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An examination of the mesoscale structure associated with the extratropical transition of Hurricane Agnes (1972)

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1. Introduction

Considerable attention has been given to the transition of tropical cyclones to extratropical cyclones in the recent literature. Transition often occurs when the tropical system passes over cooler water (or land) and interacts with a mid-latitude trough. Such transitions are often not well forecast by operational models. Over land, the low-level circulation associated with a transitioning storm can interact with terrain or a surface baroclinic zone, resulting in localized regions of intense precipitation. These regions can often extend several hundred kilometers away from the storm center, providing another challenge to forecasters.

Recent studies have focused on the use of numerical models to understand the transition process. These studies have primarily focused on the sensitivity of transition to the initial conditions. For example, McTaggert-Cowan et al. (2001) used potential vorticity (PV) inversion to modify the initial conditions in their simulations of the extratropical transition (ET) of Hurricane Earl (1998). PV inversion was used to remove the upstream trough and Earl. Klein et al. (2002) examined the sensitivity of extratropical transition to changes in the initial storm location for Typhoon Bart (1999), Supertyphoon Ginger (1997), and Supertyphoon Bing (1997) in the western Pacific. Simulations like these allow for an analysis of what would have happened if, for example, the trough and tropical storm were located closer to or farther from each other, or if either the tropical storm or upstream trough was not present.

The transition of Tropical Storm Agnes (1972) has been well documented in the literature (e.g., DiMego and Bosart 1982a,b; Dean and Bosart 1991). A noteworthy aspect of Agnes was the large amount of precipitation (15-35 cm) that fell from eastern Virginia to eastern Pennsylvania. Bosart and Dean (1991) focused on the synoptic and mesoscale features associated with the heavy precipitation that developed in the mid-Atlantic region in advance on Agnes. They showed that the precipitation was concentrated along a frontal boundary, which formed in situ east of the Appalachian Mountains. This inland coastal front served as the focal point for the intense precipitation described above.

The original intent of this study was to examine the formation of the inland coastal front ahead of Agnes and the development of the precipitation associated with it. It will be shown, however, that modeling the ET process is, in itself, a difficult task. This work will focus on the errors associated with forecasting the ET of Agnes. It will also be shown that the largest initial forecast errors are associated with the upstream trough that eventually interacts with the Agnes circulation. These errors become significant within the first 12 h of the simulation. The net result of these errors is to produce a track for Agnes that is located significantly west of the observed path.

2. Methodology

The Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) Mesoscale Model (MM5) Version 3 is used examine the transition of Tropical Storm Agnes. The model is run using two nested domains with 81 and 27 km, grid spacing, respectively. The size of each domain is shown in Fig. 1. The model is initialized at 0000 UTC 21 June using the National Centers for Environmental Prediction (NCEP) gridded reanalysis (Kalnay et al. 1996; Kistler et al. 2001). At this time, Tropical Storm Agnes is centered near Augusta, Georgia (AGS). The Kain-Fritsh (KF) cumulus parameterization is used in the control simulation (CTL).

The sensitivity of the solution to the initial conditions is tested by incorporating surface and upper-air observations into the first guess. The impact of different cumulus parameterizations and boundary layer schemes is also explored in this study. Cumulus parameterization is applied to all three domains though, strictly, they are not designed for domains with grid spacings less than 20 km.

3. Results

Figure 2 shows the track of Tropical Storm Agnes for a number of MM5 simulations, regardless of initialization technique, domain size, and parameterizations employed. All of the model simulations exhibit common forecast track and speed errors as all simulations keep Agnes much further inland and move it much faster as compared to the observed track. These errors apparently do not depend on the grid size or parameterizations used. This behavior suggests that a synoptic-scale error exists in the forecast. MM5 simulations of the extratropical transition of Hurricane Michael (2000) also produced significant track and speed errors (J. Evans 2002, personal communication).

Figure 3 shows the tracks from the CTL run. The storm position and speed errors begin early within the simulation and grow in time. In the CTL simulation, Agnes remains well inland moving along the eastern slope of the Appalachian mountains. To determine if the mountains are playing a role in controlling the track of Agnes, a simulation was run without terrain (NT). The track of Agnes in the NT simulation, shown in Fig. 3, is also well west of the observed. While the

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mountains may slightly alter the track, it is evident that terrain does not explain the significant track and speed errors.

To identify the origin of the forecast errors, Fig. 4 shows the forecast 200 hPa (upper) and 500 hPa (lower) height forecasts at 12 h (left) and 24 h (right) from domain 1 of the CTL simulation (Fig. 1). The shading represents the difference between the CTL forecast (81 km domain) and verification. At 200 hPa, the 12 h forecast (Fig. 4a), errors exceeding +6 dam are present over central Canada. It should be noted that these errors are not due to the proximity of the northern and western boundaries (Fig. 1). Smaller errors of more than +2 dam occur from the central to northwestern United States (US). The areal coverage and magnitude of these errors increase in the 24 h forecast (Fig. 4b).

Similar errors are present at 500 hPa. At 12 h (Fig. 4c), the largest errors are associated with the northern trough over Canada. The inland movement of Agnes (Fig. 3) accounts for the observed errors over the southeastern US. By 24 h (Fig. 4c), the forecast errors over the US grow in strength and coverage. These errors indicate that the model forecast is not producing a deep enough trough at 200 hPa and 500 hPa and is progressing the trough eastward too quickly.

Figure 5 shows the 12 h and 24 h forecast 500 hPa relative vorticity (ζ) and height, along with the corresponding verification from the NCEP reanalysis. Significant ζ differences are observed within the first 12 h of the forecast (Fig. 5a,b). At 1200 UTC 21 June (Fig. 5a), the ζ maximum is primarily located within the center of the Canadian trough. Based on the implied cyclonic ζ advection (and simple quasi-geostrophic reasoning), the northern trough would be expected to progress eastward. In the 12 h forecast (Fig. 5b), the largest ζ value is located along the eastern flank of the northern trough. Based on this pattern, the trough is expected to lift out to the northeast. An examination of the next 12 h period (Fig. 5c,d) verifies that the northern trough moves eastward (Fig. 5c) while the 24 h forecast (Fig. 5d) clearly shows the trough lifting northeastward.

A similar analysis can be done for the trough located over the central US. The structure of the forecast ζ in this region is considerably different from the analysis. At 1200 UTC 21 June (Fig. 5a), the ζ maximum is centered within the broad trough over central Wisconsin. Based on the implied cyclonic ζ advection, the trough would be expected to move slowly eastward. The structure of the ζ field in the 12 h forecast (Fig. 5b), however, suggests significant cyclonic ζ advection east of the main trough (and north of Agnes), implying a rapid eastward movement of the trough. It is possible that this trough/ζ advection orientation produces a favorable environment for Agnes to move poleward. By 0000 UTC 22 June (Fig. 5c), the trough over the upper midwest has progressed slightly eastward. In the analysis at this time, a clear separation remains between the trough and Agnes. In the 24 h forecast (Fig. 5d), the trough has moved significantly eastward over the 12 h period. By this time, the Agnes circulation has moved poleward toward the region of cyclonic ζ advection discussed previously. The trough and Agnes have nearly merged at this time.

An inland coastal front does begin to develop within the CTL simulation (not shown). In the simulation, however, the Agnes circulation moves quickly northward through this region. As a result, the coastal front does not have time to develop. Heavy precipitation, with rates of 30 mm $(3\ h)^{-1}$, does fall from central Virginia to central Pennsylvania (Dickinson and Bosart, 2002), though it is primarily associated with Agnes itself and not with the coastal front.

It is unclear as to how the errors are generated within the forecast. It is possible that the 2.5° grid spacing of the NCEP reanalyses used in the model initialization does not adequately capture the structure of the northern trough and Agnes. Simulations including surface and upper-air data in the initial conditions, however, did not improve the forecast.

One issue to be addressed is the role Agnes circulation. The effect of the diabatic heating associated with cumulus convection can feedback on the synoptic scale (Doswell and Bosart 2001), resulting in the development (or enhancement) of a ridge just east and north of the storm center. Studies by Dickinson et al. (1997) and Bosart and Lackmann (1995) have shown that the development of this diabatically-produced ridge can alter the structure of the upstream trough. It is unclear what role the Agnes convection played in the observed forecast errors. It is clear, however, that these results appeared to be independent of the cumulus convection scheme used in the model.

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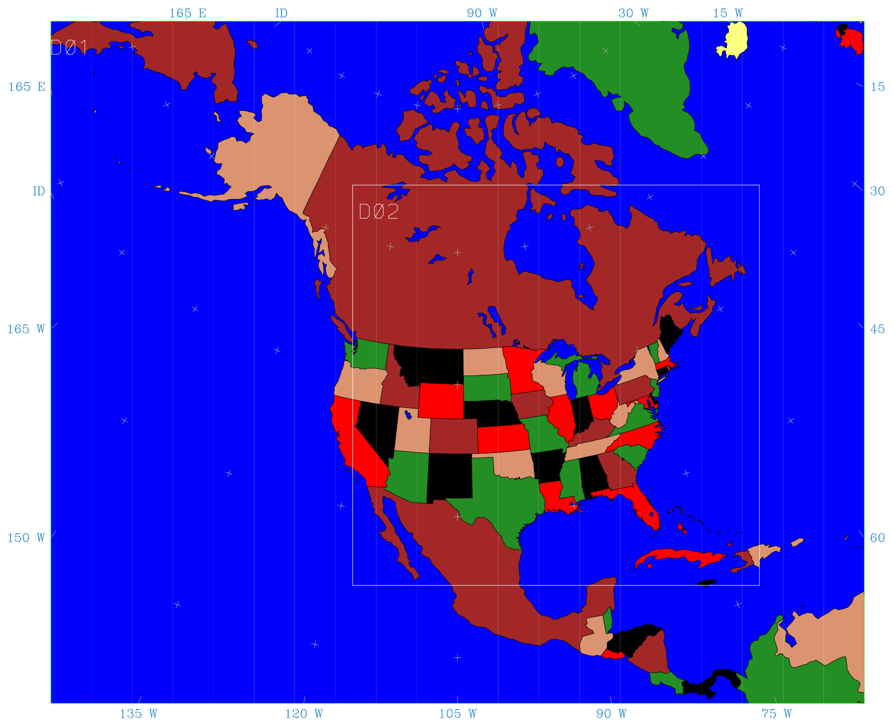

Figure 1: Areal coverage of domain 1 (D01) and domain2 (D02) used in the MM5 simulations

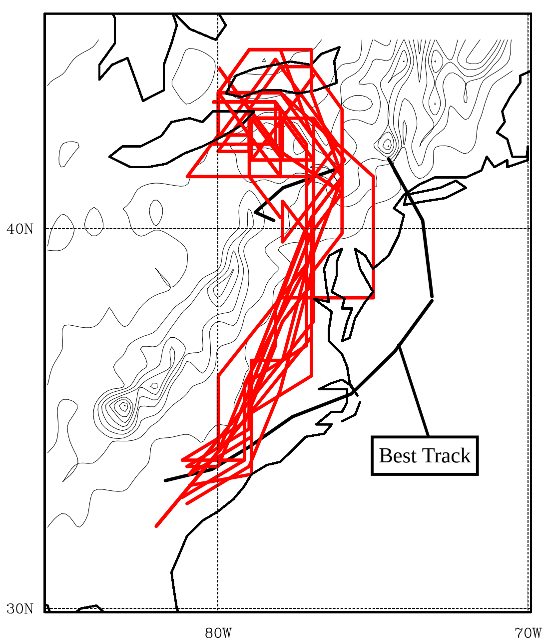

Figure 2: Tracks of minimum mean sea-level pressure (MSLP) for all Agnes MM5 simulations. The Agnes observed track curve is labelled. Contours show the terrain height (contour interval 100 m)

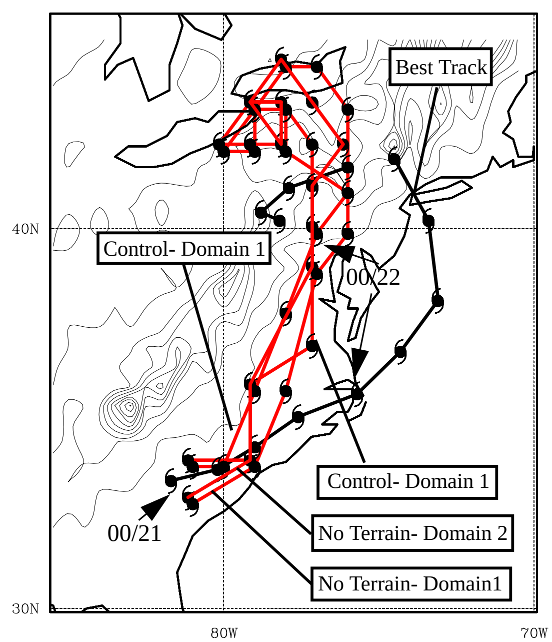

Figure 3: Six hourly positions of Tropical Storm Agnes (MSLP) for the CTL (Domains 1 and 2) and NT simulations, as well as the best-track position. Contours show the terrain height contour interval 100 m)

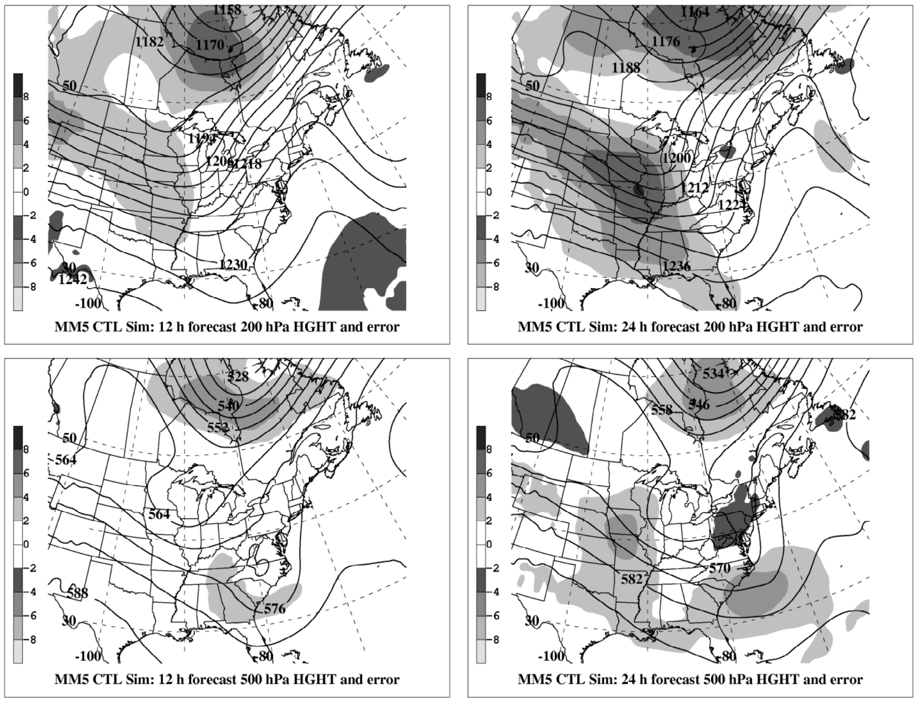

Figure 4: 12 h (a) and 24 h (b) forecast of 200 hPa height and 12 h (c) and 24 h (d) forecast of 500 hPa height (dam, contoured). Shading represents the height (dam) difference (forecast - verification)

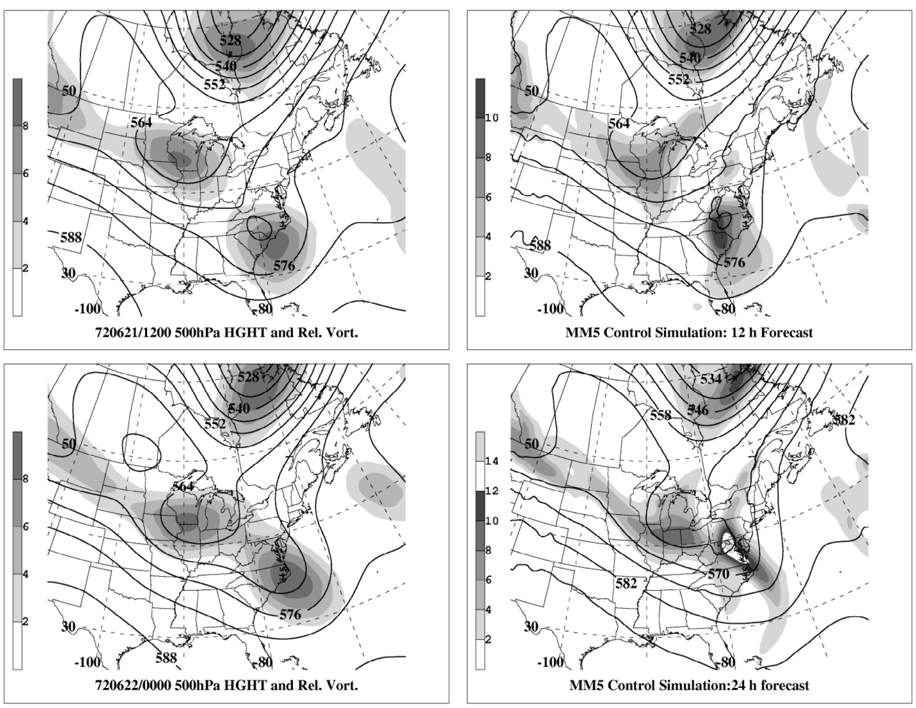

Figure 5: 500 hPa height (contoured) and relative vorticity (shaded, x 10^-5 s^-1) for (a) 1200 UTC 21 June, (b) 12 h forecast verifying 1200 UTC 21 June, (c) 0000 UTC 22 June, and (d) 24 h forecast verifying 0000 UYC 22 June.