CHAPTER III

SIMULATION OF SUMMER CASE WITH NO PRECIPITATION

3.1 Synoptic Conditions

The period, August 15, 2000 0000Z (1900 LST) through August 18, 2000 0000Z, is a summer case with no precipitation. Throughout this period, synoptic winds were typically light and variable, allowing mesoscale features to dominate the local weather. For most of the duration of the case study, high pressure dominates the southeast United States. A synoptic map obtained from NCDC at 1200Z (0700 LST) on the 15th is shown in Figure 3.1.1. Mild synoptic events in the case study include the passage of a dry trough of low pressure in western North Carolina (NC) between 1200Z (0700 LST) on the 16th and 0000Z (1900 LST) on the 17th. This passage is indicated in Figure 3.1.2 at 1200Z (0700 LST) on the 16th. Also, a dry, mild cold front passing through the domain between 0000Z and 1200Z on the 17th closely follows this dry trough (Figure 3.1.3).

Cloud cover is minimal over the Carolinas during this case study. Some thin high cirrus clouds may have been present in the inner domain at times. Exception occurs on the 17th when some thicker clouds develop in the northeast portion of the domain as seen in the infrared satellite imagery at 0000Z (1900 LST) as shown in Figure 3.1.4. These clouds move offshore and the domain remains clear until the last few hours of the period where
some heavier clouds begin to move into the domain from an approaching synoptic system.

3.2 Evaluation of Mesoscale Processes

Numerical simulation of mesoscale processes and boundary layer structure is performed. The primary focus is directed towards North Carolina (NC). The combination of topography in the west, land-use pattern variations, and close proximity to the coast in the east can cause various mesoscale interactions, which are complex in nature. Analysis of modeled boundary layer processes and interactions are evaluated and validated with observational data. Evaluation begins with an examination of simulated horizontal and vertical cross sections in the 5 km domain. Analysis of these plots could indicate model performance and its ability to capture, integrate, and simulate mesoscale processes. Surface modeled wind fields in the 5 km domain are compared with EDAS analysis winds and the 15 km domain to see if the model can capture these features at a coarser resolution. Model generated forecast soundings are also compared with observed rawinsonde sounding data at Greensboro, NC (GSO) and Newport, NC (MHX) for comparison of above surface winds; the focus remains on the boundary layer.

Additional analysis is performed to estimate model performance on a point-by-point basis. Thirty-six hourly surface observation stations across NC are selected for comparison with the closest model grid points in the 5km
domain. These stations are labeled in Figure 3.2.1. The latitude and longitude of the stations, as well as the respective model grid points, labeled I and J, closest to the stations are identified in Table 3.2.1. Names of the stations are abbreviated with a three letter call sign indicated in Table 3.2.1. The relative locations of model grid points to observational sites are shown in Figure 3.2.2. These observation stations consist of a combination of automated surface observation stations (ASOS) (McKee et al. 1996) and agricultural network stations (AgNet) managed by the State Climate Office of North Carolina (Niyogi et al. 1998).

Using time-series data from the observation stations and the model grid points, a quantitative analysis is performed at each station. Model wind, temperature, and specific humidity values are evaluated and compared at each location. Statistical analysis of temperature and specific humidity give additional insight to model performance at those locations (Stull 2000; Wilks 1995). Statistical indices used include: Absolute Correlation, Root Mean Square Error (RMSE), Bias, Normalized Mean Square Error (NMSE), Weighted Normalized mean square error of the Normalized Ratios (WNNR), Normalized mean square error of the distribution of the Normalized Ratios (NNR) (Poli and Cirilio 1993), and the Index of Agreement (Willmott 1982).
3.3 Winds

Simulated wind patterns for the inner domain are first analyzed using the horizontal wind vectors at the surface. Three geographic areas of NC are examined: coastal, mountains, and piedmont. Initial analysis of the wind vectors at 0000Z August 15th show a light northwesterly flow across much of the domain, with the strongest winds occurring offshore and over the northern piedmont region of NC as indicated in Figure 3.3.1.

Examination of the sea breeze development helps indicate how well the model simulates diurnal variation and differential heating. At 1900Z (1400 LST) on the 15th, 16th, and 17th, there is evidence of a sea breeze indicated by a reversal of surface winds towards the shore. An example of this wind reversal is shown in Figure 3.3.2 at 1900Z (1400 LST) on the 17th. Inland penetration of the sea breeze is approximately 30 km in the southern coastal region. To further determine the extent of the sea breeze, a cross section is taken along the southern coast of NC near Wilmington; the location is indicated by the letter A in Figure 3.3.3. This cross section, shown in Figure 3.3.4, shows a well-defined sea breeze circulation at 1800Z on August 15th. Similar circulations were modeled on August 16th and 17th as well. The extent of the simulated sea breeze circulation is approximately 500m above the surface over the land-water boundary.

The onset of the sea breeze is verified using surface winds at 10-meter level from Wilmington, Whiteville, Castle Hayne, Hatteras, and Beaufort
An example of the observed and modeled wind direction coinciding with the location of cross section A in Figure 3.3.3 is given in Figure 3.3.5 for Wilmington (ILM). A wind direction shift from the northwest begins at approximately 1100 LST on the 15th. By 2000 LST the wind has moved to from the southeast. The wind direction shift indicated in the observations is matched well by the model. This shift is also apparent on the 17th. A defined sea breeze did not occur on the 16th possibly as a result of the dry front moving through the area.

The Appalachian mountain surface winds are more variable and have spatial discontinuity at some locations. The general flow pattern in the mountains, for much of the simulation, is from the northwest, although there appears to be frequent areas of convergence on the leeward side of the mountains. An area of converging winds east of and parallel to the Appalachians is seen at 1200Z (0700 LST) on the 16th in Figure 3.3.6. This feature, as simulated by the model, shows strong flow, perpendicular to the mountain range on the lee side of the mountains that is most likely induced by the mountainous terrain. This flow appears to converge with the overall light, ambient flow from the southwest as seen in the rest of the domain at this time.

To examine the vertical extent of this simulated feature, a cross section is taken across the axis of the mountains (the location is indicated by the letter B in Figure 3.3.3). Complex flow patterns, including terrain induced
convergences and mesoscale circulations, are evident in Figure 3.3.7 at 0000Z (1900 LST) on the 16th. There is an accelerated flow over the top of the mountain range, about 5 to 8 ms\(^{-1}\). On the lee side of the mountains, a well-mixed layer may be a result of upward vertical motion in the simulated flow induced by mountain waves. This accelerated flow converges with slower moving air on the leeward side of the mountains, approximately 1 to 3 ms\(^{-1}\). The well-mixed layer appears to extend well above the surface to a height of about 2 km. On the leeward slope of the mountains, a return flow circulation develops during the late afternoon hours. This circulation extends 50 km in the horizontal and from the surface to approximately 1 km. The well-mixed layer, mountain waves, and circulation patterns are more pronounced during the daytime and erode as the night progresses.

Diurnal variation is well simulated as represented in Figures 3.3.8 at 0600Z (0100 LST) on the 16th and at 1800Z (1300 LST) on the 16th as seen in Figure 3.3.9, during the night and day, respectively. A fairly uniform stable flow from the northwest, where the height of the boundary layer is not clearly defined and hard to estimate is shown in Figure 3.3.8. The simulation of the winds indicates strong katabatic flow on the lee slopes of the mountain range. Mountain waves are not as pronounced and the local circulations have completely dissipated by 0600Z. A well-mixed layer up to approximately two kilometers showing the return of diurnally forced flow patterns marked by the leeward slope circulation is shown in Figure 3.3.9. Here, the lee slope
circulation is beginning to develop and is not well defined by 1800Z (1300 LST). Mountain waves are more amplified during the daytime hours.

Although diurnal variation is well modeled, local terrain effects in the mountains can cause local variability in the flow patterns. The observed and modeled wind speeds at 10 meters at Fletcher, NC (the location is indicated in Figure 3.2.1) are shown to be out of phase as indicated in Figure 3.3.10. When compared with Figure 3.3.8, the model indicates katabatic flow with an increase in wind speed at night while the observations do not indicate increased wind speed as seen in the simulated winds in Figure 3.3.10. Observations at Fletcher and Asheville show a decrease in wind speed at night and an increase during the day. The observed and model wind directions at Fletcher are in better agreement as shown in Figure 3.3.11. Throughout the most of the simulation there is a north-northwesterly flow at Fletcher as also indicated in the horizontal wind vectors. These stations are located along cross section B as indicated in Figure 3.3.3. Local topography appears to dominate the local flow pattern and is not simulated by the model even at high resolutions; in this case 5 km.

As the distance from the complex topography increases, the modeled wind speeds appear to improve as can be seen in the foothills of the mountains at the Hickory (HKY) station as shown in Figure 3.3.12. Here, the observed and model wind speeds seem to be in phase. Observed and model wind speeds appear to correlate fairly well. Inconsistencies appear to be
when the wind is light as seen in early morning hours during forecast hours 30 through 40 (0600Z through 1600Z on August 16th) and hours 50 through 60 (0200Z through 1200Z on August 17th). The simulated wind direction at Hickory also seems to match the wind pattern fairly well as recorded by the observations. Discrepancies occur when the observed wind direction is reported as variable due to light wind speed. This is evident from the lack of observed points as compared to model points as shown in Figure 3.3.13.

Forward trajectories are calculated from four points in the mountain region to investigate the potential for pollution transport. These trajectories, locations are at the Tri Cities region, Waynesville, Fletcher/Asheville, and Charlotte, are shown in Figure 3.3.14. The station locations for the trajectories are indicated in Figure 3.2.1. The release time is at 0000Z (1900 LST) on the 15th at the 10-meter level.

The trajectory calculated from the model grid point in the Charlotte area, labeled as point 1, moves to the southwest at a near surface elevation over a distance of 100 km by 1800Z (1300LST) on the 15th. The parcel then quickly turns and moves completely in an opposite direction. Slow ascension accompanies this northeast movement of the parcel to a level of approximately 950 mb (400 - 500m) by the time it reaches the North Carolina / South Carolina border near the initial parcel originating location. At this point, this air parcel turns to the east and maintains a height of about 950 mb (400 – 500m) until it reaches the coastal area where it ascends to about 900
mb (850 to 1000 m) at 0000Z (1900 LST) on the 17th. The parcel then proceeds offshore and moves toward the south while continuing to slowly rise for the rest of the simulation.

Although the parcel originating locations are approximately 50 km apart, the Fletcher and Waynesville trajectories are very similar, labeled points 2 and 3 respectively. These parcels move together towards the southwest over a distance of approximately 150 km during the first 18 hours at a height near the 10 m release height. At this point, in northeast Georgia, the parcels make a clockwise turn while rising to a level of about 800mb (1700 – 2000 m). The parcels then move to the south, exiting the domain in eastern Georgia by 1800Z (1300 LST) on the 16th.

From the Tri-Cities parcel originating location, labeled point 4, the simulation of the air parcel trajectory is shown to slowly move to the west-southwest covering a horizontal distance of approximately 50 km in the first 24 hours with little vertical motion. The parcel then turns towards the mountains and rapidly ascends to a level of approximately 800 mb (1700 – 2000 m) while accelerating and exiting the domain near the South Carolina / Georgia border by 0000Z (1900 LST) on the 17th.

Backwards trajectories from the Waynesville and Fletcher / Asheville locations are shown in Figure 3.3.15. These simulations indicate diverse paths of air parcels as a direct effect of the complex topography. The Fletcher / Asheville location, indicated by point 1, indicates that the air parcel is coming
from the Kentucky / Tennessee border. This air parcel stays near the surface while moving the east-southeast. After crossing the Appalachians, the parcel turns to the south, crosses the North Carolina / South Carolina border and immediately turns to the north ending at the Fletcher / Asheville location by 0000Z (1900 LST) on the 18th. The Waynesville site, indicated by point 2, shows the parcel coming from Kentucky at a height of approximately 800 mb (1700 – 2000 m) and rapidly descending to the surface layer by 0000Z (1900 LST) on the 18th.

Daytime winds show significant variations in the mountain, piedmont and in the coastal regions on 0000Z August 16th and 0000Z August 18th as indicated in Figures 3.3.16 and 3.3.17. Convergence on the leeward side of the mountains is evident where a northwesterly flow over the mountains converges with synoptic flow from the south in the foothills region of North Carolina. There also appears to be an area of convergence in the sand hills region where a strong southerly flow of about 6 ms⁻¹ suddenly ceases in a narrow area of near calm winds. This convergence zone extends well into South Carolina and has an orientation of northeast to southwest. A well-defined sea breeze is evident in the simulation and extends well inland, as much as 90 km as shown in Figure 3.3.17. Nighttime conditions at 0600Z (0100 LST) on the 15th and 0600Z on the 16th have a more uniform flow pattern, except in the mountains, as shown in Figures 3.3.18 and 3.3.8.
These winds are from the northwest and have a magnitude of approximately $8.0 \text{ ms}^{-1}$.

The location of cross section C taken across the sand hills region of the piedmont is shown in Figure 3.3.3. This region consists of a narrow band of sandy soil that borders the clay-based soils in the piedmont as shown in Figure 2.4. Sharp contrasts in soil characteristics can result in differential heating across this region. These heat flux gradients, which can initiate local vertical mesoscale circulations, are discussed in Sections 3.5 and 3.9.

Locally induced mesoscale circulations during the daytime hours in the sand hills region at 0000Z on the 16th and 0000Z on the 18th are shown in Figures 3.3.19 and 3.3.20, respectively. The circulation as seen in Figure 3.3.19 has horizontal coverage of approximately 35 km along the cross section and a vertical extent of 500 to 600 meters.

The sand hills circulation indicated in Figure 3.3.20 is more developed and the center of circulation is elevated to a level of approximately 1 km. The horizontal extent stretches over 70 km and has a vertical presence up to 2 km. There is a strong surface flow, about $4.6 \text{ ms}^{-1}$, associated with this circulation, with a strong upward component on the westward side of the circulation. Evolution of this feature over time shows a westward migration of this circulation feature where the center travels 35 km in the horizontal from east to west over a span of 6 hours. These circulations are not evident in the nighttime at 0600Z (0100 LST) on the 16th as shown in Figure 3.3.21. The
flow in the evening is fairly uniform and is from the west at a maximum of 4.3 ms$^{-1}$.

Modeled and observed wind speeds at 10 meters at multiple stations across NC over the 5 km domain are analyzed and compared. Although the general synoptic flow pattern is handled well throughout the state, local mesoscale point-to-point comparisons in the piedmont are variable and subject to error. The time series for the wind speeds at Raleigh Durham (RDU) (the location is shown in Figure 3.2.1) is shown in Figure 3.3.22. The observed and modeled wind speeds are often out of phase with each other. The observed winds are calm at night with an increase in wind speed during the daytime. The modeled wind speeds are out of phase and indicate increased winds during the night with calmer winds during the day.

Wind directions at RDU are shown in Figure 3.3.23. The wind directions for observations and the model are in good agreement for most of the simulation. The biggest inconsistency occurs in the evening where the observed winds are calm with a variable direction and the model indicates increased wind speeds with direction from the northwest during the first 12 hours of the simulation. These discrepancies in the winds over the domain are possibly attributed to the surface energy budget and / or the boundary layer physics.

The neighboring piedmont station, Greensboro (GSO), indicates better correlation between the observed and model wind speeds as shown in Figure
3.3.24. In general, the simulated wind speeds at GSO are in phase with the observations. The model performance of simulating the correct wind speed looks as if it improves in the piedmont as compared to the mountainous region. Observed wind directions at Greensboro are well simulated by the model as shown in Figure 3.3.25. Wind shifts observed at the stations are picked up by the model throughout the simulation.

Surface wind vectors from the model simulation are compared with EDAS analysis of surface winds at 0000Z and 1200Z during the forecast period of August 15th through August 18th for the 5km domain and the 15km domain. The surface winds at the initial time, 0000Z August 15th, for the 5 km domain and the 15 km domain are in good agreement with the EDAS analysis winds as shown in Figures 3.3.1, 3.3.26, and 3.3.27. The EDAS analysis shows a northerly to northwesterly flow over much of the domain with an anticyclonic rotation of the winds off of the South Carolina coast as illustrated in Figure 3.3.26. The wind flow in the 15 km domain is similar to the wind pattern in the EDAS analysis, including the placement of the surface high pressure (noted by the anticyclonic rotation off the South Carolina coast) as shown in Figure 3.3.27. Initial winds in the 5 km domain also agree with general flow pattern of the EDAS analysis as shown in Figure 3.3.1.

Some of the mesoscale features in the 5 km wind pattern, such as calm winds in the coastal plain region, are not represented by the EDAS analysis although the wind vectors are reduced in the region to about 5 ms⁻¹.
The wind speed in the EDAS analysis is typically greater than the model's 5 km and 15 km domains with maximum speeds offshore at 20 ms$^{-1}$, 6.5 ms$^{-1}$, and 9.9 ms$^{-1}$, respectively.

The surface winds at the 36 hour forecast time, 1200Z August 16$^{th}$, for the 5 km domain and the 15 km domain are also in good agreement with the EDAS analysis winds as shown in Figures 3.3.6, 3.3.28, and 3.3.29. The EDAS analysis shows a west-southwesterly flow across North Carolina as shown in Figure 3.3.28. A similar wind pattern to the EDAS analysis is seen in the 15 km model domain also as shown in Figure 3.3.29. Mesoscale variability in the simulated 5 km wind pattern in the mountains is shown in Figure 3.3.6. Various wind directions in this region as well as katabatic flow, are not well represented by the EDAS analysis although the variability is well simulated in the 15 km domain.

An interesting feature in the 5 km and 15 km domain in this region, not as distinct in the EDAS analysis, shows a discontinuity in the wind field on the leeward side of the mountains in North Carolina where the wind is from the northwest. This feature is most likely related to the katabatic flow the model simulates in this region as discussed in the previous paragraphs. Wind speeds in the EDAS analysis are fairly consistent with the model's 5 km and 15 km domains where the wind speeds over North Carolina are approximately 10 ms$^{-1}$. 
The surface winds at the 72 hour forecast time, 0000Z August 18th, for the 5 km domain and the 15 km domain are in fair agreement with the EDAS analysis winds over North Carolina as shown in Figures 3.3.17, 3.3.30, and 3.3.31. The EDAS analysis shows a curved flow coming from the northeast off the coast and turning into the direction of the coast and continuing to turn clockwise and becomes south-southeast in the mountainous region of North Carolina as shown in Figure 3.3.30. In the southern part of the domain, strong flow from the south is seen advancing up to the North and South Carolina border. A similar wind pattern to the EDAS analysis is seen in the 15 km domain as shown in Figure 3.3.31. Here, the extent of the penetration of the southern flow is reduced where the model has a northeasterly flow extending down to the South Carolina and Georgia border. The model surface winds in the 5 km domain also agree with general flow pattern of the EDAS analysis and the 15 km domain over North Carolina as shown in Figure 3.3.17.

Mesoscale variability in the 5 km wind pattern is seen in the coastal region; a distinct inland penetration of the sea breeze is evident with wind speeds of about 7 ms\(^{-1}\). Wind speeds in the EDAS analysis and 15 km domain over North Carolina are also approximately 7 ms\(^{-1}\). Other times in the model simulation match well with the EDAS analysis surface wind fields.

Model generated forecast soundings are compared with observed rawinsonde sounding data at Greensboro (GSO) and Newport (MHX) for
comparison of above surface winds; the focus remains on the boundary layer. Observed winds from the Greensboro (GSO) sounding at 0000Z August 16th are from the southwest at 5 kts at 925 mb veering to a northerly flow of 25 kts at 600 mb as shown in Figure 3.3.32. The model forecasted sounding at this time also shows winds from the southwest at 5 kts from the surface up to 925 mb and veering to a northerly flow of 25 kts at 600 mb as shown in Figure 3.3.33.

Observed winds from the Greensboro (GSO) sounding at 1200Z August 17th are from the north-northeast at less than 5 kts at 975 mb veering slightly to a east-northeasterly flow at 925 mb and then backing to a north-northwesterly flow of 30 kts at 600 mb as shown in Figure 3.3.34. The model forecasted sounding at this time shows the winds from the northeast at 5 kts from the surface up to about 925 mb and then backing to a north-northeasterly flow of 20 kts at 600 mb as shown in Figure 3.3.35.

Observed winds from the Newport (MHX) sounding at 0000Z August 15th are from the northwest at 5 kts near the surface, backing slightly to a west-northwesterly flow between 925 mb and 850 mb and then veering to a northwesterly flow of 20 kts at 600 mb as shown in Figure 3.3.36. The model forecasted sounding at this time shows winds from the west-northwest at 5 kts near the surface and veering to a northwesterly flow of 20 kts at 600 mb as shown in Figure 3.3.37.
Observed winds from the Newport (MHX) sounding at 0000Z August 18\textsuperscript{th} are from the east-southeast at 5 kts near the surface and backing to northwesterly flow of 20 kts at 600 mb as shown in Figure 3.3.38. The model forecasted sounding at this time shows the winds from the southeast at 5 kts near the surface backing to a north-northeasterly flow of 20 kts at 600 mb as shown in Figure 3.3.39.

3.4 Planetary Boundary Layer Structure

Planetary boundary layer (PBL) heights are examined and compared with soundings from the upper air station at Greensboro (GSO). Also, SODAR data from the Environmental Protection Agency (EPA) was obtained from the Research Triangle Park (RTP) location. This location is indicated in Figure 3.2.2 by a square marker on the map and in Table 3.2.1.

Horizontal contour plots of PBL heights show significant diurnal variation with heights as low as 100 meters at night and over 1500m during the day. These variations are consistent with the overall observed variation. The PBL heights at 1200Z (0700 LST) on August 15\textsuperscript{th} are shown in Figure 3.4.1. Here, the simulated stable boundary layer over the innermost domain indicates an average height of approximately 200 – 300m.

Off shore, near the Gulf Stream, simulated boundary layer heights are still in excess of 1 km. In comparing with the model’s placement of the Gulf Stream and the SST, a 3-day composite AVHRR image of the sea surface
temperature (SST) is shown in Figure 3.4.2. The initial SST for the model, a weekly archived composite from NCEP, at 0000Z (2000 LST) on August 15th, is illustrated in Figure 3.4.3. The comparison of Figures 3.4.2 and 3.4.3 of the modeled SST temperature, gradient, and Gulf Stream placement are in good agreement with the observations.

A Stuve diagram of the 1200Z (0700 LST) Greensboro (GSO) sounding data on the 16th is shown in Figure 3.4.4. The location of this station is indicated in Figure 3.2.1. A capping inversion at approximately 600m is indicated in the sounding. This data is compared with model output data of PBL height contours shown in Figure 3.4.5. The PBL height contours from the model indicate good agreement with the sounding data at GSO. Variations in the PBL height across North Carolina show a general decrease, about 500 m to 200 m, from east to west across the piedmont region.

PBL heights obtained from SODAR data (the location is indicated in Figures 3.2.1 and 3.2.2) on the 16th are shown in Figure 3.4.6 and 3.4.7. A stable boundary layer, beginning at 1900Z (0000 LST), as indicated Figure 3.4.6, grows over time. A boundary layer height of approximately 200 to 250 meters above the surface at 1200Z (0700 LST) is shown in Figure 3.4.7. Comparing Figure 3.4.5 and 3.4.7 shows good agreement in the vicinity of the SODAR location where the model indicates a PBL height of approximately 300 meters.
A Stuve diagram of the 1200Z (0700 LST) Greensboro (GSO) sounding data on the 17th is shown in Figure 3.4.8. There appears to be a capping inversion at approximately 400m. This data is compared with model output data of PBL height contours shown in Figure 3.4.9. The PBL height contours from the model indicate good agreement with the sounding data at GSO. Simulated PBL heights across NC increase from west to east from approximately 100 meters in the western part of NC to 600 meters near the coast.

A time series of PBL heights obtained from SODAR data on the August 17th is shown in Figure 3.4.10. An observed boundary layer height of approximately 150 to 200 meters above the surface at 0700 LST (1200Z) on the 17th is indicated in Figure 3.4.10. Comparing Figure 3.4.9 and 3.4.10 shows reduced agreement in the vicinity of the SODAR (the location is indicated by a square marker in Figure 3.2.2) where the model indicates a simulated PBL height of approximately 500 meters. Disagreement between the model and observations may be attributed to PBL physics or the energy budget. The convective growth of the boundary layer can also be seen in Figure 3.4.10. This growth begins at approximately 1230Z (0730 LST). PBL growth is observed up to approximately 500 m at 1430Z (0930 LST) where the heights exceed the range limitations of the SODAR.

Comparison of the model output with the observations is concentrated on the nocturnal boundary layer and the convective boundary layer growth
since the SODAR range does not exceed approximately 600m. Comparing the nocturnal boundary layer heights resolved by the SODAR over the 72-hour period with the simulated PBL heights at the SODAR site reveals good overall correlation. The time of occurrence of convective boundary layer growth is also well captured by the model. The model quickly grows the boundary layer, coinciding with the observations, but significantly overestimates the rate of growth.

A case representative example of SODAR observed PBL heights, shown in Figure 3.4.10 on August 17th, and modeled PBL heights, shown in Figures 3.4.9, 3.4.11, 3.4.12, and 3.4.13 from 1200Z (0700 LST) to 1500Z (1000 LST), are compared. The modeled PBL height at 1200Z (0700 LST) at the SODAR location is about 300 to 400m indicated in Figure 3.4.9. Observations at this time indicate a boundary layer height of approximately 200 meters as shown in Figure 3.4.10. At 1300Z (0800 LST), the modeled PBL height is near 400 to 500 meters near the SODAR as shown in Figure 3.4.11. SODAR observations at this time indicate a height of about 300 meters as shown in Figure 3.4.10. Along the shore, modeled PBL growth in the coastal region is about 900m. Model simulated heights in the mountainous region are still at approximately 100 to 200m above the surface.

By 1400Z (0900 LST), modeled PBL heights around the RTP area (the SODAR site location) are shown to be approximately 800 to 900m illustrated in Figure 3.4.12. Corresponding heights given by the SODAR in Figure
3.4.10 are shown to be approximately 500m. Heights along the northern coastal area are approximately 1000 to 1100m as indicated in Figure 3.4.12. Interestingly, the modeled heights along the southern coast are much lower, approximately 500m as discussed in Section 3.9. Modeled heights in the mountains are now about 500 meters above the surface.

In Figure 3.4.13, the modeled heights at 1500Z (1000 LST) are approximately 1200 to 1300m at the SODAR location. The extent of the PBL height is not discernable by the SODAR at 1000 LST as shown in Figure 3.4.10. Based on the rate of growth as indicated in Figure 3.4.10, PBL heights are most likely at about 600 to 700 meters by this time. Along the coast, the model indicates heights at approximately 1400 to 1500m as shown in Figure 3.4.13, where heights just offshore of the southern coast are still at 500 to 600m. Heights in the mountains are about 1000m as indicated by the model. This trend of convective growth is apparent on the morning of the 15th and 16th as well.

3.5 Land Surface Processes

Effects of heterogeneity in land-use and soil types were evaluated with respect to observed and modeled land surface processes. Latent heat fluxes from the model simulation at 1800Z on the 16th indicate a strong gradient in the sand hills region as shown in Figure 3.5.1. A comparison of the location of this gradient with surface characteristics, shown in Figures 2.3 and 2.4,
show a strong correlation of this latent heat flux gradient with the land use and soil type. High latent heat fluxes, on the order of 500 Wm$^{-2}$, are present in the cropland area in conjunction with loamy sand soil type. Reduced latent heat flux, about 350 Wm$^{-2}$, is noted in the area adjacent to and just west of the sand hills. The reduced latent heat flux appears to correlate with the finer grained soil and land cover change. Different field capacities for these soil textures combined with developing soil moisture gradients during the simulation may contribute to these latent heat flux gradients in the sand hills region. Another noticeable latent heat flux gradient is along the coast. The latent heat flux over the land in the coastal region, approximately 400 Wm$^{-2}$, is also greater than the flux over the coastal waters, about 200 Wm$^{-2}$ as discussed in Section 3.9.

The sensible heat flux shown in Figure 3.5.2 correspond to the latent heat flux patterns at 1800Z on the 16th as seen in Figure 3.5.1. Here, the sensible heat flux is reduced in the sand hills region. This is possibly related to evapotranspiration processes occurring in this area as indicated by the large latent heat fluxes as shown in Figure 3.5.1.

Soil temperature from the model is compared with the observations from the AgNet stations. The observed and modeled soil temperatures measurements are compared at a depth of 10 cm. Soil temperature diurnal variations are handled well by the model in all regions. There appears to be less error in the modeled values during nighttime conditions. Nighttime
observed point values of soil temperature are plotted in relation to the contours estimated by the model at 0600Z on the 16th as shown in Figure 3.5.3. Here, the observed values match well with the model simulated values. In contrast, the daytime temperature comparison shown at 1800Z on August 16th in Figure 3.5.4 indicates larger differences between the observed and modeled soil temperatures. In general, the model tends to overestimate the soil temperature at most locations by 3 to 5 degrees during the daytime.

Modeled soil moisture is also compared with point observations from AgNet stations with available soil moisture data. The initial modeled soil moisture on August 15th at 0000Z, shown in Figure 3.5.5, indicates a fairly uniform distribution of approximately 0.33 m³m⁻³. Gradients in the modeled soil moisture develop over the course of the simulation. Observed soil moisture values on the 15th at 1800Z are compared with modeled output by overlaying the values on the simulated soil moisture contours shown in Figure 3.5.6. A noticeable gradient in soil moisture is seen at the border of the coastal plain and piedmont regions. This gradient is most likely a function of soil type and texture characteristics as indicated in Table 3.5.1 and Figure 2.4. Here, observations match well with the modeled regional estimated soil moisture values. A drying of the sandy coastal plain is evident in Figure 3.5.7 on the 17th at 1800Z where the soil moisture gradient between the piedmont and coastal plain is increased in the sand hills area. The modeled soil moisture in the sand hills region has a value of approximately 0.20 m³m⁻³.
The area adjacent to and west of the sand hills still shows a soil moisture value of approximately 0.33 m$^3$m$^{-3}$.

### 3.6 Surface Temperature Evaluation and Validation

The model shows the diurnal variation of temperature at each of the grid points to be well represented and in phase with the observations at each of the stations. The exceptions arise from two of the coastal stations where grid resolution seems to be the cause of the inconsistencies between model values and observations. The closest model grid points associated with the Hatteras (HSE) and the Beaufort (MRH) observations appear to be located over water causing the lack of diurnal variation as seen in the time series indicated in Figures 3.6.1 and 3.6.2, respectively. These grid points appear to be more representative of ocean points where the diurnal variation signature associated with land based grid points is not seen.

Results from the time series comparison plots for stations Greensboro (GSO), Wilmington (ILM), Jackson Springs (JAC), and Lewiston (LEW) in Figures 3.6.3 through 3.6.6 show an overestimation of the nighttime temperatures by the model for all locations, excluding Hatteras (HSE) and Beaufort (MRH) for reasons mentioned in the previous paragraph. The station locations are indicated in Figure 3.2.1. This overestimation could be related to radiational cooling, as model performance tends to decrease in the day to night transitional period where the rate of decrease in temperature by
the observations exceeds the rate of decrease in temperature by the model. The overnight observational temperatures typically drop well below the modeled temperature by as much as 5 or 10 F at some locations. Examples of large biases at night, represented by Asheville (AVL) and Fletcher (FLE), are shown in Figures 3.6.7 and 3.6.8, respectively. Initialization errors in temperature at some of the stations are corrected within 12 hours of the start time. An example of initialization errors in temperature is noted in Figure 3.6.4 where the observed temperature at Wilmington (ILM) at 0000Z on August 15th is approximately 81F while the model initial temperature for that location is approximately 77F.

During the night to day transitional period, the model quickly falls in line with the observations, handling the maximum temperatures very well at most locations. Small overestimations and underestimations of maximum temperature occur at roughly half the stations. To obtain a better understanding of the variability in the maximum temperature biases, possible common factors are explored and analyzed at the stations that appeared to have these larger biases. Some examples of biases during the daytime hours can be seen at 1800Z on the 15th and 16th as indicated in Figures 3.6.9 and 3.6.10, respectively. Spatial interpretation of biases involves scrutinizing each time series plot for common errors. Each bias is noted by a simple categorization of overestimation, underestimation, and location of each bias. These common attributes are then grouped spatially to examine if surface
characteristics may have played a dominant role in the kinds of biases observed on a regional scale. Regional selections are based on the climate divisions of Mountain, Piedmont, Coastal Plain, and Tidewater as indicated in Figure 3.6.11.

The Mountain stations, Fletcher (FLE), Asheville (AVL), Waynesville (WAY), and Hickory (HKY), are grouped together and show similar characteristics in relation to temperature. All station locations are indicated in Figure 3.2.1. The model overestimates the temperature for the entire time period at all mountain locations. Overestimation of the maximum temperatures occurs in the northern piedmont at locations Reidsville (REI) and Winston-Salem (INT). The Triangle area (Raleigh, Durham, and Chapel Hill) is grouped together since there are four stations available for comparison. In this region, the model also overestimates the maximum temperatures at Chapel Hill (IGX), Research Triangle Park (RTP), and Reedy Creek (REE), while the grid point at the Raleigh-Durham (RDU) airport station follows the observed maximum temperature well. Other piedmont grid points simulated the maximum temperature well, except for the Charlotte (CLT) location that underestimated the maximum observed temperature.

The northern Coastal Plains locations include Lewiston (LEW), Williamston (WIL), and Roanoke Rapids (RZZ). Here, the model overestimates the maximum temperature, while in the southern Coastal Plain the model underestimates the maximum temperature at the stations Clinton
The mid Coastal Plain grid points, Clayton (CLA), Kinston (KIN), and Rocky Mount (ROC), handle the maximum temperatures well. Coastal stations, Wilmington (ILM) and Castle Hayne (CAS), including the tidewater stations of Elizabeth City (ECG) and New Bern (EWN), are well represented by the model maximum temperatures. Hatteras (HSE) and Beaufort (MRH) were neglected since the model grid points appeared to be over the ocean as previously stated. Jackson Spring’s (JAC) maximum temperature, the only sand hills station, was well represented by the model.

The biases in the maximum temperature are relatively minor compared to the biases seen in the minimum temperatures. Typical maximum temperature biases are on the order of 1 to 3F. Minimum temperature biases are on the order of 6 to 8F, typically. Examples of nighttime biases are shown in Figures 3.6.12 and 3.6.13 at 0600Z on the 16th and at 0600Z on the 17th, respectively. At most stations, the model does not handle nighttime conditions well, although at some stations it does handle them reasonably. The model better simulates the minimum temperature at grid points in the central piedmont: Greensboro (GSO), Winston-Salem (INT), and Reidsville (REI), the coastal stations: Castle Hayne (CAS) and Wilmington (ILM), and the sand hills station: Jackson Springs (JAC), than the other stations.
3.7 Surface Moisture Evaluation and Validation

Initial analysis of near surface specific humidity (q) from the time series plots show considerable moisture variability across NC. The diurnal trends in specific humidity are not as significant as was seen in the diurnal variation of temperature. Additional analysis using probability distributions are used in conjunction with the time series analysis to best describe regional similarity among stations, as the probability plots provide information on the local density and symmetry of the data. In these plots, the x-axis is scaled in probability (between zero and 100%) and shows the percentage of the moisture (q) values that are less than a given data point. The y-axis displays the range of specific humidity for that station.

The simulation of moisture (q) at model grid points coinciding with mountain stations has fair to poor representation when compared to observations. When differences from the observations occur, these modeled values at corresponding grid points are typically either out of phase or slow to respond, as observed measurements of specific humidity have high temporal variability.

This variability can be seen at the Fletcher (FLE) location as shown in Figures 3.7.1. In Figure 3.7.1, modeled values are shown to follow the general trend of drying and moistening of the air as indicated by the observations. Between the forecast hours of 35 and 40 (1800 LST and 2300 LST) on August 16th, there is a 6 gkg$^{-1}$ increase in near surface specific
humidity as indicated by the observations. The model, during this time, does not pick up the rapid transition and is actually out of phase with the observations. There is also another rapid change at forecast hour 64 (1600 LST) on August 17, where the model doesn’t respond until four hours later. Results from the Asheville location, as indicated in Figure 3.7.2, are similar since the distance between Fletcher and Asheville is small enough where the same model grid point can be used for comparison at these two stations.

The model also appears to be out of phase at the grid point associated with Waynesville (WAY) as illustrated in Figure 3.7.3. During most of the simulation, observations show an increase where the model shows a decrease and vice versa. Slow response in the model is also indicated during the last 12 hours of the simulation as was seen at the Fletcher location.

The model tends to underestimate the specific humidity during the entire simulation at the grid point associated with the Hickory (HKY) station as shown in Figure 3.7.4. The model initially overestimates the specific humidity by approximately 2.5 gkg\(^{-1}\). The model quickly tries to adjust to the observed moisture value but overcompensates. By 1200Z (0700 LST), the model is about 2 gkg\(^{-1}\) too dry and is not able to adjust to the observed specific humidity for the rest of the simulation.

In the northern piedmont, the model tends to perform better during mid to lower observed humidity amounts (10 to 14 gkg\(^{-1}\)), while under predicting higher humidity values in that region as shown in Figures 3.7.5 through 3.7.7.
Examples of probability distributions indicate that quick increases in specific humidity, as recorded by the observations, are not well simulated by the model. The observations and model values diverge as specific humidity increases at the Burlington (BUY) station as shown in Figure 3.7.5. Similarly at the Greensboro location shown in Figure 3.7.6, high specific humidities are not well simulated by the model. At the Reidsville location, moisture (q) is well represented during most of the simulation and is confirmed by the probability distribution as shown in Figure 3.7.7.

There appears to be good agreement between the model and the observations in the central piedmont as indicated in Figures 3.7.8 through 3.7.11. Probability distributions for model values and observations indicate that the range (10 to 18 gkg\(^{-1}\)) of specific humidity values is well simulated by the model.

At the Clayton (CLA) location, as shown in Figure 3.7.8, the distribution of moisture (q) values show good agreement throughout the range of values (10 to 18 gkg\(^{-1}\)). The strongest correlation occurs in the mid-range values of (12 to 15 gkg\(^{-1}\)). The extremes in model probability distributions (10 gkg\(^{-1}\) and 18 gkg\(^{-1}\)) diverge slightly from the observations, approximately 1 gkg\(^{-1}\).

The probability distribution at the Chapel Hill (IGX) location shows good agreement, as shown in Figure 3.7.9. Here, the distributions of the model values indicate that there is a small deficit of moisture (q) (1 to 2 gkg\(^{-1}\)),
the majority of the time, when compared to the observations. This deficit is more prominent at higher values of specific humidity.

There is a high level of accuracy by the model in simulating specific humidity at the Raleigh-Durham (RDU) location as indicated in the probability distributions in Figure 3.7.10. The distribution of model values and observed values are highly correlated from low to high values (10 to 18 gkg\(^{-1}\)). The nearby Reedy Creek (REE) location is also analyzed using probability distributions as shown in Figure 3.7.11. The comparison of distributions is similar to the results of the Clayton station where the extreme values (10 gkg\(^{-1}\) and 18 gkg\(^{-1}\)) are not as well represented as the mid range values (12 to 16 gkg\(^{-1}\)).

The Coastal Plains area is well represented by the model during the 72-hour simulation. Sample plots of the upper, middle, and southern regions are given in Figures 3.7.12, 3.7.13 and 3.7.14, respectively. The distribution of specific humidity values is highly correlated and comparable to the accuracy of the distributions in the central piedmont region. The modeled and observed probability distributions are highly correlated from low to high values (10 to 18 gkg\(^{-1}\)) as shown at the Lewiston (LEW) station in Figure 3.7.12. Similarly, distributions of modeled and observed values are well correlated at the Kinston (KIN) and Fayetteville (FAY) stations as shown in Figures 3.7.13 and 3.7.14, respectively.
Simulation of moisture (q) along the coast as indicated by the comparison of specific humidity from observations and the closest model grid points to these observations show fair to good representation of observed conditions. Examination of probability distributions at coastal stations indicates that the model better represents drier conditions than moist conditions in this region. The model forecast at the HSE station continues to do poorly at all times as shown in Figure 3.7.15 where the model underestimates the amount of specific humidity. Contrastingly, the moisture (q) is well simulated by the model at the Beaufort (MRH) location as shown in Figure 3.7.16 despite the fact that temperature is not well represented as was shown in Figure 3.6.2.

Probability distributions of specific humidity at the Castle Hayne (CAS) location, as shown in Figure 3.7.17, indicate high correlation during dryer conditions (10 to 14 gkg\(^{-1}\)) with underestimation of higher moisture (q) values (14 to 18 gkg\(^{-1}\)). Similarly the moisture (q) distributions at Wilmington (ILM), shown in Figure 3.7.18, are well simulated during dryer conditions and underestimate the higher values of specific humidity as well.

Overall, specific humidity (q) is simulated well by the model. The largest errors are related to the extreme values of moisture. Extreme dry conditions are identified as having a value of 10 gkg\(^{-1}\) and extreme moist conditions are labeled at 18 gkg\(^{-1}\) for this case study. Observed values tend to be over-predicted by the model during drier conditions and under-predicted
during moist conditions. Simulation of moisture at other grid points in the
domain are fairly representative of the observations, but did not fit into any of
the regionally classified categories.

3.8 Quantitative Statistical Analysis

Statistical analysis of temperature and specific humidity are performed
to quantify the relation between the point measurements of observations and
model output. Spatial analysis of this quantitative approach is used to
investigate possible regional similarities of sources of errors. Multiple
statistical indices are used to ensure that the overall results of the analyses
are based on the differences in the model and observational data and not a
function of a particular statistical index. Initially, the entire 72-hour period is
evaluated for each of the indices. After noting better correlation during the
day and poor correlation at night, the time series is also evaluated in 12-hour
blocks. This allows independent comparison of model performance for the
daytime and nighttime hours.

The absolute correlation is derived from the anomaly correlation

\[
\frac{\left[(M - C) - (M - C)\right] \cdot \left[(O - C) - (O - C)\right]}{\sqrt{\left[(M - C) - (M - C)\right]^2 \cdot \left[(O - C) - (O - C)\right]^2}}
\]

where M is the model value, O is the observed value and C is the
climatological average value. The anomaly correlation compares the model
and observations to determine if the values are varying in the same direction as climatology (Stull 2000). Stull derives the absolute correlation from the anomaly correlation equation by omitting the climatological value to obtain a direct correlation between the observed and modeled values. In this simulation, the absolute correlation is used for comparison and its values are given in percentages.

Spatial representation of the overall absolute correlation for temperature during the entire simulation is shown in Figure 3.8.1. The overall range is between 70 and 100 where the majority of the stations show correlations at a range of 90 to 100. The coastal stations, Beaufort (MRH) and Hatteras (HSE), show poor correlations in temperature and are neglected in the analysis.

When broken down into daytime and nighttime 12 hourly periods, there still appears to be high correlation at most of the stations during all times. Absolute correlation for nighttime forecast hours (25 - 36) from 1900 LST on August 15th to 0700 LST on August 16th are shown in Figure 3.8.2. Here, correlations of 80 to 100 are seen in the mountains, piedmont, and southern coastal plain. Lower correlations of 30 to 50 are seen in the upper coastal plain region. Absolute correlations for daytime forecast hours (37 - 48) from 0700 LST on August 16th to August 16th at 1900 LST are shown in Figure 3.8.3. Here, correlations seem to improve in the upper coastal plain, but worsen in the central to northern coastal plain. There appears to be no
discernable pattern to the correlation of stations and even some misleading results can be extracted from use of this index. For example, results from absolute correlations suggest that the temperatures in the mountains are good during the night and day, but time series analysis at mountain stations, indicated in Figures 3.6.7 and 3.6.8, showed distinct overestimations of observed temperature values by the model.

The 72-hour absolute correlation of moisture (q) at each of the stations is shown in Figure 3.8.4. The general range of absolute correlation is widespread for specific humidity, approximately from 10 to 100. The piedmont region has a range of correlations of 60 to 80. The overall trend for correlation of specific humidity appears to be worse in the mountains and in the coastal plain. Discrepancies in the moisture (q) values in the mountains are most likely related to the model’s inability to correctly simulate other meteorological variables in this complex topographical region, such as winds and temperature, as previously discussed. Disagreement of modeled and observed specific humidity values in the coastal plain may be associated with differences between actual land-use and land-use designated by the model in that region. This area is classified as cropland by the model as shown in Figure 2.3. Independent point stations selected for comparison may have local features, such as vegetation type and soil type, that are inconsistent with model parameterized land-use values at that point. Also, the correlations tend to worsen over time as shown during forecast hours (61 -72) from 0700
LST on August 17th to August 17th at 1900 LST in Figure 3.8.5. Decreased correlation over time between observations and modeled values at the corresponding grid locations may be related to increasing errors caused by numerical integration by the model over time.

The next index used to evaluate model performance is the root mean square error (RMSE) given by

$$\text{RMSE} = \sqrt{(M - O)^2}$$

where M is the modeled value and O is the observed value (Stull 2000). The 72-hour RMSE for temperature is shown in Figure 3.8.6. Here, the largest overall error for temperature is seen in the mountains. The rest of the state does not show any significant patterns. The large error seen in the mountains in the 72-hour forecast can be attributed to the model’s inability to forecast the nighttime temperatures as shown in Figure 3.8.7 for forecast hours 0 - 12. These large errors are reduced during the daytime (forecast hours 13 - 24) as can be seen in Figure 3.8.8. The smaller errors during the daytime support the data as seen in the temperature time series shown in Section 3.6.

The overall RMSE for the simulation at each of the stations for specific humidity is shown in Figure 3.8.9. The mountainous region shows more error overall, while the upper coastal plain appears to have large errors as well. Examination of the 12-hourly time blocks shows large errors in moisture (q) in the coastal plain and northern piedmont regions. During the nighttime forecast hours (49 - 60), from 1900 LST on August 16th to August 17th at 0700
LST, the largest errors are seen in the upper coastal plain as shown in Figure 3.8.10.

As mentioned in the discussion regarding absolute correlation, disagreement of modeled and observed specific humidity values in the upper coastal plain may be associated with differences between actual land-use and land-use designated by the model in that region. This area is classified as cropland by the model as shown in Figure 2.3. Independent point stations selected for comparison may have local features, such as vegetation type and soil type, that are inconsistent with model parameterized land-use values at that point. During the daytime hours (37 - 48), from 0700 LST on August 16th to August 16th at 1900 LST, the largest errors are seen in the upper coastal plain and the northern piedmont as shown in Figure 3.8.11.

Quantifying the model bias is determined simply by taking the difference between the modeled and observed values, (M - O) for 12-hour time intervals. The model bias for the initial temperature is low and indicates that the temperature field is initialized properly. There is a good mix of positive and negative biases as indicated in Figure 3.8.12. The biases fluctuate over time, in agreement with the time series data. Overall, the simulated air temperatures perform much better during the day with large positive biases at night.

On the other hand, the initial moisture field is underestimated except for overestimations in the southwestern piedmont as seen in Figure 3.8.13.
The southwestern piedmont region has biases on the order of 3 to 5 gkg\(^{-1}\). The biases across much of the state are approximately -1 to -2 gkg\(^{-1}\). This underestimation of the specific humidity is propagated throughout the model run where the underestimations tend to increase over time as shown in Figure 3.8.14 at the 72 hour forecast time, 1900 LST August 17\(^{th}\). The exception occurs at the 54 hour forecast (0100 on August 17\(^{th}\)), shown in Figure 3.8.15, where the specific humidities are grossly overestimated, 4 to 5 gkg\(^{-1}\). This quick spike in moisture from the model quickly erodes and the large underestimations of moisture (q) persevere throughout the rest of the model run.

Additionally, the normalized mean square error (NMSE), weighted normalized mean square error of the normalized ratios (WNNR), and normalized mean square error of the distribution of the normalized ratios, NNR, are also compared at each of the stations. These indices are used in conjunction with each other as described in Poli and Cirillo (1993). Some inherent problems with NMSE are addressed with WNNR and NNR, such as a bias towards overestimating, and not equally considering the errors associated with the modeled and observed values. WNNR addresses this issue of bias towards overestimating while NNR gives equal consideration to all values, whether they are over or under predicted. Given these reasons, the results from evaluation of these indices are given as a combined consensus. NMSE is given as
\[ NMSE = \frac{\sum s_i^2 (1 - k_i)^2}{\sum s_i k_i} \]

where

\[ s_i = \frac{O_i}{O} \quad \text{and} \quad k_i = \frac{M_i}{O_i} \]

WNNR is defined by

\[ WNNR = \frac{\sum s_i^2 (1 - \hat{k})^2}{\sum s_i \hat{k}_i} \]

where

\[ \hat{k} = e^{-|n_k|} \]

NNR is provided by

\[ NNR = \frac{\sum (1 - \hat{k})^2}{\sum \hat{k}_i} \]

Examination of the results for temperature, from these three indices, show good agreement between the model and the observations stations in NC for the 72-hour period. The NMSE for temperature is shown in Figures 3.8.16. Errors are largest in the mountainous region, about 0.0011 to 0.0150, as indicated by NMSE. All other locations do not indicate significant errors, 0.0001 to 0.0050. WNNR values are shown in Figure 3.8.17. Similarly, larger values are present in the mountains as well, 0.0011 to 0.0150. The NNR is in good agreement with NMSE and WNNR and indicates the mountainous
region as having the worst agreement between observations and model temperatures, 0.0011 to 0.0150, as shown in Figure 3.8.18. Overall, based on these indices, the simulated air temperatures in the mountainous region are least representative of the observations when compared to the rest of NC. Surprisingly, the coastal stations, Beaufort (MRH) and Hatteras (HSE), are not indicated by these indices as having poor agreement in temperature although the time series indicated a lack of diurnal variation at these locations. The analysis of the 12 hourly blocks of night and day reinforce the results as seen from the other indices. Predicted nighttime temperatures, especially in the mountains, have larger errors than during the daytime.

Results from these indices for moisture (q) also show more error for specific humidity in the mountains during the entire 72-hour period. The NMSE for moisture is shown in Figures 3.8.19. Errors are largest in the mountainous region as indicated by NMSE, 0.0450 to 0.060. All other locations, except for Williamston (WIL), do not indicate significant errors. WNNR values are shown in Figure 3.8.20. Similarly, larger values are present in the mountains as well, 0.045 to 0.090. The NNR is in good agreement with NMSE and WNNR and indicates the worst agreement, 0.030 to 0.060, between observed and modeled specific humidity values in the mountainous region as shown in Figure 3.8.21.

The 12-hour blocks show fair agreement between the model and the observations during the simulation. Exceptions occur from 0700 LST August
17th to 1900 LST August 17th (61-72 forecast hours) where the error in specific humidity is the highest for the model run. An example of these errors are shown using NNR in Figure 3.8.22. The other exception occurs at the Williamston (WIL) station where errors for the 12-hour time periods persist throughout the time series as can be seen using WNNR as shown in Figure 3.8.23 for forecast hours 13-24, 0700 LST August 15th through 1900 LST August 15th.

The last index used to analyze point-to-point comparisons of temperature and specific humidity is the index of agreement. Willmott (1982) gives the relation between the observations and the model as

\[ d = 1 - \frac{\sum_{i=1}^{N} (M_i - O_i)^2}{\sum_{i=1}^{N} (|M_i| + |O_i|)^2}, \quad 0 \leq d \leq 1 \]

where

\[ P'_i = P_i - \overline{O} \quad \text{and} \quad O'_i = O_i - \overline{O} \]

All comparisons for the index of agreement are given in percentages. Analyzing temperatures during the entire 72-hour period show good agreement at all stations, excluding the MRH and HSE stations, shown in Figure 3.8.24, where values range from 80 to 100. Daytime temperatures from each of the 12-hour time periods show good agreement especially in the coastal plains area as seen in Figure 3.8.25 for forecast hours 13-24, 0700 LST August 15th through 1900 LST August 15th where values range from 80
to 100. Nighttime temperatures show poor agreement throughout most of the state. The upper piedmont region consistently has the best agreement at night as shown in Figure 3.8.26 during forecast hours 49-60, 1900 LST August 16th through 0700 LST August 17th, where values are approximately 80 to 100.

Specific humidity values do not appear to follow a diurnal cycle as do the temperature values. There is good agreement between the model and the observations during the entire simulation in the piedmont area as shown in Figure 3.8.27. This trend, as indicated by the index of agreement, continues throughout the case study during the 12-hour blocks at night. This trend is not as prominent during the day hours. The range of values at the piedmont stations is between 80 and 100. The coastal plain and mountains have lower agreement values of 30 to 70. The model values and observations at the coastal stations also have good agreement with a range of 70 to 90.

### 3.9 Model Simulation Errors and Pollution Transport Uncertainties

Diurnal variation of temperature is well simulated in the model. Daytime conditions are better simulated than at night where there appears to be more errors. The model predicts slower cooling and overestimates the temperatures at night. Overall, model performance improves from west to east. This can be seen by evaluating the RMSE where it is smallest in the
eastern part of the domain during most of the simulation. Model biases indicate the largest overestimations in the mountainous region. Absolute correlation does not well represent the differences in the observations and model values. Model performance is best described with the results from the index of agreement where the values seem to be correlated closely with RMSE and model bias.

The overall patterns of surface winds are simulated fairly well at the coast and piedmont but not in the mountains. In the coastal region, the general sea breeze and land breeze flow patterns are well simulated. These flow patterns can be seen by looking at wind direction shifts for the coastal stations: Wilmington (ILM), Castle Hayne (CAS), Whiteville (WHI), Hatteras (HSE), and Beaufort (MRH). Along the coast, the contrast between the marine boundary layer (MBL) and the convective boundary layer (CBL) is prominent along the southern coast of NC. There is a sharp contrast between the PBL heights over land and over the ocean.

Diurnal variation in the modeled general flow patterns and mesoscale characteristics such as moisture and potential temperature is seen in the mountainous region. There appears to be local circulations and flow patterns induced by differential heating of the surface simulated by the model as a function of the complex topography. Convergence seen in the modeled 10-meter winds in the mountains is compared with cross section A (indicated in Figure 3.3.3) and shows the contrast of the accelerated flow over the
mountain top with the slower moving air as it passes over the leeward slope. The model appears to develop a return flow circulation on the leeward slope as a result of wake or flow separation as the flow comes over the mountains. This return flow circulation could provide a “trapping zone” for particulates, resulting in higher concentrations in this area during the daytime.

Katabatic flow develops during the nighttime in the model causing a substantial increase in wind speed that may help transport these pollutants from this area. In addition, these proposed higher concentrations would most likely be transported near the surface over night as a stable nocturnal boundary layer develops. This may infer that locations down stream from the local circulations zones may encounter high pollutant concentrations in the late evening and early morning until mixing can reduce surface concentrations.

However, the model results do not agree well with the observed surface wind speeds and directions. The model's ability to accurately represent the mountainous region is questionable. More observations are needed to develop regionally consistent flow patterns. Also observations in the mountains may not accurately represent the transport of particulates, as complex topography causes mesoscale variability in the flow patterns. This is evident in the horizontal plots of surface winds showing significant variability in the winds, the trajectory plots, and in the comparison of observed and modeled wind speeds and directions.
The piedmont has large variability in the winds, especially during the day, probably due to different soil and land-use characteristics. This variability is evident at the boundary near the sand hills as well as along the coast. For example, the Raleigh-Durham (RDU) station’s wind speeds and directions are highly variable when compared with the model.

A point-to-point comparison of the winds shows that the local mesoscale wind speeds and directions are not well represented. This can be related to non-regionally representative stations, a lack of data at more points for comparison, complex topography, and land-use. Trajectories calculated by the model for transport potential from local point sources may not be representative of the observations, especially if they are in the surface layer. Poor representation of the observations by the model could be the result of the model not being able to handle the influence of complex terrain and land-use even in high-resolution simulations. Additional transport issues may be related to non-regionally representative stations that are too localized to be used for validation of transport potential. The most prominent result, since model performance degrades over regions with complex terrain, is to recognize that more observations are needed for data assimilation and to develop regionally consistent flow patterns.

The overall the PBL structure is modeled well. Diurnal changes are very apparent as can be seen in the 2D plan views of the 5 km domain. The height of the nocturnal boundary layer appears to match well with SODAR
observations. The time of the convective growth of the boundary layer is well matched, although, it grows much faster in the model than indicated by the SODAR observations. Actual maximum CBL height may be lower than the estimated PBL height—which tops out at about 2000m as indicated from the model results.

Large surface flux gradients seen near the sand hills region appears to be related to soil type and land use. The large latent heat flux is aligned along an area designated as dry cropland in the model as shown in Figure 2.3. The sensible heat flux in this area is reduced and may be attributed to evaporative cooling. Also, the heterogeneity of the soil types can have a strong influence as available soil moisture may play a role in differential surface heating. Along the coast, large latent heat flux and PBL height gradients could possibly be attributed to dry air from the northwest becoming near saturated from available soil moisture as it passes over the sand hills and coastal plain regions. When this saturated air reaches the coastal water, the latent heat flux is drastically reduced.
Figure 3.1.1. Synoptic surface map at 1200Z (0700 LST) on August 15, 2000.
Figure 3.1.2. As in Figure 3.1.1 except at 1200Z (0700 LST) on August 16, 2000.
Figure 3.1.3. As in Figure 3.1.2 except at 1200Z (0700 LST) on August 17, 2000.
Figure 3.1.4. 4 km infrared satellite imagery at 0015Z (1915 LST) on August 17, 2000.

Figure 3.2.1. Hourly surface observation stations across North Carolina. Triangle markers indicate ASOS stations. Circle markers indicate AgNet stations. The square marker indicates the location of the SODAR station.
Table 3.2.1. Hourly surface observation stations across North Carolina. Station ID, latitude, longitude (negative for west) and corresponding model grid points (I and J) for the 5 km domain are listed.

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Figure 3.2.2. MMS model grid for the 5 km domain overlaid on the hourly surface observation stations across North Carolina. Triangle markers indicate ASOS stations. Circle markers indicate AgNet stations. The square marker indicates the location of the SODAR station.
Figure 3.3.1. Horizontal wind vectors at 10 meters above the surface for the 5 km domain on August 15, 2000 at 0000Z (1900 LST August 14th).

Figure 3.3.2. As in Figure 3.3.1 except at 1900Z (1400 LST) on August 17, 2000.
Figure 3.3.3. Lines A, B, and C show the locations of the vertical cross sections. A is along the coast in North Carolina (NC) near the city of Wilmington. B is across the Appalachian mountains in western NC. C is located across the sand hills of NC.

Figure 3.3.4. Vertical cross-section showing circulation vectors (m/s), potential temperature (K), and water vapor mixing ratio (g/kg) for cross section A at 1800Z (1300 LST) on August 15, 2000.
Figure 3.3.5. Observed and modeled wind direction at 10 meters above the ground at Wilmington, NC. Forecast hours span 72 hours beginning at 0000Z (1900 LST) on August 15, 2000 and ending on August 18, 2000 at 0000Z (1900 LST). The onset of sea breeze is shown by the wind direction shifts at forecast hours 14 through 20 (0900 – 1500 LST) and 62 through 68 (0900 – 1500 LST).
Figure 3.3.6. As in Figure 3.3.1 except at 1200Z (0700 LST) on August 16, 2000.

Figure 3.3.7. Vertical cross-section showing circulation vectors (m/s), potential temperature (K), and water vapor mixing ratio (g/kg) for cross section B at 0000Z (1900 LST) on August 16, 2000.
Figure 3.3.8. As in Figure 3.3.7 except at 0600Z (0100 LST) on August 16, 2000.

Figure 3.3.9. As in Figure 3.3.7 except at 1800Z (1300 LST) on August 16, 2000.
Figure 3.3.10. Observed and modeled wind speed at 10 meters above the ground at Fletcher, NC. Forecast hours span 72 hours beginning at 0000Z (1900 LST) on August 15, 2000 and ending on August 18, 2000 at 0000Z (1900 LST). Observed and modeled wind speeds are shown to be out of phase during night and day.

Figure 3.3.11. Observed and modeled wind direction at 10 meters above the ground at Fletcher, NC. Forecast hours span 72 hours beginning at 0000Z (1900 LST) on August 15, 2000 and ending on August 18, 2000 at 0000Z (1900 LST).
Figure 3.3.12. Observed and modeled wind speed at 10 meters above the ground at Hickory, NC. Forecast hours span 72 hours beginning at 0000Z (1900 LST) on August 15, 2000 and ending on August 18, 2000 at 0000Z (1900 LST).

Figure 3.3.13. Observed and modeled wind direction at 10 meters above the ground at Hickory, NC. Forecast hours span 72 hours beginning at 0000Z (1900 LST) on August 15, 2000 and ending on August 18, 2000 at 0000Z (1900 LST).
Figure 3.3.14. Forward trajectories (72 hours) starting on 0000Z (1900 LST) August 15, 2000 at 4 different locations in and around the North Carolina mountains at 10 meters showing the effect of complex topography on the winds. 1 is located at Charlotte. 2 is located at Fletcher / Asheville. 3 is located at Waynesville. 4 is located at the Tri-Cities, Tennessee.

Figure 3.3.15. Backward trajectories (72 hours) ending on August 18, 2000 at 2 locations in the North Carolina mountains at 10 meters. 1 is located at Fletcher / Asheville. 2 is located at Waynesville.
Figure 3.3.16. As in Figure 3.3.1 except at 0000Z (1900 LST) on August 16, 2000 (August 15th).

Figure 3.3.17. As in Figure 3.3.1 except at 0000Z (1900 LST) on August 18, 2000 (August 17th).
Figure 3.3.18.  As in Figure 3.3.1 except at 0600Z (0100 LST) on August 15, 2000.

Figure 3.3.19.  Vertical cross-section showing circulation vectors (m/s), potential temperature (K), and water vapor mixing ratio (g/kg) for cross section C at 0000Z (1900 LST) on August 16, 2000 (August 15th).
Figure 3.3.20. As in Figure 3.3.16 except at 0000Z (1900 LST) on August 18, 2000 (August 17th).

Figure 3.3.21. As in Figure 3.3.17 except at 0600Z (0100 LST) on August 15, 2000.
Figure 3.3.22.  Observed and modeled wind speed at 10 meters above the ground at Raleigh-Durham, NC.  Forecast hours span 72 hours beginning at 0000Z (1900 LST) on August 15, 2000 and ending on August 18, 2000 at 0000Z (1900 LST).  Observed and modeled wind speeds are shown to be out of phase during night and day.

Figure 3.3.23.  Observed and modeled wind direction at 10 meters above the ground at Raleigh-Durham, NC.  Forecast hours span 72 hours beginning at 0000Z (1900 LST) on August 15, 2000 and ending on August 18, 2000 at 0000Z (1900 LST).
Figure 3.3.24. Observed and modeled wind speed at 10 meters above the ground at Greensboro, NC. Forecast hours span 72 hours beginning at 0000Z (1900 LST) on August 15, 2000 and ending on August 18, 2000 at 0000Z (1900 LST).

Figure 3.3.25. Observed and modeled wind direction at 10 meters above the ground at Raleigh-Durham, NC. Forecast hours span 72 hours beginning at 0000Z (1900 LST) on August 15, 2000 and ending on August 18, 2000 at 0000Z (1900 LST).
Figure 3.3.26. EDAS analysis of surface horizontal wind vectors at 0000Z on August 15, 2000 obtained from NOAA-ARL.

Figure 3.3.27. Horizontal wind vectors at 10 meters above the surface for the 15 km domain on August 15, 2000 at 0000Z (1900 LST August 14th).
Figure 3.3.28. As in Figure 3.3.21 except at 1200Z (0700 LST) on August 16, 2000.

Figure 3.3.29. As in Figure 3.3.22 except at 1200Z (0700 LST) on August 16, 2000.
Figure 3.3.30.  As in Figure 3.3.21 except at 0000Z (1900 LST) on August 18, 2000 (August 17th).

Figure 3.3.31.  As in Figure 3.3.22 except at 0000Z (1900 LST) on August 18, 2000 (August 17th).
Figure 3.3.32. Observed sounding overlaid on a Skew-T diagram at Greensboro (GSO) from rawinsonde data on August 16, 2000 at 0000Z obtained from the University of Wyoming.

Figure 3.3.33. Forecasted sounding overlaid on a Skew-T diagram Greensboro (GSO) from MM5 on August 16, 2000 at 0000Z obtained from the University of Wyoming.
Figure 3.3.34. As in Figure 3.3.27 except at 1200Z on August 17, 2000.

Figure 3.3.35. As in Figure 3.3.28 except at 1200Z on August 17, 2000.
Figure 3.3.36. Observed sounding overlaid on a Skew-T diagram at Newport (MHX) from rawinsonde data on August 15, 2000 at 0000Z obtained from the University of Wyoming.

Figure 3.3.37. Forecasted sounding overlaid on a Skew-T diagram at Newport (MHX) from MM5 on August 15, 2000 at 0000Z obtained from the University of Wyoming.
Figure 3.3.38. As in Figure 3.3.31 except at 0000Z on August 18, 2000.

Figure 3.3.39. As in Figure 3.3.32 except at 0000Z on August 18, 2000.
Figure 3.4.1. Planetary boundary layer heights for the 5 km domain on August 15, 2000 at 1200Z.

Figure 3.4.2. A 3-day composite AVHRR image of the sea surface temperature ending on August 18, 2000.
Figure 3.4.3. Initial surface temperature field for MM5 derived from weekly Navy analyses of ship observations from the NCEP global analyses.

Figure 3.4.4. Observed sounding overlaid on a Stuve diagram up to 700 mb at Greensboro (GSO) from rawinsonde data on August 16, 2000 at 1200Z obtained from the University of Wyoming.
Figure 3.4.5. As in Figure 3.4.1 except on August 16, 2000 at 1200Z.

Figure 3.4.6. Color enhanced SODAR data obtained from the EPA near Research Triangle Park on August 16, 2000 from 0000 LST to 0600 LST showing the height of the nocturnal boundary layer.
Figure 3.4.7. Color enhanced SODAR data obtained from the EPA near Research Triangle Park on August 16, 2000 from 0600 LST to 1200 LST showing the convective growth of the boundary layer.

Figure 3.4.8. As in Figure 3.4.4 except at 1200Z on August 17, 2000.
Figure 3.4.9. As in Figure 3.4.1 except on August 17, 2000 at 1200Z (0700 LST).

Figure 3.4.10. As in Figure 3.4.7 except from 0600 LST to 1200 LST on August 17, 2000.
Figure 3.4.11. As in Figure 3.4.1 except on August 17, 2000 at 1300Z (0800 LST).

Figure 3.4.12. As in Figure 3.4.1 except on August 17, 2000 at 1400Z (0900 LST).
Figure 3.4.13. As in Figure 3.4.1 except on August 17, 2000 at 1500Z (1000 LST).

Figure 3.5.1. Latent heat flux for the 5 km domain on August 16, 2000 at 1800Z (1300 LST). A sharp gradient in the latent heat flux is seen in the central piedmont near the sand hills region.
Figure 3.5.2. Sensible heat flux for the 5 km domain on August 16, 2000 at 1800Z (1300 LST). A sharp gradient in the sensible heat flux is seen in the central piedmont near the sand hills region.

Figure 3.5.3. Modeled soil temperature contours overlaid with actual observed soil temperature values obtained from AgNet stations in North Carolina at 0600Z (0100 LST) at 10cm soil depth.
Figure 3.5.4. As in Figure 3.5.3 except at 1800Z (1300 LST) on August 16, 2000.

Figure 3.5.5. Initial modeled soil moisture contours overlaid with actual observed soil moisture values obtained from AgNet stations in North Carolina at 0600Z (0100 LST) at 10cm soil depth. The initial field is noted to be fairly constant over North Carolina with a value of approximately 0.33 m3/m3.
Figure 3.5.6. Modeled soil moisture contours overlaid with actual observed soil moisture values obtained from AgNet stations in North Carolina at 1800Z (1300 LST) at 10cm soil depth.

Figure 3.5.7. As in Figure 3.5.6 except at 1800Z (1300 LST) on August 17, 2000.
Table 3.5.1. Hourly surface observation stations across North Carolina. Station ID, latitude, longitude and corresponding model grid points for the 5 km domain are listed. Land-surface characteristics for each of the stations are listed including: dominant surface soil type, field capacity, wilting point, and land use/land cover.

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Figure 3.6.1. Observed and modeled temperature at 2 meters above the ground at Hatteras (HSE), NC. Forecast hours span 72 hours beginning at 0000Z (1900 LST) on August 15, 2000 and ending on August 18, 2000 at 0000Z (1900 LST). Observed temperatures show diurnal variation unlike the modeled temperatures. The closest modeled grid points appear to be located over water causing the lack of diurnal variation.

Figure 3.6.2. As in Figure 3.6.1 except for the Beaufort (MRH) station.
Figure 3.6.3. Observed and modeled temperature at 2 meters above the ground at Greensboro (GSO), NC. Forecast hours span 72 hours beginning at 0000Z (1900 LST) on August 15, 2000 and ending on August 18, 2000 at 0000Z (1900 LST). Modeled and observed temperatures are in phase and match well during the daytime. The model over predicts nighttime temperatures.

Figure 3.6.4. As in Figure 3.6.3. except for the Wilmington (ILM) station.
Figure 3.6.5. As in Figure 3.6.3 except for the Jackson Springs (JAC) station.

Figure 3.6.6. As in Figure 3.6.3 except for the Lewiston (LEW) station.
Figure 3.6.7. As in Figure 3.6.3 except for the Asheville (AVL) station.

Figure 3.6.8. As in Figure 3.6.3 except for the Fletcher (FLE) station.
Figure 3.6.9. Temperature bias (Model temperature – Observed temperature) at the surface observation stations across North Carolina at 1800Z August 15, 2000 (18 hour forecast).

Figure 3.6.10. As in Figure 3.6.9 except at 1800Z August 16, 2000 (42 hour forecast).
Figure 3.6.11. Climate divisions of North Carolina showing the Mountains, Piedmont, Coastal Plain, and Tidewater areas.

Figure 3.6.12. As in Figure 3.6.9 except at 0600Z August 16, 2000 (30 hour forecast).
Figure 3.6.13. As in Figure 3.6.9 except at 0600Z August 16, 2000 (54 hour forecast).

Figure 3.7.1. Observed and modeled specific humidity at 2 meters above the ground at Fletcher (FLE), NC. Forecast hours span 72 hours beginning at 0000Z (1900 LST) on August 15, 2000 and ending on August 18, 2000 at 0000Z (1900 LST).
Figure 3.7.2. As in Figure 3.7.1 except for the Asheville (AVL) station.

Figure 3.7.3. As in Figure 3.7.1 except for the Waynesville (WAY) station.
Figure 3.7.4. As in Figure 3.7.4 except for the Hickory (HKY) station.

Figure 3.7.5. Normal probability distribution of observed and modeled specific humidity at 2 meters above the ground at Burlington (BUY), NC. The x-axis is scaled in probability (0 – 100%) and shows the percentage of the specific humidity values that are less than the given data point. The y-axis displays the range of specific humidity.
Figure 3.7.6. As in Figure 3.7.5 except for the Greensboro (GSO) station.

Figure 3.7.7. As in Figure 3.7.5 except for the Reidsville (REI) station.
Figure 3.7.8. As in Figure 3.7.6 except for the Clayton (CLA) station.

Figure 3.7.9. As in Figure 3.7.6 except for the Chapel Hill (IGX) station.
Figure 3.7.10. As in Figure 3.7.6 except for the Raleigh-Durham (RDU) station.

Figure 3.7.11. As in Figure 3.7.6 except for the Reedy Creek (REE) station.
Figure 3.7.12. As in Figure 3.7.6 except for the Lewiston (LEW) station.

Figure 3.7.13. As in Figure 3.7.6 except for the Kinston (KIN) station.
Figure 3.7.14. As in Figure 3.7.6 except for the Fayetteville (FAY) station.

Figure 3.7.15. As in Figure 3.7.6 except for the Hatteras (HSE) station.
Figure 3.7.16. As in Figure 3.7.6 except for the Beaufort (MRH) station.

Figure 3.7.17. As in Figure 3.7.6 except for the Castle Hayne (CAS) station.
Figure 3.7.18. As in Figure 3.7.6 except for the Wilmington (ILM) station.

Figure 3.8.1. Absolute temperature correlation given in percentages between the model and observation stations at 2m above the ground across North Carolina for the 72-hour period from 0000Z August 15, 2000 to 0000Z August 18, 2000.
Figure 3.8.2. As in Figure 3.8.1 except for the 12-hour period (forecast hours 25 – 36) from 0000Z August 16, 2000 to 1200Z August 16, 2000.

Figure 3.8.3. As in Figure 3.8.1 except for the 12-hour period (forecast hours 37 – 48) from 1200Z August 16, 2000 to 0000Z August 17, 2000.
Figure 3.8.4. Absolute specific humidity correlation given in percentages between the model and observation stations at 2m above the ground across North Carolina for the 72-hour period from 0000Z August 15, 2000 to 0000Z August 18, 2000.

Figure 3.8.5. As in Figure 3.8.4 except for the 12-hour period (forecast hours 61 –72) from 1200Z August 17, 2000 to 0000Z August 18, 2000.
Figure 3.8.6. Root mean square error (RMSE) for temperature between the model and observation stations at 2m above the ground across North Carolina for the 72-hour period from 0000Z August 15, 2000 to 0000Z August 18, 2000.

Figure 3.8.7. As in Figure 3.8.6 except for the 12-hour period (forecast hours 0 – 12) from 0000Z August 15, 2000 to 1200Z August 15, 2000.
Figure 3.8.8. As in Figure 3.8.6 except for the 12-hour period (forecast hours 13 – 24) from 1200Z August 15, 2000 to 0000Z August 16, 2000.

Figure 3.8.9. Root mean square error (RMSE) for specific humidity between the model and observation stations at 2m above the ground across North Carolina for the 72-hour period from 0000Z August 15, 2000 to 0000Z August 18, 2000.
Figure 3.8.10. As in Figure 3.8.9 except for the 12-hour period (forecast hours 49 – 60) from 0000Z August 17, 2000 to 1200Z August 17, 2000.

Figure 3.8.11. As in Figure 3.8.9 except for the 12-hour period (forecast hours 37 – 48) from 1200Z August 16, 2000 to 0000Z August 17, 2000.
Figure 3.8.12. As in Figure 3.6.9 except at 0000Z August 15, 2000 (model initial time).

Figure 3.8.13. Specific humidity bias (Model temperature – Observed temperature) at the surface observation stations across North Carolina at 0000Z August 15, 2000 (model initial time).
Figure 3.8.14. As in Figure 3.8.13 except at 0000Z on August 18, 2000 (72 hour forecast).

Figure 3.8.15. As in Figure 3.8.13 except at 0600 on August 17, 2000 (54 hour forecast).
Figure 3.8.16. Normalized mean square error (NMSE) for temperature between the model and observation stations at 2m above the ground across North Carolina for the 72-hour period from 0000Z August 15, 2000 to 0000Z August 18, 2000.

Figure 3.8.17. Weighted normalized mean square error of the normalized ratios (WNNR) for temperature between the model and observation stations at 2m above the ground across North Carolina for the 72-hour period from 0000Z August 15, 2000 to 0000Z August 18, 2000.
Figure 3.8.18. Normalized mean square error of the distribution of the normalized ratios (NNR) for temperature between the model and observation stations at 2m above the ground across North Carolina for the 72-hour period from 0000Z August 15, 2000 to 0000Z August 18, 2000.

Figure 3.8.19. Normalized mean square error (NMSE) for specific humidity between the model and observation stations at 2m above the ground across North Carolina for the 72-hour period from 0000Z August 15, 2000 to 0000Z August 18, 2000.
Figure 3.8.20. Weighted normalized mean square error of the normalized ratios (WNNR) for specific humidity between the model and observation stations at 2m above the ground across North Carolina for the 72-hour period from 0000Z August 15, 2000 to 0000Z August 18, 2000.

Figure 3.8.21. Normalized mean square error of the distribution of the normalized ratios (NNR) for specific humidity between the model and observation stations at 2m above the ground across North Carolina for the 72-hour period from 0000Z August 15, 2000 to 0000Z August 18, 2000.
Figure 3.8.22. As in Figure 3.8.21 except for the 12-hour period (forecast hours 61 – 72) from 1200Z August 17, 2000 to 0000Z August 18, 2000.

Figure 3.8.23. As in Figure 3.8.20 except for the 12-hour period (forecast hours 13 – 24) from 1200Z August 15, 2000 to 0000Z August 16, 2000.
Figure 3.8.24. Index of agreement for temperature between the model and observation stations at 2m above the ground across North Carolina for the 72-hour period from 0000Z August 15, 2000 to 0000Z August 18, 2000.

Figure 3.8.25. As in Figure 3.8.24 except for the 12-hour period (forecast hours 13 – 24) from 1200Z August 15, 2000 to 0000Z August 16, 2000.
Figure 3.8.26. As in Figure 3.8.24 except for the 12-hour period (forecast hours 49 – 60) from 0000Z August 17, 2000 to 1200Z August 17, 2000.

Figure 3.8.27. Index of agreement for specific humidity between the model and observation stations at 2m above the ground across North Carolina for the 72-hour period from 0000Z August 15, 2000 to 0000Z August 18, 2000.