Numerical Simulation of the Transformation of the Pre-Hurricane Gabrielle (2001) Disturbance into a Warm-Core System

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ABSTRACT

Tropical cyclones, often called hurricanes or tropical storms, can cause thousands of deaths and billions of dollars in damages to homes and businesses. Research on the formation of tropical cyclones, while spanning decades, has been limited compared to research on the dynamics and prediction of mature tropical cyclones. The relative de-emphasis on tropical cyclone formation research is linked with the tendency of these systems to form several days away from land. Sometimes, however, tropical cyclones form close to land, giving forecasters as little as a few hours to attempt to prepare the public for their potentially devastating impacts. With soaring coastal populations, this small amount of time is insufficient, necessitating better prediction of the formation of these tropical cyclones.

Hurricane Gabrielle (2001) formed a few hundred miles from the Florida coast only three days before making landfall. This project simulated the formation of Gabrielle using the fifth-generation Pennsylvania State University-National Center for Atmospheric Research mesoscale model (MM5). The simulation results, along with available observations, were examined for the large-scale and mesoscale factors that influenced Gabrielle’s transition from a cold-core non-tropical disturbance to a warm-core tropical cyclone. This project found that asymmetric rainfall created circulation anomalies that, when axisymmetrized, provided the energy to fuel the transition of the disturbance to the warm-core Gabrielle. This asymmetric rainfall was organized by vertical wind shear interacting with the disturbance. This system’s reliance on vertical wind shear for development significantly differs from previous research on tropical cyclone formation, which stresses low vertical wind shear.

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1. INTRODUCTION

Tropical cyclones have the distinction of being one of the most deadly and destructive types of natural disasters on the Earth. These warm-core low-pressure systems, which in the Atlantic basin are more commonly referred to as hurricanes and tropical storms, are often associated with intense winds and heavy rainfall. A single tropical cyclone can cause thousands of deaths and billions of dollars in damage. Coastal populations often need warnings several days in advance of a tropical cyclone’s landfall to prepare for its effects.

In order to better predict tropical cyclone landfall, much of the research done in the past has focused on understanding changes in track and intensity in already developed systems. Since most tropical cyclones in the Atlantic form several days away from land, research in the area of tropical cyclone formation has been limited. The typical area of tropical cyclone formation, thousands of miles out in the open ocean, creates several challenges for researching tropical cyclone formation. Observational coverage is poor over the oceans, especially upper air observations. The distance involved in sending reconnaissance aircraft to investigate any cloud cluster that might develop into a tropical cyclone would require a huge drain of resources, assuming the aircraft could even fly the large distances to investigate. These challenges, combined with the fact that these systems form so far away from land that several days’ lead time is available to warn affected populaces, has led to a higher emphasis placed on the dynamics of mature tropical cyclones. However, some tropical cyclones can form within a few hundred miles of the coast, with lead times ranging from a few days to a few hours before landfall. The need for large lead times requires a better understanding of tropical cyclone formation, which can lead to better forecasting of this event. Montgomery and Farrell refer to understanding and predicting tropical cyclone formation as “a central problem in meteorology and atmospheric forecast” (1993, p. 285).

Both large-scale and mesoscale influences are important in the formation of tropical cyclones. Previous research (Gray 1968, Riehl 1948, Palmen 1948) has established several large-scale factors that are commonly believed to be necessary for tropical cyclone formation, including: warm sea surface temperatures, an environment supportive of deep convection, an absence of significant vertical wind shear, and a preexisting cyclonic disturbance (see Bosart and Bartlo 1991 and references therein). Past research (Bister and Emanuel 1997, Simpson et al 1997, Montgomery and Kallenbach 1997) has also established several mesoscale processes that can influence the formation of a tropical cyclone. These processes, which act within the largescale disturbances, include vortex mergers and asymmetric forcing. This project examines how these large-scale and mesoscale factors influenced the formation of Hurricane Gabrielle (2001), which formed in the Gulf of Mexico within a few hundred miles of the west coast of Florida.

Developing tropical cyclones are believed to require sea surface temperatures of at least 26° C to 27° C (Palmen 1948, Bosart and Bartlo 1991). The water acts as a heat source for the forming disturbance, providing energy that is released when water vapor condenses. The forming tropical cyclone also needs an environment that will support deep convection, since sustained deep convection is necessary to condense water vapor rapidly, allowing the disturbance to develop.

A significant amount of deep tropospheric vertical wind shear, which is usually defined as at least 10 to 15 m/s, is believed to be detrimental to the formation of tropical cyclones. Significant vertical wind shear deforms the vertical structure of the disturbance, displacing deep convection away from the low-level center. The role that vertical wind shear plays in the formation of tropical cyclones is currently being argued because of cases like Hurricanes Diana
(1984) (Bosart and Bartlo 1991), Michael (2000), and Karen (2001) (Davis and Bosart 2002 (2)), which developed in the presence of a significant amount of vertical wind shear. Some research has also looked into the possibility that a small amount of vertical wind shear is necessary for development (Bracken and Bosart 2000), as opposed to the previous belief that minimal or zero vertical wind shear was optimal (Gray 1968).

Tropical cyclones are believed to develop from preexisting cyclonic disturbances (Gray 1968). These disturbances include easterly waves and baroclinic disturbances. Most tropical cyclones in the Atlantic basin develop from easterly waves (EWs) originating off the west coast of Africa. These classical systems are the focus for the majority of research into tropical cyclone formation. Some tropical cyclones develop from baroclinic waves. These developing systems draw energy from temperature gradients throughout the troposphere, turning the potential energy from the temperature difference into kinetic energy. These systems are often noted for violating the large-scale factor that there must be a lack of significant vertical wind shear (Bosart and Bartlo 1991). One mechanism through which both EWs and baroclinic disturbances can produce tropical cyclones is by producing mesoscale convective systems (MCSs), which can then develop into tropical cyclones. Other features can produce MCSs, including topographical features like extended mountain ranges.

Mesoscale processes influence the formation of the central vortex of the developing system, creating a vortex capable of self-amplitude through air-sea interaction. The processes by which the vortex can be created include forming from one vorticity anomaly, the merger of multiple vorticity anomalies, and asymmetric forcing. A single MCS can produce a vortex (positive vorticity anomaly) strong enough to become the seed for a developing tropical cyclone, or multiple MCSs can form weaker vortices (vorticity anomalies), which can then merge to act as the seed for tropical cyclone development. Montgomery and Kallenbach (1997) proposed that moist convective forcing causes vorticity asymmetries, which decay and thus accelerate the mean tangential winds, acting as a mechanism for tropical cyclone formation (Montgomery and Enagonio 1998). Using theoretical simulations, Montgomery and Enagonio (1998) tested this theory of asymmetric forcing. Asymmetric forcing involves the vortex merger theory, with the convectively forced vorticity asymmetries merging with the system's central vortex.

This project examined the influence of these large-scale and mesoscale factors on the formation of Hurricane Gabrielle (2001). This project focused on the transition from cold core to warm core as defining the start of Gabrielle as a tropical cyclone, since the tropical cyclone is unique among storm systems in its warm-core structure\(^1\) (XX). Gabrielle formed only three days before landfall, within a couple hundred miles of the Florida coast. Forecasters need to be able to predict the formation of systems like Hurricane Gabrielle due to their proximity to people, which is one reason Gabrielle was chosen for this project. Gabrielle was also chosen because the system formed outside the tropics. Most of the commonly accepted factors for tropical cyclone formation have been developed through examining the formation of systems in the deep tropics. Examining Gabrielle will help establish whether the same factors that are believed important in the deep tropics also influence systems forming outside the tropics.

Storms like Gabrielle, which form relatively close to land, are not as likely to become major hurricanes as those that form in the deep tropics, but can still cause large loss of life and massive destruction. In 2001 alone, at least four systems (Allison, Erin\(^2\), Gabrielle, and Karen) developed outside the tropics. Of those systems, Allison and Gabrielle made landfall in the

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1 Other warm-core systems exist, but do not produce the warm core by warming through latent heat release

2 Hurricane Erin formed, dissipated, and reformed; the formation being referred to would be when she reformed
United States as tropical storms and together accounted for at least 43 deaths and an estimated $5 billion in damage (Lawrence and Blake 2001, Stewart 2001 (1), Stewart 2001 (2), Pasch and Brown 2001).

This project examined the observations of Hurricane Gabrielle (Section 2); then simulated the formative stage of Gabrielle’s development using the fifth generation Pennsylvania State University – National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5) (Section 3). The simulation results were compared to the National Center for Environmental Prediction’s (NCEP) analyses and the National Hurricane Center’s (NHC) best track data to check that the simulation did not drastically diverge from the observed events, and then analyzed to determine the influences of the large- and small-scale factors (Section 4). Then conclusions were presented (Section 5) based on the results of the simulation.

2. HURRICANE GABRIELLE

Overview

The pre-Hurricane Gabrielle disturbance formed in the Gulf of Mexico near the tail end of a stationary front around 9 September 2001. The disturbance was recognized as a tropical depression on 11 September 2001, and was classified as Tropical Storm Gabrielle at 1200 UTC 13 September 2001. Gabrielle was only 175 n mi southwest of Venice, Florida, when she was declared a tropical storm, and made landfall as a tropical storm near Venice around 1200 UTC 14 September 2001. During her trek across Florida, Gabrielle spawned 18 tornadoes and was responsible for the deaths of at least two people. Gabrielle intensified to hurricane strength by 0000 UTC 17 September 2001, after crossing the state of Florida and entering the Atlantic Ocean. Gabrielle was classified as an extratropical system on 19 September 2001, while off the coast of Newfoundland (Lawrence and Blake 2001). NHC’s “best track” positions for Hurricane Gabrielle from September 11 through 19 September 2001 are shown in Figure 1.

![Figure 1. NHC Best Track positions for Hurricane Gabrielle 11-19 September 2001.](image-url)
Formation

According to NHC’s Tropical Cyclone Report for Hurricane Gabrielle, “Gabrielle’s origin was non-tropical” (Lawrence and Blake 2001). Lawrence and Blake (2001) discuss a nearly stationary low- to mid-tropospheric trough that produced a cut-off low over Florida by September 9. The disturbance associated with the cut-off low was cold core at this time. A surface low formed beneath the cut-off low by September 11. The transition to a tropical system is marked by the shift of the maximum amplitude of the vortex from the mid-troposphere cut-off low to the surface low. This shift of maximum vorticity is also seen as the transition of the system from cold core to warm core at the surface. Once the surface low formed and convection about the system produced an extensive anvil on the scale of the cut-off low itself, the system was classified as Tropical Depression 8. Tropical Depression 8 intensified into a tropical storm by 1200 UTC September 13, and was given the name Gabrielle. This project examined the period from 1200 UTC September 9 until 1200 UTC September 13 to capture the transition to a tropical system.

Observations

The NCEP final operational analysis for September 2001 and NHC’s “best track” data for Hurricane Gabrielle were used to provide information about Gabrielle’s track and intensity. Also, radar and satellite images were obtained from NCAR to examine the convective features associated with the system. The convective features that were examined included the strength and location of the convection associated with the system.

NHC published its best track information for Hurricane Gabrielle in its Tropical Cyclone Report for that system (Lawrence and Blake 2001). The best track information includes their best estimates for location, minimum central pressure, maximum sustained wind speed, and stage of the tropical cyclone every six hours from the point where the cyclone was classified a tropical depression until it no longer was a tropical system. The best track information for Gabrielle for the period of 11-13 September 2001 is shown in Table 1. There is no best track information for Gabrielle before 1800 UTC 11 September 2001, which is when Gabrielle was first named a tropical depression.

<table>
<thead>
<tr>
<th>Date/Time (UTC)</th>
<th>Lat. (°N)</th>
<th>Lon. (°W)</th>
<th>Minimum Sea Level Central Pressure (mb)</th>
<th>Maximum Sustained Surface Wind Speed (kt)</th>
<th>Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>11/1800</td>
<td>25.8</td>
<td>84.1</td>
<td>1010</td>
<td>25</td>
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<tr>
<td>12/0000</td>
<td>25.7</td>
<td>84.6</td>
<td>1009</td>
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<td></td>
</tr>
<tr>
<td>12/0600</td>
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<td>85</td>
<td>1008</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>12/1200</td>
<td>25.6</td>
<td>85.3</td>
<td>1008</td>
<td>25</td>
<td></td>
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<tr>
<td>12/1800</td>
<td>25.4</td>
<td>85.4</td>
<td>1007</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>13/0000</td>
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<td>1005</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>13/0600</td>
<td>25.2</td>
<td>85.3</td>
<td>1005</td>
<td>30</td>
<td></td>
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<tr>
<td>13/1200</td>
<td>25.3</td>
<td>84.9</td>
<td>1003</td>
<td>35</td>
<td>tropical storm</td>
</tr>
</tbody>
</table>

Table 1. NHC best track information for the pre-Hurricane Gabrielle disturbance from 1800 UTC 11 September 2001 to 1200 UTC 13 September 2001. Includes location, pressure, wind speed, and the stage of the system.
The NCEP final operational analysis combines the available observations to provide a large-scale picture of atmospheric conditions every 6 hours on a 1° by 1° grid. The NCEP analyses between 8 and 14 September were examined for the minimum pressure and location of the pre-Gabrielle disturbance. In addition, the analyses were used to initialize the simulation (Section 3). The coarseness of the analysis grid, however, caused differences between the NCEP analysis and the NHC best track. The minimum central pressure data from the NCEP analysis is shown in Table 2.

<table>
<thead>
<tr>
<th>Date (UTC)</th>
<th>Minimum Sea Level Central Pressure (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 /1200</td>
<td>1013</td>
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<tr>
<td>11 /1800</td>
<td>1013</td>
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<tr>
<td>12 /0000</td>
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<td>13 /0000</td>
<td>1007</td>
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<tr>
<td>13 /0600</td>
<td>1008</td>
</tr>
<tr>
<td>13 /1200</td>
<td>1005</td>
</tr>
</tbody>
</table>

Table 2. NCEP analysis pressure information for the pre-Hurricane Gabrielle disturbance from 1200 UTC 9 September 2001 to 1200 UTC 13 September 2001.

NHC’s best track data only provides information about the track and intensity of the disturbance itself, and that only after it falls under their monitoring. The NCEP analysis data provides information about environmental conditions including wind shear, relative humidity, and temperatures. The NCEP analysis data also provide a means of looking at precursor disturbances, and the data exist whether or not there is a disturbance that is being monitored. The NCEP analysis data, however, cannot resolve mesoscale features. With 1° grid spacing, the minimum resolved features are about 400km in scale, more than twice the size of the radius of maximum winds of the pre-Gabrielle disturbance.

NCAR’s locust archives (http://locust.mmm.ucar.edu/) provided the satellite and radar imagery. This imagery was used to examine convection associated with the pre-Gabrielle disturbance.

Visible satellite imagery, available approximately between 1200 – 0000 UTC each day, indicated that the most extensive cloud cover was systematically located south and southeast of the system’s center, wrapping around to the east of the center by 13 September and to the northeast of the center by the time Gabrielle made landfall on 14 September.

Satellite infrared imagery, available approximately between 0000 – 1200 UTC each day, showed the highest cloud tops (-70° C) south of the center of the system at about 0700 UTC on 12 September, with a large area of sustained high cloud tops (-70° C) shifted from south to east of the center of circulation by 13 September.

Radar imagery, as shown in Figure 2, indicated the highest reflectivity south and east of the system’s center, slowly wrapping around counterclockwise, showing to the north and east of
the center by time of landfall 14 September. Radar is somewhat unreliable for studying tropical cyclones over the ocean, since the further away the cyclone was from radar, the more likely the radar is to miss the convection associated with the system. Satellite/radar composites were consistent with the radar and satellite information and showed heavier precipitation south of the pre-Gabrielle disturbance by 11 September, rotating around to the east of the storm by 13 September (there was a data void for the composite between 0000 – 2000 UTC 12 September).

Figure 2. Radar composite images for 1200 UTC 9-13 September.
3. MODEL DESCRIPTION

This project used the fifth generation Pennsylvania State University – National Center for Atmospheric Research Mesoscale Model version 3 (MM5, Grell et al 1994). MM5 gives users the option of several different methods to represent the physics of the atmosphere. The physical parameterizations chosen for this simulation were the Numerical Weather Prediction (NWP) Explicit Microphysics (NEM) scheme (Schultz 1995), the Kain-Fritsch cumulus scheme (Kain and Fritsch 1993), the Blackadar representation of the planetary boundary layer (PBL) (Zhang and Anthes 1982), cloud radiation, a multi-layer soil temperature model, and no shallow convection.

The NEM scheme was chosen as an efficient scheme that still includes rain, snow, and graupel. The Kain-Fritsch cumulus scheme was chosen as a sophisticated representation of clouds. The Blackadar PBL scheme was chosen for its simplicity compared to other schemes and for having a higher reliability in strong winds than the medium-range forecast model PBL scheme (MRF, Hong and Pan 1996) (Braun and Tao 2000).

For the simulation MM5 used three nested domains. The layout of the three domains is shown in Figure 3. The largest domain had a grid spacing of 111 km, with 91 x 91 grid points. The middle domain has a grid spacing of 37 km, with 79 x 73 grid points. The smallest domain had a grid spacing of 12 km, with 91 x 91 grid points. All three domains had 23 vertical levels from surface level to 50 mb, with more closely spaced levels near the surface.

![Figure 3. The three domains used in the MM5 simulation.](image-url)
Domains 1 and 2 were run for 96 hours, from 1200 UTC 9 September 2001 until 1200 UTC 13 September 2001. Domain 3 was added to the model 48 hours into the simulation, and ran for the last 48 hours, from 1200 UTC 11 September 2001 until 1200 UTC 13 September 2001. Domain 3 was run only for the last 48 hours to reduce computations and to allow the larger mesoscale features to develop. The time step used for domain 1 was 180 seconds, with the time step decreasing by a factor of three for each successive inner domain. The model produced output every three hours for domains 1 and 2, and every hour for domain 3.

The model was initialized using the NCEP final operational analysis for 1200 UTC 9 September 2001. The analysis data provided both the initial conditions and the boundary conditions. The boundary conditions were then updated by tendency every six hours.

4. SIMULATION

The simulation output\(^3\) was compared with available observations to assess how well the model captured the essential components of the formation of Gabrielle. The model run was then examined for information regarding the large-scale factors and mesoscale processes influencing Gabrielle’s formation.

Comparison with Observations

The model output was compared with several sets of observations, including the NHC best track data, NCEP final operational analyses, available ship and buoy data (provided by UNIDATA), the National Oceanic and Atmospheric Association (NOAA) Hurricane Research Division’s (HRD) experimental surface wind analyses, and radar and satellite imagery provided by NCAR. This project examined minimum central pressure, maximum sustained winds, and surface wind contours to compare the strength of the pre-Gabrielle disturbance as well as trends in intensification. Satellite infrared imagery was compared to cloud-top temperatures produced by the model to determine if the convective features of the modeled Gabrielle were in general agreement with the observed organization of convection.

Figure 4 shows the minimum central pressure as determined by the NHC best track data and the simulation. The simulation’s minimum central pressure is either equal to or less than the NHC best track for the entirety of the model run, differing by at most 2 mb. Both show an almost steady decrease in the minimum central pressure, indicating a steady intensification of the system. The four boxes in Figure 4 highlight four periods of dropping pressure in the simulation. Three of those four periods also show corresponding drops in pressure in the NHC best track data, although caution must be used when considering the first drop in pressure for the NHC best track, since it is produced by rounding to the nearest 1 mb.

\(^3\) Unless otherwise noted, discussion of the simulation will focus on the last 48 hours of the model run, when the third domain was active.
Figure 4. Minimum sea-level central pressure as determined by the NHC best track and the simulation. NHC best track does not begin until 1800 UTC 11 September and is only available every six hours. Boxes indicate time periods in simulation with distinctly decreasing pressure.

Figure 5 shows the maximum sustained winds as determined by the NHC best track data and the simulation. The model run produces slightly weaker winds than NHC best track until 14 hours into the simulation. At this point, the simulation maximum sustained winds increase sharply, going from 12 m/s to 17 m/s in the course of three hours. During this time no increase is seen in the NHC best track, leading to larger values of maximum sustained winds in the simulation than in the NHC best track. These values differ at most by about 6 m/s. The data sets approach each other again at the end of the simulation. One reason for the difference between the simulation and the NHC best track maximum sustained winds is that the measurements of the winds were taken at different levels. NHC best track surface winds were taken at 10 m above the surface, while the model surface winds were predicted at 40 m above the surface. Taking friction into account would reduce the predicted winds by 15%-20% over water, yielding a better agreement with observations. The timing of the velocity increase would still differ, however.
Figure 5. Maximum sustained wind speed as determined by NHC best track and the simulation. NHC best track data did not start until 1800 UTC 11 September. Also shown are the maximum wind speeds reported by surface observations (ship and buoy data from UNIDATA).

The NHC best track is an estimate based on limited amounts of information. Reconnaissance aircraft, which provide additional detailed information for NHC best track, did not fly into Gabrielle until 0000 UTC 13 September. Comparing the NHC best track’s minimum central pressure and maximum sustained winds shows discrepancies in the first day of the model run. Between 1800 UTC 11 September and 0600 UTC 12 September, NHC indicates a pressure drop of 2mb, but no change in the maximum sustained winds. The decrease in minimum central pressure should relate to a corresponding increase in maximum sustained winds, yet the winds did not increase until 1800 UTC 12 September, after another drop in pressure. It is possible, however, that the central pressure was responding to large-scale changes that did not affect the maximum sustained winds. One note that needs to be considered when looking at pressure and wind speed is that the wind values may have changed, but not enough to alter the NHC best track, which rounds to the nearest 1 mb for pressure and 5 kts for wind speed. Figure 5 also shows the maximum winds reported by ship and buoy data, obtained from UNIDATA. These surface observations are random and sparse, leaving large areas without observations. A consequence of few surface observations being available is a low possibility of capturing the maximum sustained winds. The surface observations therefore function as a lower bound on maximum sustained winds.

Figure 6 shows the track as determined by the NHC best track data and the simulation. Since the simulation track was very noisy, the figure only displays six hour increments. The simulation places Gabrielle’s track 1°-2° north of the NHC best track. Towards the end of the
simulation the track deviated about 1° west of the NHC best track as well. Both tracks keep the system over water for the duration of the simulation.

Figure 6. Track positions for the pre-Gabrielle disturbance for every six hours, from 1200 UTC 11 September to 1200 UTC 13 September for NHC best track and the simulation. NHC best track was not available until 1800 UTC 11 September.

Figure 7 shows six satellite infrared images from 11-13 September. Figure 8 shows the model cloud top temperatures produced by domain 2 (cropped for easier comparison with Figure 7) at six different times in the model run. These times include 0300 and 1200 UTC 11 September, which occurred before domain 3 was initialized. The cloud top temperatures were compared with the satellite infrared imagery for a general measure of the strength and location of convection associated with Gabrielle.

Both the satellite infrared images and the simulation output indicated general agreement in the location of convection relative to the disturbance. Both placed deep convection downshear of the center of the disturbance throughout the simulation period. Both show the convection wrapping around the disturbance by the end of the simulation period. Although in general the model run showed higher (colder) cloud tops in larger areas than the satellite infrared images, both showed the highest cloud tops beginning to appear at approximately 0700 UTC September 12 (not shown). One reason the model run showed more widespread deep convection than the satellite is that the coarseness of the grid necessitates a parameterization for convection instead of explicit convection and the Kain-Fritsch parameterization tends to produce a little too much area covered by rainfall; another reason is that the grid aspect of the model does not allow for shallow layers of clouds that appear partly transparent, as the satellite does.
Figure 7. Satellite infrared images for 0345 and 1115 UTC 11, 12 and 13 September. The L's denote the center of the pre-Gabrielle disturbance; arrows indicate the direction of the vertical wind shear as determined by the simulation (missing for 0345 UTC 11 September). ➔ = approximately 5 m/s
Figure 8. Cloud top temperatures from domain 2 for 0300 and 1200 UTC 11, 12 and 13 September. The L's denote the center of the pre-Gabrielle disturbance; arrows indicate the direction of the vertical wind shear (missing for 0345 UTC 11 September).
Large-Scale Factors

The large-scale factors – warm SSTs, environment supportive of deep convection, lack of significant vertical wind shear, and preexisting cyclonic disturbance – were examined using the simulation. The SSTs under the center, shown in Figure 9, were above threshold values. Threshold values for sufficiently warm SSTs for tropical cyclone formation usually range between 26° C and 27° C (Palmen 1948, Bosart and Bartlo 1991), while SSTs during Gabrielle’s formation ranged between 28° C and 30° C. Deep convection was present in both the simulation and the satellite infrared images (as shown in Figures 7 and 8), indicating that an environment supportive of deep convection was present.

![Graph showing temperature over time](image)

Figure 9. Sea surface temperature (SST) under the center of the pre-Gabrielle disturbance from 1200 UTC 11 September through 1200 UTC 13 September.

The direction of the vertical wind shear shifted from north-northeast during earlier times to north-northwest by 12 September and northwest by 13 September. The vertical wind shear’s magnitude for the model run is shown in Figure 10. Examining the vertical wind shear for the large scale indicated that the shear was bordering on significant levels. Looking at smaller scales, both spatial and temporal, showed an interesting feature of the vertical wind shear. For approximately a six-hour period, from 0100 UTC 12 September to 0700 UTC 12 September (as indicated by the box in Figure 10), the wind shear decreased dramatically to only about 3 m/s. It is during this period that several events took place, including, most notably, the initial development of a sustained warm core in the disturbance. Warmer temperatures appeared in the center of the pre-Gabrielle disturbance by 0000 UTC 12 September (as shown in Figure 11), and a sustained warm core developed at 0600 UTC 12 September through the 850 mb and 700 mb levels (not shown). Figure 10 also includes the time series of the maximum sustained winds and the maximum azimuthally averaged tangential winds. The maximum azimuthally averaged
tangential winds were determined by grouping grid points within radius rings and then averaging over each ring, with the highest average being the maximum. Both wind measurements increased during the period of reduced vertical wind shear, but the maximum sustained winds increased more steeply than the maximum tangential winds during this time. The differences between the maxima indicated that strong asymmetries had developed during this time period.

![Graph showing wind speed trends over time](image)

**Figure 10.** Vertical wind shear over the pre-Gabrielle disturbance as derived from the simulation. Also shown are the maximum tangential winds and the maximum sustained winds of the disturbance.
Figure 11. Time series of potential temperature. The values shown are the difference between the potential temperature at the center and the potential temperature in the environment (175 km radius from the center).

For determining if a preexisting cyclonic disturbance was present, the first step was examining domain 1 at the beginning of the simulation (1200 UTC September 9). Inspection of domain 1 indicated that the disturbance did not originate from an EW, the most common origin for tropical cyclones. Examination of potential vorticity and wind vectors in domain 1 showed that a cut-off low developed in the mid-troposphere from a stationary front draped over the state of Florida (Figure 12 (a)). The baroclinic origin of the disturbance is in agreement with the observations as described by the NHC in their report on Gabrielle (Lawrence and Blake 2001). This baroclinic disturbance then developed into Gabrielle, but not through baroclinic development. Baroclinic development relies on a temperature gradient on the surface, and produces distortions of that temperature gradient. No distortions of the temperature gradient field were evident at this stage of Gabrielle’s formation.
Figure 12. Potential vorticity at 700 mb from domain 2 at 1200 UTC 9 September (a) and satellite infrared from the 1115 UTC 9 September (scale for infrared same as in Figure 7).

Mesoscale Processes

Examining the beginning of the model run (1200 UTC 9 September) also helped to determine whether MCSs played a role in the development of a central vortex for the system, whether from one vortex (Bister and Emanuel 1997) or vortex merger (Simpson et al 1997). No large areas of sustained deep convection that would be identified as MCSs were evident from satellite infrared (Figure 12 (b)). The lack of organized convection at the beginning of the formation process indicates that the central vortex did not originate from a single vortex or from vortex merger. The convection present, identified in Figure 12 (b), was diurnal and did not move with the vortex or coincide with its formation.

Both satellite infrared images (Figure 7) and cloud-top temperatures derived from the simulation (Figure 8) indicated persistent convection downshear from the center of the pre-Gabrielle disturbance as it developed. This is consistent with the theory that asymmetric forcing was active in the development of Gabrielle. To see if the rainfall produced by the interaction of vertical wind shear and the disturbance was responsible for intensifying the central vortex of Gabrielle, lower tropospheric relative vorticity was examined. Figure 13 shows the vorticity and
wind field at 900 mb for 0000, 0600, 1200 and 1800 UTC 12 September. Note that 0600 UTC 12 September falls within the period of low vertical wind shear, and the maximum sustained winds increased much faster than the maximum azimuthally averaged winds at this point, indicating strong asymmetries. As can be seen in Figure 13, the spiral bands of high vorticity evident at 0600 UTC have merged into the central vortex, appearing as a ring of high vorticity by 1800 UTC and remaining in that configuration for the remainder of the simulation.

Figure 13. Relative vorticity from domain 3 for 0000, 0600, 1200, and 1800 UTC 12 September.

5. DISCUSSION AND CONCLUSIONS

The simulation did reproduce the general features of Gabrielle with an acceptable amount of accuracy, allowing the examination of the simulation output to determine the large-scale factors and mesoscale processes that influenced her formation. Gabrielle developed from an extratropical disturbance through wind-shear-dependent asymmetric forcing. This type of
tropical cyclone formation differs significantly from traditional formation processes described in previous research (Bister and Emanuel 1997, Simpson et al 1997).

Vertical wind shear bordered on significant levels during the model run. The vertical wind shear decreased to approximately 3 m/s for a six-hour period, from 0100 UTC 12 September until 0700 UTC 12 September. During this period the pre-Gabrielle disturbance made the transition from a cold-core extratropical disturbance to a warm-core tropical cyclone. This period also saw the maximum sustained winds increase much more than the maximum azimuthally averaged tangential winds, pointing to strong asymmetries in the building system. The cause of this period of decreased vertical wind shear is unknown, further work would include investigating whether the decrease in shear was related to convection near the pre-Gabrielle disturbance.

Asymmetric forcing seemed to play a major role in the development of the pre-Gabrielle disturbance. Both the satellite infrared and the model cloud-top temperatures showed deep convection consistently downshear of the center of the disturbance. This convection produced vortices that underwent shearing from the central vortex. According to the theory of asymmetric forcing (Montgomery and Kallenbach 1997), these vortices gave their energy to the central vortex as they were destroyed. Examination of the vorticity revealed spiral bands of vorticity about the central vortex by 0600 UTC 12 September, evolving into a ring of high vorticity about the center by 1800 UTC 12 September. This vorticity structure is consistent with the theory of asymmetric forcing as described by Montgomery and Kallenbach (1997) and modeled in Montgomery and Enagonio (1998).

Additional information could be gained from adding a fourth domain to the model run to explicitly handle convection. Adding a fourth domain would allow for a better analysis of the asymmetric forcing process. Also, running sensitivity tests to determine the differences that varying model parameterizations would cause could give information on the robustness of the processes involved. Altering or removing the initial disturbance or the vertical wind shear would provide information on how important these factors were in the formation of Gabrielle. From this project it appears that the presence, rather than the absence, of vertical wind shear was crucial to the formation of Gabrielle, which runs counter to what has been established as the necessary ingredients for tropical cyclone formation, and requires further examination.

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