (~200–250 mm). While these two PREs developed within different synoptic-scale environments, and their parent TCs differed both in track and intensity, they were similar in strength, longevity, mesoscale organization, spatial extent, and translation speed.

The purpose of this presentation is to establish key similarities and differences in the synoptic-scale environments for the respective PREs associated with TC Rita and TC Erin in order to document two distinct scenarios favorable for the development of high-impact PREs. This objective will be accomplished by: (1) illustrating the role of the TCs in contributing to the poleward supply of deep tropical moisture to the regions of their respective PREs, and (2) assessing how each TC influences and interacts with the upper- and lower-tropospheric flow to facilitate the development of quasi-stationary heavy rain events. *[Corresponding author address: bm453975@albany.edu]*

Hydrologic Impacts from Inland-Moving Tropical Systems: From Welcome Rainfall to Devastating Floods

J. John Feldt
NOAA/NWS Southeast River Forecast Center

Many parts of the Southeast U.S. depend upon inland-moving tropical systems for the annual replenishment of soil moisture, the recharge of rivers and reservoirs, and for the overall health of coastal estuaries. However, tropical systems can also result in devastating flooding, leading to significant property damage and loss of life.

This presentation will describe the spectrum of hydrologic impacts – from the beneficial annual recharge of water resources to the high risk of extreme flooding. Key meteorological and hydrologic assessment and analysis techniques will be described. A hydrologic risk assessment for the 2009 tropical season will be included. *[Corresponding author address: John.Feldt@noaa.gov]*

The RMS TC-Rain Model

Juergen Grieser, Steve Jewson, Dag Lohmann
Risk Management Solutions Ltd. (RMS)

Tropical cyclones (TC) threaten human lives and property due to strong winds and storm surge near the coast and torrential rains inland. The strongest ever observed rains on the 12 hour to 15 day timescale result from land-falling tropical cyclones. This rain can cause widespread flooding and landslides: the rain-driven floods from tropical cyclone Allison (2001) caused damages of several billion US dollars even though the wind speed did not reach hurricane strength.

Risk Management Solutions Ltd. (RMS) is a private company that specializes in providing estimates of natural hazard risk to the insurance industry. In order to estimate the flood risk due to inland rain from tropical cyclones RMS has developed a tropical cyclone rain model based on stochastic storm tracks, parameterized thermodynamic and cloud microphysical processes and observed rain data. This presentation describes this model (the `TC-Rain model') and discusses its performance.

The TC-Rain model takes a number of physical mechanisms into account, including (a) the effect of surface roughness change at land fall, (b) orographic rain enhancement, (c) drift of rain due to strong horizontal winds, (d) asymmetry, (e) outer rain bands and (f) the dependence on sea surface temperature. It has been calibrated using 35 US-landfalling tropical cyclones from 1998 to the 2007, and verified against all US-landfalling TCs since 1948.

Based on an event set of simulated TC tracks the model allows the calculation of several hundred thousand TC rain footprints which can then be used for the estimation of flood levels and their return periods via a complex dynamical hydrological model.

The model is not designed as a forecasting tool, but rather a tool for risk assessment. Nevertheless using the model to make forecasts can provide a useful test, and we describe the results of such a test from the 2008 US TC season.

Since the RMS TC-Rain Model is generic and physically based, it can be applied to other regions of the world with only minor changes in order to meet local and regional conditions. Furthermore since it is based on physics it also allows for sensitivity analyses such as estimating the impact of climate change (via sea surface temperature rise) on tropical cyclone rain. *[Corresponding author address: juergen.grieser@rms.com]*

Improved Areal Precipitation Estimates for Tropical Storm Fay Due to Community Collaborative Rain, Hail and Snow Network Observations

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Tropical Storm Fay brought record-breaking rain to portions of Florida, Georgia and Alabama during its ten-day passage over the southeast United States from August 19 through 28, 2008. Of the 337 storm total rainfall reports referenced by the National Weather Service's Tallahassee, Melbourne and Tampa offices in their storm summaries, 125 (37%) were observations from the Community Collaborative Rain, Hail and Snow Network (CoCoRaHS). Satellite precipitation estimates depicted maximum storm totals of 300 millimeters (11.81 inches) of rain over Florida. Radar estimated precipitation storm totals had a maximum of 635 millimeters (25 inches). During that same period, Florida CoCoRaHS observers reported as much as 685 millimeters (26.96 inches). This study demonstrates that CoCoRaHS observations led to improved areal precipitation estimates for Tropical Storm Fay by complimenting existing precipitation estimation methods. *[Corresponding author address: Christine.Mcgehee@noaa.gov]*

Tropical Cyclone Hydrologic Forecast Tools at the Lower Mississippi River Forecast Center

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Hurricanes and tropical storms cause significant river flooding within the NWS Lower Mississippi River Forecast Center (RFC) hydrologic service area. The RFC currently provides routine and flood forecasts for 223 gage sites, all of which are susceptible to flooding rains from tropical systems. About 30 gage sites may also be directly impacted by storm surge. Throughout the years the RFC has developed a set of forecast tools including hydrologic/hydraulic models, customized scripts and data archives to help forecast these events, and to provide scenario-based guidance.

The RFC currently has operational hydraulic models for the Lower Mississippi and Vermilion Rivers in Louisiana, with the capability to use an elevation hydrograph from the Sea, Lake, and Overland Surge Heights (SLOSH) model issued by the Tropical Prediction Center. Another hydraulic model is under development for the lower Pascagoula River in Southern Mississippi. Each of these hydraulic models can also be run with the Extratropical Water Level forecast produced by the NWS Meteorological Development Laboratory. Scripts have been written to automate the formatting and ingest of these boundary conditions into the models.

Scenario-based forecasts can be run at any time on the Lower Mississippi River model using any one of over 1640 SLOSH elevation hydrographs developed for West Pointe A La Hache, Louisiana, based on storm direction, intensity, speed and distance to the left or right of New Orleans. Scripts have been written to merge National Ocean Service astronomical tide forecasts with the Extratropical Water Level forecast as a run-time modification in other coastal forecast locations where hydraulic models do not exist. In these locations the SLOSH model output is used qualitatively, as well as a forecast tool.

For all sites, coastal and inland, the RFC uses archived precipitation and gage heights as forecast aids. Geographic Information System graphics, depicting the storm track with storm total rainfall or mean areal precipitation by RFC forecast basin, have been created for all named storms that affected the area between 1970 and 2000. An interactive site on the NWS Southern Region Intranet enables users to view these data by selecting a storm by its attributes, such as direction of motion, speed, intensity, month, state, or storm name. Archived storm tracks, radar and gage precipitation amounts, satellite and radar imagery, and stage hydrographs are also available on the regional Intranet for use as forecast aids for current storms. *[Corresponding author address: David.Welch@noaa.gov]*

An Analysis of Past River Flooding at Select National Weather Service River Forecast Locations in Florida

Jeff C. Dobur
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Flooding has been a considerable part of Florida's long history of natural disasters. As recent as August 2008, Tropical Storm Fay produced major to record flooding along sections of the St. Johns River. As in Fay, tropical systems have played a large role in many of the widespread river flood events in Florida.
The National Weather Service issues river forecasts and warnings for over fifty river gage locations in Florida. The purpose in issuing these warnings is to call people to action so that lives will be protected and property will be saved. Five-day forecasts are made on a daily basis for several of these gages while others are event-driven issuances. Flood stages at these locations are set by the National Weather Service in coordination with local emergency management officials and are based on flooding impacts at different stages. A three-tier categorical system of "minor", "moderate" and "major" is used to define the impact of river flooding at certain heights of the river. The National Weather Service defines "Significant Flooding" as river levels exceeding the moderate flood category.

In this study, daily peak flows are estimated using United States Geologic Survey daily mean flow data at select Florida river forecast points from 1975 to 2006. This peak flow was compared to flood flow and "significant" flood flow based on the latest rating curves and latest flood stages as of February 2009. A historical examination of river floods is made to determine seasonality and geographic distribution of river floods in Florida. *[Corresponding author address: Jeff C. Dobur, National Oceanic and Atmospheric Administration, Southeast River Forecast Center, 4 Falcon Drive, Peachtree City, GA 30269, Jeffrey.Dobur@noaa.gov]*

An Analysis of the Hydrologic and Hydraulic Factors during Flooding on the St. Johns River Caused by Tropical Storm Fay, August 2008

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Tropical Storm Fay spent the period August 19-23, 2008 in and near the St. Johns River basin of Florida. As it passed, Fay dumped 16 inches or more of rainfall in parts of the basin. Record river flooding was experienced near Geneva. Major flooding was experienced at several points downstream with some tributaries of the St. Johns River reaching record flooding. This study will investigate the flood event and how the many various physical processes affected the rising flood waters. The behavior of the river is unusual due to its extremely flat slope. The river stage and discharge are poorly correlated, exhibiting an unusual progression of events as the flood wave moved downriver. Winds exerting friction on the broad water surface caused additional rises over and above rises due to rainfall. *[Corresponding author address: E. Wylie Quillian, NOAA-NWS - Southeast River Forecast Center, 4 Falcon Drive Peachtree City Georgia 30269, Wylie.Quillian@noaa.gov]*

Installing Streamgages in Flash Flood Prone Areas: A Success Story

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Flash flooding continues to be a major concern in Georgia, especially in the mountainous terrain of the state and in the urbanized areas of Atlanta, Athens and numerous other growing cities. The threat to property and potential loss of life becomes a greater risk each year as more land is developed for commercial and residential use. The increasing impervious surfaces and encroachment on the flood plains increase the runoff of heavy rain events into streams, creeks and smaller rivers that were never designed to handle that volume of water. This trend will continue in the future.

In June 2006, a meeting was held between the U.S. Geological Survey, the National Weather Service and the Georgia Emergency Management Association. County EMA Directors in north and central Georgia indicated there were chronic flooding problems in portions of their counties. The current hydrologic monitoring network was not dense enough to observe and record all of these flooding problems.

This study will show how this multi-agency partnership was successful by installing stream and precipitation gages in flash flood prone areas of north Georgia in 2007. The new gages became part of the USGS Real-Time Hydrologic

Monitoring Network and were vital to the National Weather Service's mission by improving flash flood warning services during Tropical Depression Fay in August 2008.

These gages not only provided stage height readings which confirmed significant rises and flooding on Big Creek and Hiwassee River, but also provided one hour precipitation data used for mean areal precipitation analysis. The precipitation data was used to compare with the uncorrected radar precipitation estimates and derived a one hour bias value which was then used to create bias corrected precipitation amounts.

These bias corrected amounts were more accurate in determining how much and where precipitation had reached the ground and its potential hydrologic impact. They improved the precipitation analysis in the Flash Flood Monitoring and Prediction Program (FFMP) which was used by hydrometeorologists in the decision process for issuing flash flood warnings. The end result was increased lead time so action to save life and property could be taken by the public. *[Corresponding author address: Kent.Frantz@noaa.gov]*

Beyond Peeks Creek…Lessons Learned From the Landslides of September 2004

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In September 2004, rain from the remnants of Hurricanes Frances and Ivan triggered at least 155 landslides across the Blue Ridge Mountains of North Carolina. At least 33 debris flows occurred in Macon County alone, causing 5 deaths, destroying 16 homes, and damaging infrastructure. A possible trigger for the deadly Peeks Creek debris flow was a spiral rain band within the remnant circulation of Ivan that moved across the area with short duration rainfall rates of 150–230 mm/h. Research has shown that rainfall amounts exceeding 125 mm in a 24 hour period are sufficient to cause landslides across the mountains of western North Carolina, particularly on slopes modified by human activity. As a result of the Peeks Creek debris flow, a partnership formed between the National Weather Service (NWS) Greenville-Spartanburg (GSP) and the North Carolina Geologic Survey (NCGS) to increase landslide awareness and to improve short-range landslide prediction and dissemination. Since September 2004, the NCGS has issued landslide advisories, based on NWS quantitative precipitation forecasts, which are included in NWS Flood Watch and Flood Warning products issued by GSP after coordination between the agencies. *[Corresponding author address: pat.moore@noaa.gov]*

Tropical Cyclone Tornadoes: Past, Present, and Future

Bart Hagemeyer
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Tornadoes associated with tropical cyclones are a significant threat to life and property for inland areas, often well before the center makes landfall. A review of the history of tropical cyclone tornadoes, their characteristics, and prediction will be presented. Future challenges to improving prediction and preparedness will also be discussed. *[Corresponding author address: bart.hagemeyer@noaa.gov]*

A Climatology and Potential Precursors of Tornadoes Associated with Tropical Cyclones Across the U.S. Mid-Atlantic Region

Jim Hudgins
NOAA/NWS Blacksburg, Virginia

Tropical cyclones that affect the Atlantic Seaboard as well as the Gulf of Mexico often produce tornadoes along their paths across parts of the eastern U.S as their remnants curve northward and northeastward. These tornadoes have been observed in most instances as the storm system initially makes landfall, and then again when the remnants interact with other synoptic or mesoscale features such as the land/sea breeze.

Data from tornado producing tropical cyclones were gathered from 1950-2008 with the focus across six states including the Virginias, Carolinas, Tennessee, and Maryland. Over 500 tornado events were examined in order to better understand the climatology of tropical cyclones that produced tornadoes, including the likely causative factors associated with each. Many of the tropical systems studied tended to only result in a few known tornadoes during their lifetime, while several stronger (Category 2, 3 or 4) cyclones at landfall produced widespread tornado outbreaks. Although a clustering of tornadoes was seen in several cases, many of these could be classified as weaker EF0 or EF1 tornadoes, with only about fifteen percent being EF2 and stronger tornadoes. Most of the stronger tornadic events appear to be linked to tropical systems that originally made landfall as a hurricane, especially those that came inland along the Gulf Coast or along the east coast of Florida. Some of the larger and more damaging tornado outbreaks could be classified as "exit" tornadoes, in which the residual tropical system soon emerged back over the ocean as a tropical or non-tropical entity after spending at least twelve hours over land (Edwards 1998).

An additional component of this study focuses on external atmospheric features that may have enhanced the potential for the tropical cyclone to produce tornadoes after moving inland. One of the most common features was the presence of a residual frontal boundary. It is hypothesized that these boundaries helped increase low level helicity, especially along and to the right of the track of the residual storm center in the favored northeastern quadrant, as shown by Curtis and others. Mid-level dry air intrusions were also seen as a large contributor to tornadogenesis, especially when the right front quadrant coincided with relative humidity gradients at the 700 mb or 500 mb levels. This dry air appeared to have been associated with jet energy impinging from the west, or under residual upper level ridging to the east or northeast of the track of the tropical system. This drying aloft likely enhanced the tornado potential by generation of potential instability through increased solar surface heating. Timing of the tornado occurrences varied from late night or early morning across the coastal areas, likely aided by land breeze or coastal front interaction, to more of an afternoon or evening scenario farther inland, as supported by instability from heating. Other factors including theta-e and the lifting condensation level (LCL) were also examined. The larger tornado outbreaks were observed in areas of 850 mb theta-e ridging and associated with values of 340K or higher.

Results of this study will aid forecasters in assessing the potential for tornadoes with various landfalling tropical systems affecting the region, and provide a better understanding of which may be more likely to produce the larger tornadic outbreaks. The presentation will include the climatology of the tropical systems and associated tornadoes in this study, as well as an examination of the contributing factors using satellite, surface, upper air, and sounding analyses. The "exit" tornado theory will also be explained using past tropical storm and tornado tracks from other studies, and similar examples will be shown from a few recent tropical systems. *[Corresponding author address: james.hudgins@noaa.gov]*

Environmental Characteristics for Tropical Cyclone Tornadoes

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UNC Charlotte

Tropical cyclones (TCs) making landfall commonly spawn tornadoes within their rainbands. In the United States, as much as 10% of the lives lost during tropical cyclones are a result of the tornadoes spawned in these storms (Novlan and Gray 1974). Forecasting such tornadoes has proven difficult due to the small nature of the shallow supercells which produce these tornadoes. Previous research has found a common climatology for TC tornadoes (Novlan and Gray 1974; Gentry 1983; McCaul 1991). McCaul (1991) found that over 70% of the storms with a Gulf Coast landfall produced tornadoes. This is due to the location of the onshore flow of the TC rainband in the favorable right-front quadrant. Most tornadoes occur 200-400 km from the center of the TC in convective cells embedded within the outer-rainbands. A majority form within 200km of the coastline with a distinct spike at a range of 100km from the coast. Another important aspect of the climatology is the TC motion. Gentry (1983) found that 81% of the hurricanes producing at least six tornadoes were moving between 300° and 30° as they crossed the coastline or in other words they were recurving.

Several observational and numerical studies have recognized environmental conditions that seem favorable for TC tornado formation (Novlan and Gray 1974; Spratt et al. 1997; Curtis 2004; Schneider and Sharp 2007). Atmospheric instability can be enhanced by the intrusion of midlevel dry air adjacent to the rainband. As a result of the dry air above 850 mb, the Convective Available Potential Energy (CAPE) is increased. Eleven out of 13 tornado outbreak cases, producing 20 or more tornadoes, were found to have evidence of a dry intrusion at midlevels over the outbreak area for landfalling TCs. A moderate CAPE (> 500 J/kg) is typical of the TC tornado environment. Strong low-level shear (> 20 m/s over lowest 3 km) and low –level storm-relative helicity (> 100 m2/s2) are other important factors for tornadogenesis. Lastly, a low-level convergence axis (e.g. the coastline) seems to be a triggering mechanism for outbreaks due to the increased horizontal vorticity which can be tilted and stretched by an updraft.

The primary focus of this study is to update McCaul (1991) with the environmental conditions in which TC's have produced tornadoes in the past 10 years. Using atmospheric sounding data from United States raob sites that were within 800 km of a TC center, environmental characteristics such as CAPE and helicity will be calculated to display the typical environment for a tropical cyclone that makes landfall. This data will be stratified based on radius from the storm center, azimuth (or octant), and tornadic/non-tornadic storms. McCaul's study will be furthered by including recently developed supercell and tornado indices, such as the Supercell Composite and the Significant Tornado Parameters, which were developed for the Great Plains but could be useful in a tropical environment. A general proximity composite sounding for a TC tornado environment will also be computed using soundings that were launched within the general area and time of a tornado. To better identify the environment which is producing these tornadoes, a more stringent close proximity sounding will be completed using soundings that were launched the inflow region within a close distance and time of a tornado. By using these environmental characteristics, meteorologists could provide earlier warning for the public and further prevent the loss of lives. *[Corresponding author address: mclink@uncc.edu]*

Variability of Tornadoes Due to U.S. Landfalling Tropical Cyclones

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Tornadic activity associated with landfalling tropical cyclones (TCs) from the Gulf of Mexico is examined for the period 1948-2008 in the context of TC size, intensity, and mid-level moisture data at landfall. New datasets are assembled for TC tornadoes and for TC size at landfall as indicated by radius of the outer closed isobar and distance of tornado measurements. Owing to uncertainties in the observed TC tornado record particularly prior to 1990, a statistical model for the number of TC tornadoes induced by each Gulf landfalling TC is developed based upon the more reliable tornado data since 1990 using TC size, intensity, and mid-level specific humidity gradient data as predictor variables. The model adequately reproduces the reliable portion (1990-2008) of the tornado record explaining 64% of the variance in the number of observed TC tornadoes for individual TCs and 87% of the variance in the annual number of observed TC tornadoes. In terms of the 2008 hurricane season, the model performed particularly well in capturing the magnitude of the TC tornado outbreaks for five of the six Gulf landfalling TCs including Hurricane's Gustav and Ike.

Given the performance of the statistical model, it is then used to reconstruct the TC tornado climatology back to 1948—the start of mid-level moisture measurements in the NCEP/NCAR Reanalysis II dataset. Relative to the previous active period for Gulf TC landfalls of 1948-1964, the current active period since 1995 is associated with an increase in the number of total TC tornadoes and an increase in the median tornadoes per TC landfall according to the reconstructed TC tornado dataset. These changes are linked to an increase in the median size and frequency of large landfalling TCs on the Gulf coast as revealed through radius of outer closed isobar and distance of tornado from TC center measurements. The significance of this increase in TC size and landfall frequency is placed into greater historical context by extending the TC tornado analysis back to 1920 (using a modified statistical model that does not include mid-level specific humidity gradient as a predictor) to encompass the entire period of previous elevated Gulf landfall TC activity. From the reconstruction, the frequency of TC tornadoes particularly during 2004 and 2005 is shown to be at unprecedented levels according to the TC tornado climatology. *[Corresponding author address: James I. Belanger, School of Earth and Atmospheric Sciences, 311 Ferst Drive, Georgia Institute of Technology, Atlanta, GA 30332-0340]*

Identifying Supercells in a Simulated Landfalling Hurricane

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It is well-known that tropical cyclones spawn supercells, some of which are tornadic. These phenomena contribute substantially to the already elevated potential for wind-related loss of life and property associated with a tropical cyclone. High-resolution numerical simulations of an idealized, hurricane-like vortex using the compressible, non-hydrostatic Straka Atmospheric Model show that supercell-like circulations can form. Analyses of vertical motion, vertical vorticity, pressure minima, and updraft helicity fields are used to identify regions within the hurricane-like vortex that may be supportive of supercell-like structures. Simulated radar reflectivity analyses allow the display of the supercell-like structures in relation to the larger circulation of the hurricane-like vortex. These results can be a useful comparison for operational forecasters using WSR-88D radar to identify tropical cyclone supercells in real-time. In addition to a numerical simulation over open-ocean, other simulations employ a base wind to uniformly advect the hurricane-like vortices over land to simulate landfall at different translational speeds. Tropical cyclone supercell potential may increase after landfall in part due to frictional effects and the resulting storm relative helicity increase. These simulations are in agreement with previous observational studies of tropical cyclone supercells. *[Corresponding author address: owen@ou.edu]*

An Examination of Tornado Warning Decisions in the Greenville-Spartanburg County Warning Area During Tropical Storm Fay

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Tropical Storm Fay moved across the Gulf Coast and Tennessee Valley regions on 23-26 August 2008. This tropical cyclone presented the first opportunity for forecasters at the National Weather Service Weather Forecast Office at Greenville-Spartanburg (GSP) to utilize the warning decision guidelines as presented by Schneider and Sharp (2007; SS07) for tornadoes associated with remnant tropical cyclones. Three confirmed tornadoes occurred in the GSP County Warning Area as the remnants of Fay moved across the Tennessee Valley on 26 August 2008. GSP forecasters issued successful tornado warnings for these three events. However, use of the techniques presented by SS07 also resulted in a high number of false alarms. While the radar-derived warning thresholds for rotational velocity as presented in SS07 are much smaller in magnitude than those suggested by traditional mesocyclone and tornado vortex signature recognition nomograms, analysis of radar data on 26 August 2008 revealed that the three tornadic convective cells produced rotational velocities and/or rotational shear values similar to classic tornadic supercells. The stronger signatures developed rapidly on 26 August 2008, almost in conjunction with tornadogenesis. This rapid intensification appeared to occur as the convective cells moved across a pre-existing, east/west oriented, weak baroclinic boundary characterized by positive surface-based Convective Available Potential Energy on the north side of the boundary. The results of the current study indicate that utilization of the thresholds presented in SS07 combined with careful monitoring of the evolution of the mesoscale environment, particularly with regard to the position of baroclinic boundaries, provide the most effective method for optimizing warning services during tropical cyclone tornado outbreaks. *[Corresponding author address: Justin.Lane@noaa.gov]*

Landfalling Hurricane Research Activities at University of Alabama - Huntsville

Dan Cecil, Kevin Knupp, Walt Petersen, Larry Carey, Lori Schultz, and Christina Crowe
University of Alabama - Huntsville

Landfalling hurricanes have been a growing area of research at the University of Alabama - Huntsville (UAH) in recent years. I will give an overview of our activities and recent findings. We deployed a mobile dual-polarization radar, profiling system, and surface instrumentation for Fay, Gustav, and Ike in 2008. Research emphasis has been on tropical cyclone (TC) tornadoes, TC precipitation, and TC wind fields. Examination of a TC tornado climatology reveals a distinction between the tornado threat near the TC center (mostly F0 with little diurnal signal) and those a few hundred kilometers away (strong afternoon maximum with more damaging tornadoes). The Hurricane Rita (2005) case demonstrates the importance of low level instability in delineating the region with tornadoes. Some conventional and dual-polarization radar characteristics are also examined for this case. Measurements from the 2008 deployments will also be presented. *[Corresponding author address: cecild@uah.edu]*

Modeling the Inland Impact of Tropical Cyclone Surge

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Hurricane surge travels well inland for low-lying coastal areas. However, the vast majority of the public are not aware of their exposure to this risk. Attempting to make the risk of surge more understandable, an interactive website was developed that combines SLOSH estimated surge with elevation and tide data and then simulates the level of surge on photographs of a thousand landmarks throughout the metropolitan area. The intent of the model is to allow citizens to navigate the model to find a landmark near their home, and then to easily simulate the water depth at that location for a variety of hurricane scenarios. Multiple problems that were encountered in constructing this simulation will be discussed. Upon model completion, randomly selected members of the public will be surveyed to examine the effectiveness of this approach.

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Effects of Tropical Storm Andrea on Air Quality in Florida

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Subtropical storm Andrea formed off the southeastern coast of the United States on 9 May 2007 from a large extra-tropical system in the western Atlantic. Andrea slowly weakened after classification as a tropical storm to depression stage by 12 UTC May 10 and a remnant low by 00 UTC May 11. Despite its short lifetime, the wind-field associated with Andrea had an important impact on air quality in the southeastern U.S., especially Florida. Throughout late April and early May, large wildfires had been burning along the Georgia – Florida boarder in response to an extreme drought. As a result of Andrea, smoke was transported into central and southern Florida, causing very poor air quality conditions. PM2.5 concentrations in excess of 300 g m-3 were observed at several Florida stations between 9 – 12 May, which falls into the EPA's worst air quality category (Hazardous). Trajectory analysis of parcels originating near the location of the fire indicate a travel time of 12 hours to central Florida and 24 hours to southern Florida.

Precipitation associated with Andrea was relatively minimal and only reduced the intensity of the fires briefly on 9 May. The cyclonic circulation around what was to become Andrea resulted in low-level winds from the northeast near the fires on May 8 – 9, transporting much of the smoke southwestward (in-between EPA monitoring stations) before looping back eastward in southern Florida. By 1800 UTC 9 May, 0 – 3 km winds were from a north and northwest transporting the smoke down the Florida Peninsula, before curving eastward into the Atlantic. Near Mandarin in northern Florida, (which is only 3 hours downwind of the fire), air quality was very poor between 12 and 22 UTC. Trajectory analysis of a parcel released a 1 km, shows the smoke being transported all the way around Andrea, which is consistent with satellite observations. By 1800 UTC 10 May, low level winds became more northeasterly transporting much of the smoke southwestward into the eastern Gulf of Mexico and the western coast of Florida as evidenced by the decreasing air quality Pecia while air quality improved substantially at Mandarin. *[Corresponding author address: tjones@nsstc.uah.edu]*