13.5 NUMERICAL SIMULATION OF THE GENESIS OF TROPICAL STORM ALLISON (2001)

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1. INTRODUCTION

In June 2001, Tropical Storm Allison inundated states along the Gulf and Atlantic coasts and became the costliest tropical storm in United States history. Although the effects of Allison were felt across many states, the storm reserved its biggest impact for parts of Southeast Texas. The deluge brought much of the area, including the Houston metropolitan district, to a standstill. Allison's widespread rains dumped cumulative rainfall totals of nearly 90 cm in some isolated areas over a period of five days, resulting in nearly $5 billion in damage and claiming the lives of 22 Houston residents.

In the present study, the genesis and subsequent evolution of Tropical Storm Allison are studied with the Pennsylvania State-National Center for Atmospheric Research fifth-generation Mesoscale Model (MM5 v 5-3). Our intention is to gain an understanding of the mechanisms involved in the genesis of the storm and the initial nature of the storm itself. TPC discussions mentioned that the storm was a hybrid system, and questions remain about whether or not the system was a long-lived mesoscale convective system (MCS). Detailed study of this event will allow forecasters to look for key indicators to distinguish developing tropical systems from MCS's or hybrid systems, allowing them to use the proper conceptual framework for forecasting structure and evolution.

Section 2 describes the particular setup of the MM5 model used in this study. Section 3 presents an overview of the synoptic background and evolution of the storm itself, and Section 4 compares the results of the model simulation to the actual event. In Section 5, the results of the model simulation are analyzed in relation to the evolution of the system. A summary and concluding remarks are presented in Section 6.

2. MODEL SETUP

In this study, the MM5 domain configuration consists of a coarse grid and two nested domains, each with two-way nesting. The resolution of the coarse grid (CG), the first nest (N1), and the second nest (N2) are 54, 18, and 6 km respectively. Use of the NCEP ETA model analysis for initialization and boundary conditions limits the southern extent of the coarse grid model domain to approximately 20N.

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Because this study focuses only on the initial stages of the storm, the model integration is only carried out until about 12 hours after landfall. Integration starts for all three grids at 18 UTC 4 June 2001 and continues until 12 UTC 6 June. This period spans the formation, intensification, and landfall of Allison.

The physics options chosen for this experiment are based on a comparison of the output from several different combinations. The simulation examined in this paper used the combination with the most accurate storm track and intensity. The options are as follows: the Kain-Fritsch scheme for cumulus parameterization; the High-Resolution Blackadar scheme for the planetary boundary layer; the Dudhia simple ice scheme for explicit moisture; and the RRTM longwave scheme for radiation. All of these except for the cumulus parameterization scheme were applied to every grid. No cumulus parameterization was used on the 6-km grid.

3. BACKGROUND AND EVOLUTION OF SYSTEM

ETA model analyses suggest that the environment prior to tropical storm formation was favorable for convection. A weak trough at 300 mb, extending down through 600 mb, developed over Southeast Texas and the Northwest Gulf of Mexico on 3-4 June. This trough had the effect of destabilizing the atmosphere along the Texas coast, as evidenced by soundings from Brownsville and Corpus Christi on 4 and 5 June. At 0 UTC 4 June, Brownsville's sounding indicates moderate levels of convective inhibition (CIN) and high levels of convective available potential energy (CAPE) with the moist layer extending to roughly 900 mb. By 0 UTC 5 June the CAPE had raised slightly, CIN had disappeared, and the moisture had deepened to 750 mb. Despite this, the airmass above 650 mb was still very dry as late as 12 UTC 5 June. Further south, ETA model analyses indicate even deeper moisture over the Gulf of Mexico with relative humidity values near 100% from 850 to 500 mb.

While the 300 mb trough destabilized the atmosphere over the Northwest Gulf, the tropical wave that Allison emerged from entered the scene from the south. Infrared and visible satellite images show a disorganized area of deep convection moving slowly northward through the western Gulf of Mexico on 4 June. By 12 UTC, thunderstorms began to develop explosively southeast of Brownsville, while other areas over the Bay of Campeche and Yucatan remained active. Within 24 hours several more deep convective clusters developed closer to Texas and the focus of the disturbance changed from a broad region to several intense clusters in the Northwest Gulf. Radar and satellite imagery shows that the storms nearer the Gulf coast were outflow dominant, which is supported by the presence of drier air aloft over that region. However, infrared satellite images and buoy observations imply that a circulation began to develop in the deeper moisture south of Houston by 12 UTC 5 June.

Although ETA suggested a thermodynamic environment favorable for convection over the western Gulf of Mexico, the shear in this region made it initially unfavorable for tropical development. Scatterometer-derived surface winds exceeded 20 knots over much of this area on 4 June, and according to ETA analyses, these southeasterly winds strengthened with height to a wind maximum at 850 mb. By 0 UTC 5 June, ETA analyzed winds at this level from almost 40 knots north of the Yucatan to about 25 knots near the Texas coast. With the presence of a 300 mb trough, winds aloft were from the southwest at 20 knots near the Yucatan to over 40 knots along the Texas coast. This implies zonal wind shear over the entire Western Gulf of about 40 knots, which is unfavorable for tropical development (DeMaria, Knaff, and Connell 2001). However, the 300 mb trough shifted eastward in the ETA analyses on 5 June, which left an area of light 300 mb winds from Central Texas to East of Brownsville by 12 UTC 5 June. At any rate, the magnitude of the shear had now dropped to about 20 knots immediately over the area where low-level circulation seemed to be developing.

Reconnaissance aircraft found a closed circulation center at 19 UTC, 5 June, and with 50-knot surface winds on its east side, the system was immediately upgraded to tropical storm strength by the Tropical Prediction Center (TPC). Note that because the first reconnaissance flight into the storm found tropical storm force winds, it is unknown at what point the system attained depression or tropical storm strength. In addition, disorganization, a broad low-level circulation, and several small vortices outside of the main center made tracking the system difficult.

Visible satellite imagery of the storm on 5 June suggests that the storm may have weakened somewhat by the time the first reconnaissance flight intercepted it. The first visible images of the day, near 12 UTC, show deep convection near or over the center of circulation. As the day progressed, this convection moved away from the center, possibly due to entrainment of drier midlevel air from the northwest. Later reconnaissance flights found that the maximum winds dropped to 40 knots as Allison approached the coast.

The storm moved inland around 2 UTC on 6 June, with the center displaced well south of the convection. Although disorganized, the storm still produced very intense rainfall over Southeast Texas during this time. Rainfall totals on the west side of Galveston Bay to the east side of Houston neared 25 cm, and totals elsewhere ranged from 10 to 15 cm. While these rains caused major flooding, they paled in comparison to what Allison would dump on the area several days later.

While the storm weakened as it moved inland and to the north of Houston, the circulation remained well defined on radar and satellite. With weakening steering winds and remnants still capable of producing heavy rains, the threat of flooding remained. Indeed, between 6 and 10 June, more than 40 cm of rain fell over much of Southeast Texas, with nearly 75 cm over the immediate Houston area. A majority of the rain over Houston fell from the afternoon of 8 June until midday 9 June, causing all 22 deaths and most of the damage.

After the torrential rains during the morning of 9 June, little additional rainfall fell on Southeast Texas. When Allison finally left Texas, Louisiana was next in line with rainfall totals again in excess of 75 cm over a large area. The storm continued along the Gulf and Atlantic coasts, dumping 25 cm of rain as far north as southeast Pennsylvania.

4. COMPARISON OF SIMULATION RESULTS

Comparison of the MM5 simulation results with satellite imagery, radar imagery and with surface and buoy observations indicates that the model simulated the structure, intensity, and path of the storm reasonably well. However, it failed to accurately predict where the storm actually formed.

Initially, simulated deep convection agrees well with that observed. Infrared satellite and radar imagery shows intense convection developing about 200 km south of Houston and an ongoing cluster east of Brownsville between 0 and 6 UTC 5 June. Between 6 and 12 UTC more storms developed, forming a north south oriented line of individual clusters. Other isolated storms also developed just off the coast of Brownsville to near Corpus Christi. Although the model brings the convection inland a few hours too quickly, it initiates the line well. It also captures the isolated convection along the lower Texas coast.

The biggest problem with the simulation is that the model fails to develop Tropical Storm Allison within the deep convection off the Texas coast. Satellite imagery indicates that the storm developed in this area around 12 UTC 5 June. However, the model brings the 850 mb height perturbation responsible for the storm's development into the 54 km grid at around 7 UTC.

Imbedded in strong southeasterly flow, this disturbance races northeastward at about 25 knots. Deep convection breaks out with this feature at 11 UTC in the model simulation, and the first closed isobar becomes evident at 16 UTC near 26N 93W. This is more than 250 km from where satellite imagery suggests the storm actually formed. Nevertheless, because the modeled storm moves much faster than observed one, the simulated storm makes landfall at about the same time the actual storm did.

The reason for the difference in movement lies in the differences between the mid-level (600 mb) wind field and initial scale differences between both systems. The modeled disturbance that caused Allison is initially so small that a circulation does not become evident on the 54 km grid until nearly 20 UTC 5 June. This disturbance travels northwestward, along the gradient in mid-level winds, but near a 45 knot maximum. Thus, the initial disturbance only feels the effects of the strong mid-level winds. It does not slow until its circulation grows larger and it approaches the minimum in mid-level winds. In the model run, the 600 mb trough is oriented in such a way that nearly calm winds exist close to where the observed storm formed. In contrast to the simulated storm, the observed tropical storm had a larger circulation, again along the gradient in mid-level winds, but this time near the minimum. The overall effect of the wind field around the observed storm was to give it a northward movement at around 5 knots. This, combined with the fact that the modeled storm was still moving a little to fast at the time of landfall, gave the modeled storm time to 'catch up' with the observed one.

Near the end of the model run at 12 UTC 6 June, the MM5 stalls the storm north of Houston, but south of the observed center. The distance between the simulated and observed circulation centers at this time is less than 100 km.

Despite the above problems, the model did an excellent job simulating the strength of Tropical Storm Allison. Reconnaissance reports indicated a minimum surface pressure of 1002 mb and winds of 50 knots. By the time storm made landfall, the storm weakened slightly, with a pressure of 1003 mb and winds of 40 knots. The modeled disturbance slowly strengthens, with winds near 45 knots and a surface pressure near 1001 mb when it makes landfall.

The MM5 also did a good job simulating the overall structure of Allison. While early-modeled convection occurred too far west and inland, radar images and model derived one-hour precipitation totals looked similar later in the simulation. By the final hour of the model run, the precipitation map looked nearly identical to the Houston radar. The only difference was the position of the modeled center, again slightly south and west of that observed.

Because the model did such a good job with the structure of the system, rainfall totals indicated by the model from 18 UTC 4 June until 12 UTC 6 June agree well with Doppler estimations. Aside from the precipitation being shifted slightly too far west, the overall pattern looks similar to that observed in both amount and distribution.

5. ANALYSIS OF SIMULATION

Though the simulated and actual storms differed significantly in terms of where they formed, the similarities in strength, structure, and environment allow us to use the MM5 simulation to gain insight into the event.

Previously mentioned, an area of lower pressure enters the southern boundary of the 54 km grid at approximately 7 UTC 5 June. This disturbance is strongest at 850 mb, with an increased pressure gradient and stronger winds. However, its effects are also seen at the surface with increased wind speeds. The limitation of the model domain being restricted to the ETA analysis area means that the origin of this disturbance is too far south to be resolved. One feature that offers a hint of where the disturbance came from is a surface trough analyzed in the southern part of the 54 km grid. A potential vorticity analysis of the layers from 975 to 925 mb (the surface trough) and from 900 to 850 mb (the disturbance) shows that the disturbance and trough are related as the disturbance enters the model domain. We believe that the disturbance originated from deep convection south of the model domain, possibly in connection with the trough.

Already embedded in a strong southeasterly flow, the disturbance has the effect of increasing the wind speeds to its east and decreasing them to the west. Our hypothesis is that convection and strong winds combined to meet the threshold conditions required for air-sea instability (Rotunno and Emanuel 1986) on the east side of the disturbance. Indeed, as the disturbance progresses northwestward, deep convection soon breaks out on its east side. The disturbance then strengthens to tropical storm strength through self-amplification (Rotunno and Emanuel 1986), (Emanuel 1989). Though we cannot prove that Allison definitely formed in the above manner, we hypothesize that similarities in the model to observations suggest this is the case.

Though Allison formed near the Texas coast, the model failed to generate the storm in this area for two reasons. First of all, much of the initial convection generated in the model run produced cold outflow, with theta-e values near 350K. This is likely due to the presence of drier air aloft. On the other hand, the deep convection that generated the tropical storm in the simulation produced no discernable outflow. In fact, theta-e values were enhanced to near 360K in these areas. Some convection that initiated separate from the tropical storm, but away from the coast, also had enhanced values of theta-e. However, the model indicates that surface winds in this area were about 10 knots lighter than those in the area where the 'Allison disturbance' strengthened. In conclusion, the weaker surface winds and cool outflow inhibited air-sea instability with other convection.

Finally, the issue of what exactly Allison was must be addressed. Analysis of the simulated event shows lack of any cold pool with the system, which suggests that the storm was not a mid-latitude MCS. Indeed, other convection that did generate a numerically simulated cold pool and observed outflow failed to organize into an MCS. In addition, our hypothesis is that the storm developed through interactions typical of tropical systems. So, while the storm did not look like a typical tropical system, in the numerical simulation it initiated through the same mechanisms as tropical cyclogenesis.

6. CONCLUSION

The intention of this study was to gain an understanding of the mechanisms involved in the genesis and the initial nature of Tropical Storm Allison. To do this, the synoptic environment and the contribution of each significant synoptic feature to the rapid deep convective development had to be analyzed. In addition the cause of cyclogenesis where it took place had to be understood.

It is our hypothesis that the weak upper level trough over the Northwest Gulf of Mexico and Southeast Texas acted on the thermodynamic environment to make it favorable for rapid development of deep convection. It may be that this feature that helped focus convection from a tropical wave over the Northwest Gulf. Convection previous to the clusters in the Northwest Gulf were unorganized and scattered through the entire tropical wave. In addition, the movement of the tropical wave into the area of already strong southeasterly flow produced even stronger surface winds on the east side and weaker flow on the west side. These winds and the surface fluxes induced by them helped feed the deep convection in which Tropical Storm Allison developed. It is therefore our hypothesis that simulated and observed convection was enhanced by an air-sea instability outlined by Rotunno and Emanuel. Any pressure perturbation caused by this convection could then amplify in a process outlined by Emanuel.

We have also shown that given a high-resolution numerical model, Tropical Storm Allison was forecastable. Our simulation begins more than 24 hours before Allison was declared a tropical storm and is successful in generating a storm of similar strength and structure to that observed. In addition, rainfall totals in our simulation agree well with those observed over Southeast Texas. Because rainfall was the largest impact from the storm, we regard this as very important.

Because the model simulation was successful, it will now be possible to look further into the evolution of the remnants of Allison, possibly as late as 8 and 9 June, when the worst flooding took place over Houston.

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