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-two rain gauge stations obtained from the National Climatic Data Center (NCDC). Rainfall from these stations was 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. Conversely, 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°X2.5° 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	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	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.

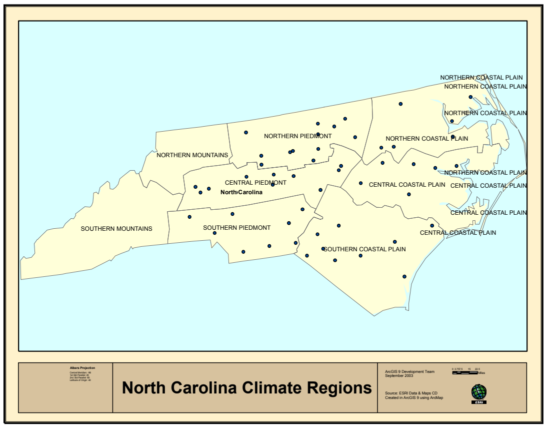

FIG. 1. Climate regions of North Carolina with 52 rain gauge stations used in the study (indicated by dots).

3.3. Numerical Simulation

A numerical simulation 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 Strom 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) were used in all eight simulations. The Kain-Fritsch cumulus parameterization scheme (CP) (Kain and Fritsch 1993) was used in the 36 km, 18 km, and 6 km simulations. The 2 km simulation turned off the CP scheme and used explicit physics. The model runs consisted of 90 vertical levels with staggered spacing, which allowed for higher resolution in the PBL and a 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 study 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 feature 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 exist 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.

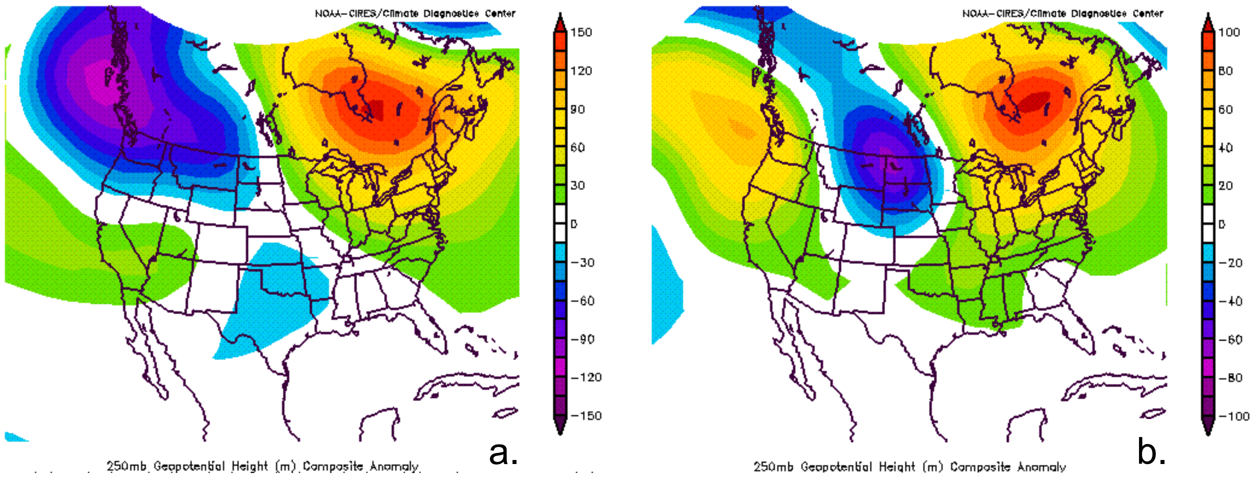

FIG. 2. 250 hPa composites of geopotential height anomalies (m) of (a) 14 heavy and (b) light precipitation events at 72-hours prior to landfall in NC.

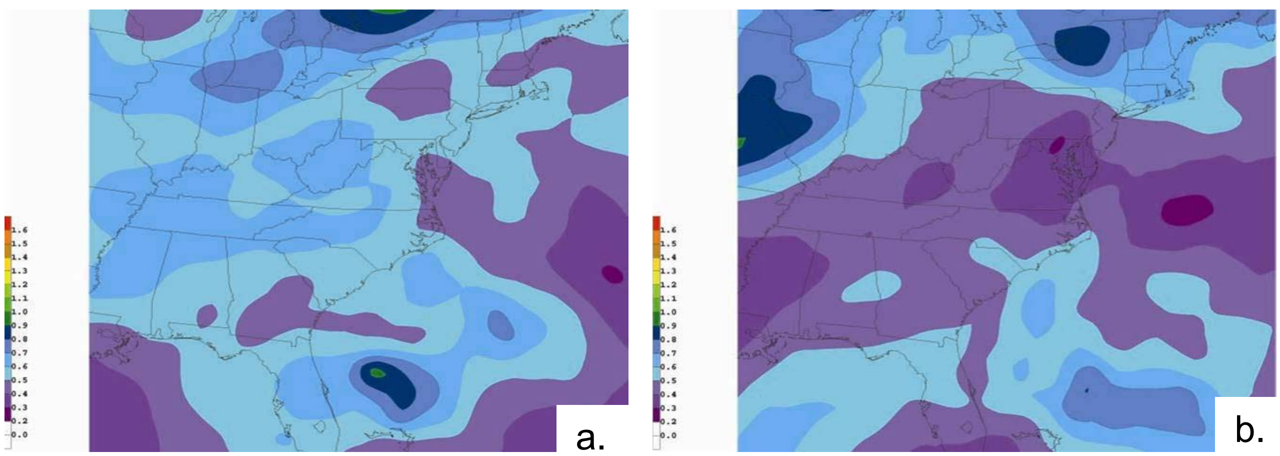

FIG. 3. Composite of 250-500 hPa potential vorticity (PVU) for (a) 6 heavy and (b) light precipitation events at 24-hours prior to landfall in NC. Significantly higher PV over eastern U.S. associated with heavy events.

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 of the heavy events, 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.

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 were calculated. The moisture flux convergence is a

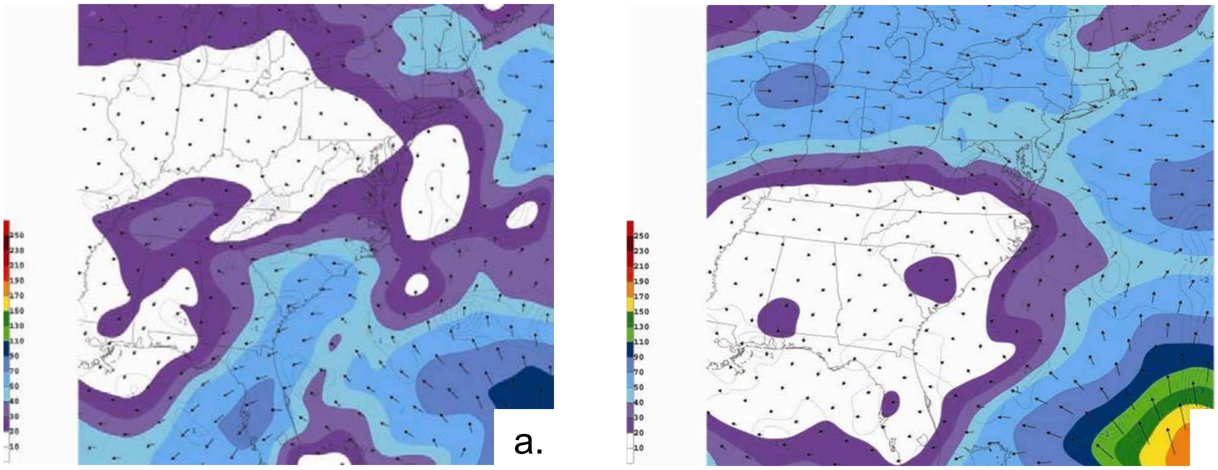

FIG. 4. Moisture flux vectors (x10-4 m s^{-1} black arrows), moisture flux (x 10-4 m s^{-1} shaded) and moisture flux convergence (contours, $gkg^{-1}ms^{-1}$) for (a) heavy and (b) light precipitation events at 48-hours prior to landfall in NC.

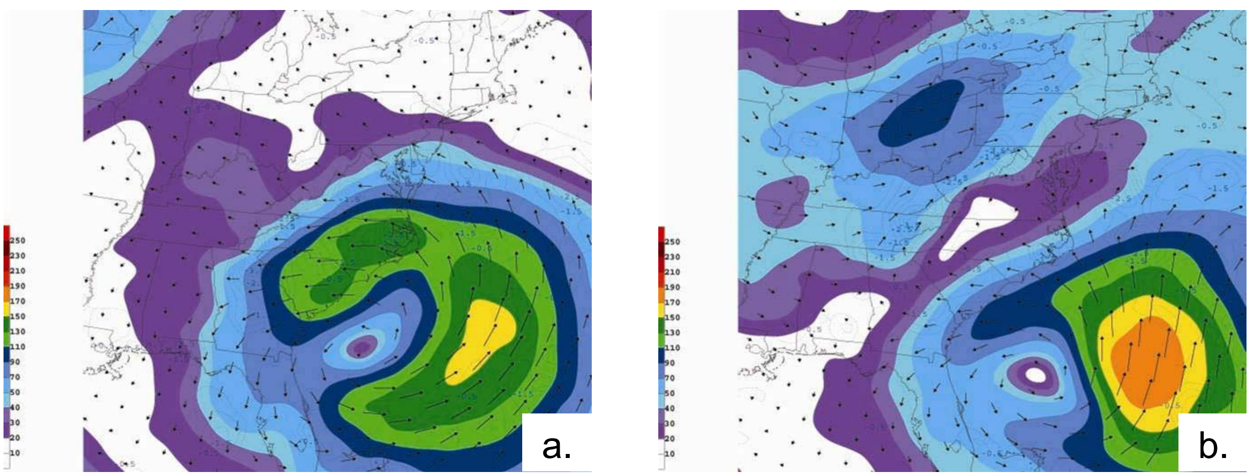

FIG. 5. As in Fig. 4 except for 12-hours prior to landfall in NC.

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. 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.

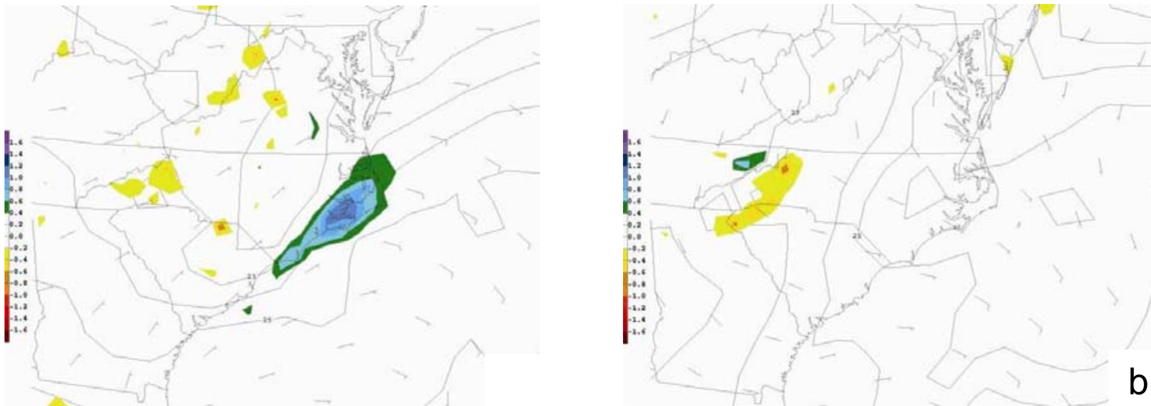

FIG. 6. Composite analysis of 1000 hPa frontogenesis (color fill, °C 100km^{-1} 3hr^{-1}), temperature (contours, °C) and wind barbs (ms^{-1}) for 6 (a) heavy and (b) light precipitation events at 18-hours prior to landfall.

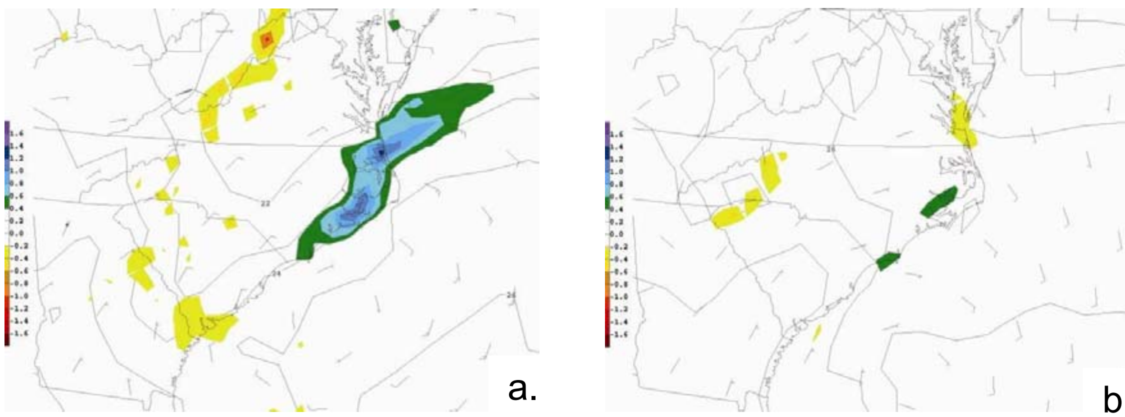

FIG. 7. As in Fig. 6 except for 6 hours prior to landfall.

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. Modeling also served to further investigate the mesoscale environment the TCs were entering prior to and at landfall. The model analysis performed for Hurricane Floyd 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. Results indicate 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 moving southward into North Carolina (Fig. 8) as well as a coastal front. Figure 9 is a model analysis of frontogenesis, indicating high levels of frontogenesis along coastal North Carolina.

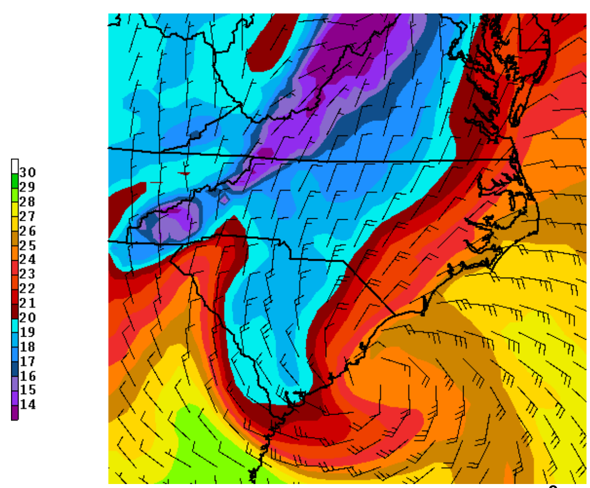

Fig. 8. NHMASS model 1000 hPa temperature (°C) and wind (ms^{-1}), 3-hours prior to landfall (0300 UTC 99/09/16) of Hurricane Floyd.

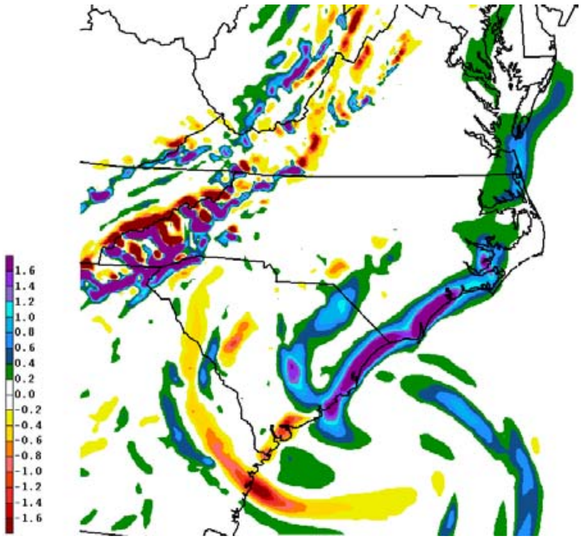

Fig. 9 NHMASS model 1000 hPa frontogenesis ($^{o}C100km^{-1}3hr^{-1}$) 3-hours prior to landfall of Hurricane Floyd (0300 UTC 99/09/16).

The accelerations within the right entrance region of the polar jet located to the north of Hurricane Floyd created 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 turned the winds to the left due to the strong southerly flow ahead of the trough (Fig. 10). Such wind shifts 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 build the ascending flow south and west of the coastal front triggering precipitation farther west as the trough moves north. 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.

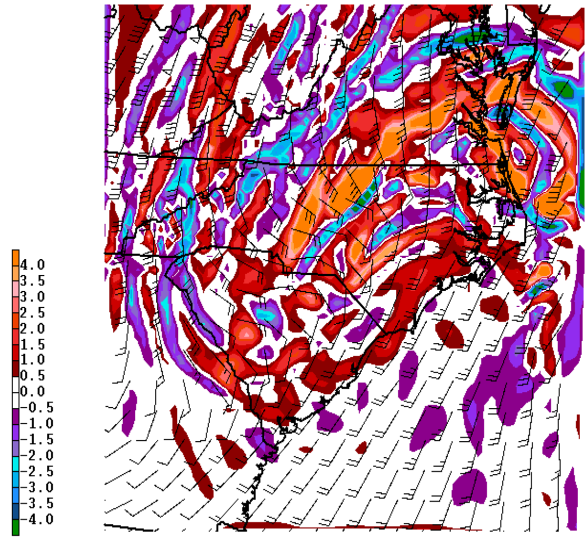

Fig. 10 NHMASS model 250 hPa divergence ($s^{-1}*10^{-4}$) and winds (ms^{-1}) 2-hours after landfall (0800 UTC 99/09/16) of Hurricane Floyd.

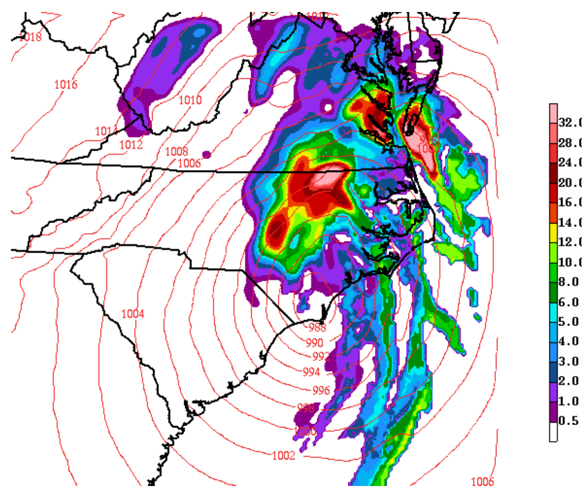

Fig. 11 NHMASS model precipitation (mm) and mslp (hPa) 7-hours after landfall (1300 UTC 99/09/16) of Hurricane Floyd.

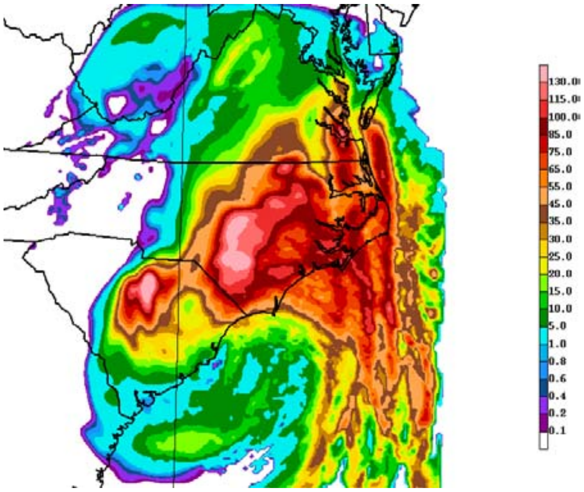

Fig. 12 NHMASS model accumulated precipitation (mm) from 0300 UTC 99/09/16–1300 UTC 99/06/16 for Hurricane Floyd.

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 northeast 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 exhibited higher values of PV across the southeast. In particular, a trough of negatively tilted upper-level PV, penetrating southeastward through the Ohio River Valley can interact with the lower-level (850-700 hPa) PV associated with the TC. This serves 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 increase 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. Finally, 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 its 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 Southeast River Forecasting Center can then use this evaluation to aid in the decision of issuing flood watches and warnings.

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