Verification of Pre-convective Environments in WRF 3-km forecasts using Sounding Data from the Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX 2)

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SOARS® Summer 2010

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Abstract

The Weather Researching and Forecasting (WRF) model has been used operationally to predict weather. Previous studies have mentioned the difficulty of predicting convective weather accurately in Numerical Weather Prediction (NWP) models. The focus of this study is to examine the pre-convective environment in high-resolution WRF forecasts using sounding data. Pre-storm environments in the WRF 3-km forecasts from the NOAA Hazardous Weather Testbed (HWT) 2010 Spring Experiment were compared to sounding and observed radar data from the Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX2). Data from June 7, 9-11, and 13-15, of 2010 of the VORTEX2 field campaign were selected for comparison with model forecasts. The examined WRF 3-km forecasts were initialized at 0000 UTC on these days. Sounding data taken before storms initiated in the model and observations were compared to observe differences in the pre-convective environment. Significant differences included consistently warm profiles in the boundary layer and a weak or missing capping inversion in the model; however, above the boundary layer, the model temperature and wind profiles were fairly accurate. The differences seen in the profiles and radar composites suggest that a good long-term forecast (18-24 hr) is dependent upon a good short-term forecast (0-12 hr). Model vertical resolution may have been an issue in resolving capping inversions. The VORTEX2 data set proved valuable in evaluating model representation of the pre-convective environment. These findings reveal the need for further investigation into the high-resolution WRF forecast capabilities to represent the pre-convective and/or convective environment.
1. Introduction

There have been many uses of proximity soundings in the past to explore storm environments. Bryan and Parker (2010) used rawinsonde data from the Second Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX2) to examine the environment of a squall line. Thompson et al. (2003) used close proximity soundings from the Rapid Update Cycle (RUC) to explore supercell environments along with comparing those to previous studies of analyzed properties of supercell environments. Paddock et al. (2001) did work similar to Thompson et al. (2003), but used soundings from the observed atmosphere and RUC Version II to analyze the pre-convective environment of heavy rainfall producing storms. All of these studies aided in increasing the atmospheric knowledge on environments relative to certain systems and revealed the need to investigate verification of forecasts with respect to what was observed in the atmosphere. Paddock et. al (2001) stated it best saying that the increased accuracy of forecasting the location and amount of precipitation is crucial in not only saving lives but also lessening property damage.

The investigation into the verification of Numerical Weather Prediction (NWP) models to predict the observed atmosphere has been on-going for many years as the need for accurate forecasts has always been important (i.e., public life, property damage, transportation, etc.). Weisman et al. (2008) exemplifies this need stating that convective weather remains a significant challenge for numerical weather prediction systems, and is recognized as a major contributor to poor warm season quantitative precipitation forecasting (QPF). Others such as Davis et al. (2006) and Rezacova et al. (2005) have also claimed radar precipitation based verification of NWP models should be evaluated at high resolutions to examine forecast quality. Baldwin et al. (2008) also discussed the issue of verifying forecast and observed fields that contain high-amplitude, small scale features. The need to explore high-resolution forecasting is evident in resolving mesoscale features. Some of the issues discussed in previous studies reveal the WRF model producing too many systems (Davis et al. 2006) and significant errors in the timing and location of convective events (Weisman et al. 2008). Baldwin et al. (2008) states that more useful verification information could be obtained if one were to classify or categorize the forecast and observed fields prior to verification. These studies provide motivation for examining pre-convective environments and how these conditions affect the forecasts of convection. Higher resolution models are also requested to be used for better quantification of issues as mentioned by Davis et al. (2006).

b. Goal of this study

The combination of the need for verification of model forecasts along with the ability to explore vertical environmental profiles through proximity soundings motivates this study. Thompson et al. (2003) stated that many obstacles to an advanced understanding of severe thunderstorm environments exist when considering observed proximity soundings. Among those obstacles mentioned were the sounding sampling size and the time and space scales appropriate for representing the storm environment. With a unique data set from VORTEX2, we will be able to explore the pre-convective storm environment with relatively large sample sizes and close proximity to observed storm locations. VORTEX2 was a fully mobile experiment in spring 2009.
and 2010 that repeatedly collected sounding and other data in regions of expected severe thunderstorms, along with high-resolution data within these storms after they formed. The VORTEX2 data set has multiple sounding data points that vary over space and time. With the number of soundings present, the pre-storm and storm environment of systems can be investigated more accurately than in previous studies. The focus of this study is to examine the pre-convective environment in high-resolution WRF forecasts using sounding data collected from VORTEX2. Comparisons of forecasted and observed sounding profiles will be conducted at exact locations before storms initiated on selected days. Observed radar and model-forecasted radar composites will also be compared to explore the verification of the environments. How the cases were selected will be discussed in section 2. The data and methodology used to compare the observed atmosphere to the modeled atmosphere will be discussed in Section 3. Section 4 will illustrate and analyze the radar and sounding profiles between the observations and model forecast. Section 5 will discuss the reasoning and details of the similarities and differences of the comparisons. Section 6 will summarize the study and suggest avenues for future studies.

2. Selection of Cases

There were a total of 7 days selected for this study. Those days included June 7, 9-11, and 13-15 of the VORTEX2 field experiment. These days covered roughly the last week of VORTEX2’s operations. Over the course of these 7 days, a total of 25 pre-convective soundings were collected. These days were selected for this study based on the proximity of the pre-convective soundings to the onset of convection, the activity of the period, and the period when the author was in the field. Another consideration that aided in selecting these cases was the synoptic pattern throughout the period. These cases experienced a similar pattern where the synoptic state involved an advancing upper-level trough just off the West coast of the United States moving eastward and residing with positive tilt over eastern New Mexico to the northeast towards Iowa. The VORTEX2 teams were in position chasing a frontal system that continually moved southward from eastern Colorado on June 7th to central Texas on June 15th. Although these cases experienced a similar synoptic pattern, this study does not analyze all cases together but instead each case individually due to the mesoscale features for each day being forced by properties on a smaller scale within the synoptic pattern.

3. Methods

The 48-hour forecasts from the National Center for Atmospheric Research (NCAR) 3km Central US WRF for the 2010 convective season (http://hwt.nssl.noaa.gov/Spring_2010/) were used for real-time forecast radar products for the days that included June 7, 9-11, and 13-15 of 2010. The forecasts were initialized at 0000 UTC with the Rapid Update Cycle (RUC) 13-km data as the initial condition, and with the Global Forecast System (GFS) forecast providing lateral boundary conditions. For this forecast model, the horizontal grid spacing was 3 km. The model had 35 vertical levels and extended to a top of 65 millibars (mb). For the complete initialization and physics parameters used in the forecast model, refer to Table 1. The full model grid covered the eastern ¾ of the continental United States with 1320 x 1000 grid points. For this study, a sub-domain of the full grid, covering the region of VORTEX2 operations, was examined. This sub-domain can be viewed in Figure 1.
The majority of the WRF 3-km forecasts from VORTEX2 were available in online directories. For the days with missing forecasts, WRF 3-km forecasts model output data were downloaded from mass storage. Version 4.5 of the Read Interpolate Plot (RIP) program was used to interpolate the meteorological output data from the WRF model onto the selected domain for viewing. The RIP program is a Fortran program that invokes graphic routines for the purpose of visualizing output from meteorological data sets (Stoelinga 2009). Several parameters were plotted for comparison with the observational data. These parameters included sea-level pressure, temperature, dewpoint, relative humidity, surface winds, and shortwave radiation. All of the parameters were viewed over the time period from 18-24 hours within the model forecast.

After the data were plotted using the RIP program, this information was then compared with data sets from the VORTEX2 field catalog (http://catalog.eol.ucar.edu/vortex2_2010/) on the selected cases. The VORTEX2 field catalog (2010) contained daily reports, research products, radar products, and model/forecast products. The daily reports were used to gather mobile soundings reports for pre-storm sounding locations and times. They were also helpful in discerning what days to choose for this study. The research products contained the raw images of the soundings for viewing purposes. These were compared directly to forecast soundings in the pre-convective environment. The radar products contained the observed national radar composites along with base reflectivity and velocity images from individual radars. The section also included visible satellite imagery used for determining cloud cover over the areas of interest for each case. The National NCAR West composite was used to view our region of interest in the Plains of the United States. The model/forecast section contained the WRF 3-km forecasts initialized at 0000 UTC and 1200 UTC for each day of the field experiment. The forecasts at 0000 UTC for each case from the VORTEX2 field catalog were compared to the National NCAR West radar composite. The 0000 UTC radar forecasts plotted in RIP were also compared to this composite. The Hydrometeorological Prediction Center (HPC) surface analysis archive
was used to examine the observed frontal locations, dry lines, and etc. Along with surface observations, these were compared to model output data from RIP. (Note: Both forecasts from the field catalog and RIP output are the same. The forecasts were re-plotted in RIP for viewing purposes and missing forecast data in the online registry of the field catalog.)

To take a detailed look between the differences of the sounding profiles in the pre-convective environment, the NCAR Command Language (NCL) graphics program was used to overlay corresponding observed and model soundings on the same skew-t diagram. NCL is an interpreted language designed to visualize and analyze scientific data (http://www.ncl.ucar.edu). This graphics program was able to input stored observed sounding data along with the WRF model output. The script used to plot these soundings would take the observed sounding file input into it, find the nearest model grid point and use that in selecting the model sounding location.

4. Results

a. Model vs. Observed Convective Comparison

Before investigating the observed and forecast soundings for each case, it is important to compare the WRF 3-km model forecasts of convection to what was observed in the atmosphere. The WRF 3-km model forecasts at 0000 UTC for each of the selected cases were compared to the observations over the time period near the onset of convection. In the model, this convective start to end time was from 18 hours to 24 hours in the forecast. For brevity, it is best to explore the two cases that revealed the trend seen among all the cases. The following paragraphs will discuss the similarities and differences between the observations and WRF 3-km model forecasts for June 10 and June 11.

In the radar observations for June 10, convection began close to 2100 UTC (Figure 2) in Southeast Wyoming. Those storms continued to track east and east northeast across Southeast Wyoming. Around 2300 UTC (refer to Figure 3) storms began to form across the Front Range in Northeast Colorado near Briggsdale, Colorado and near Limon, Colorado. In the model, convection began near 1800 UTC with some cells moving into Southeast Wyoming (refer to Figure 4). This convection seen in the model was earlier than that seen in the observations. Around 2200 UTC (refer to Figure 5), a large storm developed in Northwest Nebraska. The observations showed a similar storm but definitely smaller in footprint near 0000 UTC June 11. Front Range development began near 2200 UTC, an hour earlier than observed. The main difference between the forecast and the observed atmosphere is that the model forecasted convection too early that was too widespread later on.
On June 11, the observed radar composites showed convection beginning in central Colorado to the west of Denver near 1800 UTC (refer to Figure 6). After 1900 UTC, spotty convection remained to the west and northwest of Denver, Colorado. Near 2000 UTC, another cell formed in the same location mentioned near 1800 UTC. From 2000 UTC to 2300 UTC, small convection remained evident in north central Colorado. Near 0000 UTC in the observed radar, the northeast Front Range and borders of northern, central, and southeast Colorado were populated with many severe cells (refer to Figure 7). In the forecast for June 11 initialized at 0000 UTC, storms began to form in southeast and northern Colorado near 1900 UTC (refer to...
Figure 8). At 2000 UTC, a strong cell formed near Denver with developing convection to its south. By 2200 UTC, southeast Colorado was taken over by a large system. Near 0000 UTC June 12 (refer to Figure 9); the entire Front Range was engulfed with storms that connected to a larger system positioned over the Nebraska and Kansas border. This system then formed a large system of storms covering most of Nebraska after 0000 UTC. This forecast performed well although some differences did occur with the model producing a larger footprint of dispersed storms throughout Eastern Colorado.
b. Model vs. Observed Sounding Comparison

To observe key differences between each forecast sounding and the corresponding observed sounding in the pre-convective environment, NCL was used to overlay the two soundings at each location on a skew-t diagram. The observed soundings are shown in black while the model soundings are shown in red. These environments were examined on a day-by-day basis similar to the way the forecast radar and other various indices were compared to the observed data. We will focus on 2 cases in the subsequent paragraphs that are representative of general results for all the selected cases. The other cases will be related in the Discussion section as we discuss some of the reasons why differences occurred in the model and observed sounding profiles.

These two cases are June 10 and June 11. June 10 is considered to be the case that shows a poor model forecast while the June 11 case shows a better model forecast. On June 10, the VORTEX2 mobile sounding teams sampled the pre-convective environment from northeastern Colorado to western Nebraska. There were a total of 6 pre-convective soundings collected over the region. Since most of these soundings were consistent in their vertical profiles, only 3 of the soundings are shown.

At 1915 UTC June 10, sounding data were collected from Sidney, Nebraska in the pre-storm environment. Refer to Figure 10 for comparisons to the forecast sounding at 1900 UTC. The forecast sounding is similar to the observed sounding. The wind profile is nearly identical. The forecast wind profile has southeast winds in the lowest levels then turning west southwestward. This is also evident in the observed sounding but the wind profile is more easterly instead of southeast. The winds turn to the southwest as seen in the forecast at the same level in the atmosphere as the forecast sounding. The vertical temperature and dewpoint profiles
are similar with the exception of some major temperature differences in the lowest levels that could have resulted in poor model convective forecasts. The forecast sounding is warmer than the observed sounding. There is a strong capping inversion in the observed sounding. The model has a slight inversion but it is at a lower level in the atmosphere than the observed sounding. The dewpoint profile is very similar with the forecast sounding becoming drier around 800 mb. Around 700 mb and higher, the vertical profiles of the dewpoint are similar. Both profiles show the evidence of CIN. LCL heights are nearly the same but the amount of CIN seems to be greater in the model. The amount of CAPE seems to be almost the same. The capping inversion in the observed sounding gives more chance of inhibiting convection. But, with the dryness in the lowest levels of the forecast sounding, in the absence of a strong inversion, gives the forecast model sounding the amount of CIN needed to correctly forecast the pre-convective environment.

Figure 11 illustrates the pre-convective observed sounding for Briggsdale, Colorado sampled at 2108 UTC. The corresponding forecast sounding time was 2100 UTC. The wind profile of the forecast has slight differences when compared to the observations. Above 725 mb, the forecast sounding wind profile is representative of the observed profile with wind directions from the southeast. At the levels below 725 mb, the forecast sounding wind direction is mainly from the south southeast while the observed profile wind directions are from the west and then progress into a south southeast to south southwest direction. The temperature and dewpoint profiles display some differences between the forecast and what was observed. The forecast temperature profile is warmer from the surface to approximately 675 mb. A capping inversion exists at this level that is not resolved in the model. Because of this difference, minimal CIN is seen in the forecast sounding. CAPE values are also higher in the forecast sounding. Above 675 mb, the profiles are very similar remaining dry adiabatic. There are discrepancies in the dewpoint profiles throughout the troposphere. The observed sounding has an increasing mixing ratio from the surface to 700 mb. The model seems to initially follow this same profile but around 800 mb becomes increasingly dry and does not show the near saturation seen in the observed sounding. Above 700 mb, although the temperature profiles are similar, the model forecast becomes more saturated aloft while the observed sounding dries out.

At 2235 UTC, sounding data were collected from Brush, Colorado and compared to the forecast sounding at 2200 UTC. Refer to Figure 12, which portrays these soundings. The wind profiles are very similar with low-level (~850-700 mb) winds primarily from the southeast. There is some difference as the observed sounding shows westerly winds around 800 mb that the forecast sounding does not depict. Above the lowest levels, both profiles take a more southeast profile turning more westerly proceeding through the atmosphere. There seem to be some differences in the magnitude of the winds aloft at certain levels. The dewpoint profiles are nearly identical throughout the atmosphere. The only area that these profiles do not agree is around 400 mb where the observed sounding is drier than the forecast sounding. As for the temperature profile, there are some key differences in the lowest levels. The forecast sounding is much warmer than the observed sounding -- by 8 degrees C. The forecast temperature decreases steadily from the surface throughout the atmosphere while the observed sounding reveals a capping inversion of about 4 degrees C at the 700 mb level. The observed sounding has more CIN, less CAPE, and lower LCL heights than the forecast sounding. The PBL is more mixed in the model than the observations. These differences in the lowest levels of the atmosphere could have caused major differences in the onset of convection in the model.
On June 11, the VORTEX2 mobile sounding teams collected data of the pre-convective environment from northeast Colorado to central-eastern Colorado. There were 6 samplings of the environment. At 1814 UTC, the mobile soundings team sampled the pre-convective environment in Limon, Colorado. Figure 13 reveals the comparison between the aforementioned observed sounding to the forecast sounding at 1800 UTC. The wind profiles for the observed sounding and forecast sounding are similar. At the lowest levels both exhibit northeast winds at the surface veering throughout the profile at the same depths in the atmosphere to east wind, southeast winds, south winds, and southwest winds. The only major differences are in the wind speeds. LCL heights are similar. CAPE values are nearly the same but there is more CIN in the observed sounding due to a warm nose at 700 mb. The surface dewpoint and environmental temperatures are nearly the same. The model dewpoint profile follows the observed sounding to 700 mb. Above 700 mb, the two profiles intertwine with the model forecast becoming moist throughout the depth of the atmosphere. Besides the warm nose at 700 mb, the temperature profiles are nearly equivalent. The Brush, Colorado1843 UTC sounding compared to the 1900 UTC forecast sounding shows very strong resemblance to the 1814 UTC sounding in Limon, Colorado. This sounding comparison can be seen in Figure 14 for reference.
Figure 15 depicts the observed sounding taken at 2220 UTC at Byers, Colorado with the corresponding forecast sounding at 2200 UTC. The wind profiles of the forecast and observed soundings are nearly the same with easterlies in the lowest levels shifting to south to southwesterly winds at the same levels of the atmosphere. The PBL depth appears to be similar in both profiles with the lowest levels mirroring each other up to about 700 mb. Above 700 mb there is some discrepancy between the forecast sounding and the observed profile. The model profile is drier and warmer than the observed sounding around 700 mb. The two profiles switch places as the observed sounding becomes drier and the forecast sounding becomes almost saturated with respect to ice above 500 mb. The two profiles don’t coincide again until about 200 mb for the dewpoint profile and 300 mb for the temperature profile. LCL heights are similar with minimal CIN in both sounding profiles and more CAPE in the forecast sounding. In the near vicinity of this sounding comparison, another vertical profile sounding was collected in Last Chance, CO. This sounding at 2147 UTC is compared to the 2200 UTC forecast sounding for that area. The same issues with the upper levels being saturated in the model are seen. This comparison can be seen in Figure 16.
c. Time Sensitivities

Some of the observed soundings collected were compared to different forecast soundings. These forecast soundings were at different times within the model but remained at the same location to see time variation in the pre-convective environment comparisons made above. The selection for the observed soundings undergoing this sensitivity test was based on the relative time at which the observed sounding occurred. The forecast soundings were only available every hour. If the observed sounding occurred between the hours of the forecast sounding time, there was potential for it to be selected for this test.

On June 9, a pre-convective sounding was collected in Sidney, Nebraska at 2128 UTC. It was initially compared to the 2100 UTC forecast sounding (refer to Figure 18). Figure 19 displays the observed sounding compared to the forecast sounding available at 2200 UTC. The forecast sounding wind profile is similar to the 2100 UTC sounding profile; therefore, we know there hasn’t been a significant mesoscale change, such as a frontal passage. The model is still warmer than the observations to the same degree. This profile has a better handle on the PBL depth almost to the point seen in the observed profile. The profiles seem almost the same except the forecast sounding becomes saturated around 550 mb. There is more CAPE in the forecast sounding in this profile. Figure 17 displays the observed sounding at 2229 UTC in Kersey, Colorado compared to the 2200 UTC forecast sounding. Figure 20 takes the same 2229 UTC observed sounding and compares it to the forecast sounding an hour later at 2300 UTC. The wind profile is similar to the 2200 UTC profile except for the fact that there is hardly any veering with surface winds coming from the south southeast. The temperature profile is still dry adiabatic and 4 degrees C warmer than the observed sounding at the surface. It is extremely dry in the low levels and becomes saturated near 600 mb to 400 mb. The observed sounding and this model
forecast are visibly different. There are not any similarities besides the wind profile. This forecast sounding is not representative of the atmosphere at 2229 UTC.

On June 10, the 2235 UTC Brush, Colorado sounding was compared to the 2200 UTC forecast sounding (refer to Figure 12). Figure 21 illustrates the observed sounding compared to the forecast sounding for Brush, Colorado at 2300 UTC. This forecast sounding did not resolve the dewpoint profile as well as the 2200 UTC profile. The same issue occurs with the
temperature profile but it seems to lose coherence in the upper levels as well in this profile comparison. The dewpoint profile is definitely not as dry in the model forecast. Initially, the model dewpoint profile resembles the lowest levels of the observed sounding but then becomes dissimilar aloft. The difference in the lowest levels still remains as an issue as seen an hour earlier.

5. Discussion

In the previous section, we discussed the technical differences of the model forecast to what was observed in the atmosphere by viewing the resemblance and discrepancy of radar composites and sounding profiles. To understand the variation between the WRF 3-km forecast and observed environment, there needs to be an in depth look into why these similarities or differences occurred. In the subsequent paragraphs, the main 2 cases will be analyzed with reasoning behind the variance in the model forecast to the observed atmosphere. The 5 other cases will be referenced as they experienced similar conditions to the June 10 and June 11 cases. This will aid in determining flaws or consistencies that can improve how we forecast.

On June 10, the forecast soundings compared to the observed soundings experienced the same issues of representing the low-level mesoscale features of the atmosphere. Each sounding at its relative time and location encountered warmer environmental temperature profile with corresponding lower relative humidity in the low-levels. The dewpoint profiles were forecasted well initially, however, near storm initiation times in the model forecast, these profiles were not. From 1800 UTC 10 June to 0000 UTC 11 June, the observed sounding profiles revealed a capping inversion. This mesoscale feature was strongest at 2100 UTC with an inversion covering more than 4 degrees C. At 1900 UTC, the inversion level was near 725 mb. As the day progressed into the early evening, the inversion lifted to 700 mb. This lifting of the inversion probably resulted from PBL mixing due to surface heating that occurred until 2100 UTC 10 June.

Fig. 22. Model composite reflectivity (dBZ) at 1200 UTC on June 10.

Fig. 23. Observed composite reflectivity (dBZ) at 1200 UTC on June 10.
At 2200 UTC in Kersey, Colorado, the capping inversion in the model erodes due to rainfall occurring in near the vicinity of the sounding location, causing evaporational cooling to take place aloft. The model forecast revealed plenty of storm initiation. This storm initiation was a by-product of the forecast warming and clearing the small resolved capping inversion aloft that was seen earlier in the forecast soundings. Heating and mixing made the environmental profile nearly dry adiabatic from this point forward into the forecast. Once the capping inversion is removed, the forecast model handles convection location decently, but the magnitude of convection was forecasted poorly as the model produced too much convection. This can be attributed to the warm temperatures in the model forecast. Overall, the main issue that was seen for differences in the forecasted and observed sounding was the displacement of the MCS-like system. The model forecasted the system farther north and to the west than the observed radar composites. This can be seen in the comparisons of Figure 22 to Figure 23, both at 1200 UTC on June 10. The red circle in each figure represents the area of interest for the June 10. This had great impacts on the sounding profiles. This system affected the sounding sampling area with increased cloud cover and outflow boundaries giving cooler profiles in the observed soundings. With this system displaced in the model forecast, the outflow boundary behind the system was not able to affect the region, allowing for more heating to occur as cloud cover also decreased. This difference in cloud cover can be seen in comparing Figure 24A to Figure 24B. It is visible that the highest temperature differences are located in the region where no cloud cover is seen. This shows the evidence of no cloud cover left in the model, increasing the surface heating, therefore warmer boundary layer profiles.

Fig. 24. A) On the left, this image displays the model minus the observed 2m temperature along with the model forecasted shortwave radiation flux at the surface at 2000 UTC on June 10. B) Displays the observed visible satellite imagery at 2000 UTC on June 10.
Several other cases also showed the same pattern, with boundary layer profiles too warm in the model, corresponding to poor morning convective forecasts. On June 7, in Figure 25, we see a warmer low-level boundary layer. This profile is almost similar to Figure 10 on June 10, as the capping inversion is not well resolved. This day experienced similar conditions as the morning convective forecast was off, with storms occurring over Northwest Nebraska near the collected sounding stations in the observed atmosphere, where the model forecast did not show any convection occurring early on. June 9 was also very similar to the June 10 case as the convective morning forecast was missed. In Figure 18, we see evidence of a capping inversion near 700 mb that is smoothed out in the model forecast. As for this day being a poor forecast day, too much convective initiation was seen. Very similar to what we saw on the June 10 case with missing the morning convective storms in the model resulted in the afternoon capping inversion being too weak, and thus, there was too much afternoon convection in the model. Another case that was similar was the June 15 case, in which the warm boundary layer in the model was seen. As mentioned for the other cases, we see a bias towards the capping inversion not being resolved in the low-level profiles. On this day, the entirety of the forecast was problematic, with convection beginning in the model where there were no storms seen in the observed atmosphere. Figure 26 displays this warm bias in the boundary layer seen once again over these similar cases with poor forecasts.

The sounding profiles for June 11 ranged from Northeast Colorado to Eastern Colorado. The forecast sounding paralleled the observed soundings accurately. There were minor issues reported in the Sounding Analysis section of the results section. Besides these issues, the low-
level mesoscale features were resolved well. The well mixed PBL layer was resolved accurately in the model forecast. The observed and forecast temperature profiles aloft were nearly identical for the Byers, Colorado and Last Chance soundings near 2200 UTC. In these two areas, the model seemed to be slightly moist above the PBL height to 500 mb. Near 2000 UTC, the observed sounding profile is almost saturated near 700 mb, which is most likely due to the rawinsonde passing through a cloud as it rose through the atmosphere. The observed soundings after this time reveal the dryness that was mentioned. At 2200 UTC (refer back to Figures 15 and 16), the model sounding profile becomes saturated with respect to ice. In the model forecast at 2200 UTC, Byers and Last Chance, Colorado are in a stratiform precipitation region. Because of this, it could be raining aloft but not reaching the ground, producing some saturation aloft. The area was clear of storms in the observed radar composites which as mentioned were dry aloft.

Two of the 5 cases not mentioned showed the trend of a good morning forecast with the evening forecast being much better than what was seen in the June 10 case. Those case days that resembled the June 11 case were June 13 and June 14. Both of these days resolved the low-level mesoscale features of the atmosphere well, similar to June 11. The June 13 case was slightly different though, only having 2 available pre-storm soundings. One was located on the cool side of a frontal boundary (refer to Figure 27A) while the other was located on the warm side of the frontal boundary (refer to Figure 27B). While the warm side sounding comparison was forecasted well, the cool side comparison did not do so well. This difference was mainly due to the fact of the positioning of the dew-point axis between the forecast sounding and the observed sounding. Higher dewpoints were not seen enveloping the Perryton, Texas area in the model forecast. While this case had slight differences, the June 14 case was forecasted well, including during the morning. The evening forecast was good as the main convective location and modes were represented in the model forecasts. With only one pre-storm sounding for this case (refer to Figure 27C), not much can inferred from this sounding comparison besides the fact that the low-level mesoscale features were well resolved. In comparison with the June 11 case, we see the similarities of a good morning forecast with resolved low-level features being indicative of a good evening forecast.
6. Summary

This study analyzed a set of cases using sounding profiles from the WRF 3-km forecasts along with observed sounding profiles collected during the VORTEX2 field experiment. There were a total of 25 pre-convective soundings sampled over the 7 days selected from the VORTEX2 campaign. These soundings documented the profiles of the pre-storm environment. Observed and model-forecasted radar composites were analyzed to examine the impact of the differences between the observed and model-forecasted soundings in the pre-storm environments.

The comparisons of the sounding profiles and radar composites revealed a consistent trend among the cases. For the cases of June 7, 10, and 15, the model consistently had warmer sounding profiles than what was observed. In all of these cases, there was a trend of the morning convective forecasts being missed; whether it was the displacement of a large-scale system (such as June 10), morning cells with accompanying outflow boundaries, or strong capping inversions not being resolved. The main trend seen was the model not having the lingering clouds from the storms that should have been produced in the morning, allowing for more surface heating to occur. This in turn led to warmer profiles along with capping inversions being absent. The vertical resolution of the model could be an issue in resolving the stronger capping inversions. The other trend was that of good morning forecasts followed by sounding profiles representing low-level mesoscale features well during the afternoon. This type of trend was seen on June 9 and 13-14. On these days, the morning convective storm forecasts were relatively accurate. In the sounding profiles, small caps were resolved. The PBL heights and mixing were also key in
the low-levels being resolved well. Lastly, the wind and temperature profiles of the soundings were fairly identical throughout the depth of the atmosphere. The area of convection was forecasted well, however, there were issues with the magnitude of convection being much stronger than what was observed.

This analysis gives insight into the role in which the pre-convective environment forecast plays in the convective forecast. This study could give further indication of needed changes to forecast models and/or data assimilation to accurately predict the atmosphere. With more proximity soundings, data assimilation, and observed radar comparisons; models can be enhanced for future uses. Further work is still needed to identify relationships between short-range and long-range forecasts. The vertical resolution issue could use further investigation to see if capping inversions may be better resolved with more vertical levels. Other avenues that can be explored through this work for analysis could be the test of the sensitivity of the models’ microphysics. All in all, more work is needed to support these findings that were presented from only a one week period during the VORTEX2 field campaign.

Acknowledgements

First and foremost, I would like thank the SOARS staff (Raj Pandya, Moira Kennedy, Rebecca Haacker-Santos) and the SOARS steering committee for giving me the opportunity to be a part of the SOARS program. I would also like to thank my fellow SOARS protégés for their support throughout the summer. Special thanks to my mentors David Dowell and Kevin Manning for creating a great project in which I only had 5 weeks to conduct. I would like to thank Joanne Dunnebecke for aiding in furthering my writing skills along with her input for suggestions in describing my work. I would like to give special thanks to the VORTEX2 experiment, without this happening I would not have such a unique project. I would like to thank Dr. Matthew Parker for giving me the opportunity to be in the field with mobile soundings team for the VORTEX2 project. I would also like to give thanks to William Brown, George Bryan, and Matt Parker for allowing me to use the sounding data received from the VORTEX2 operation for my study. I would like to also thank the mobile soundings crew whom I worked with in the VORTEX2 field experiment. Lastly, I would like to show my appreciation to the Microscale and Mesoscale Meteorology (M-Cubed) division at UCAR and NCAR for allowing me to use their facilities and equipment to conduct this study.
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