A Look at the NSSL-WRF Forecast Output for the Violent Tornado Events in Central Oklahoma on May 19 and 20, 2013

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1. Introduction

Tornado forecasting has improved dramatically in the past 30 years due to technological improvements, such as faster computers, higher resolution forecast models, and advancements in radar technology [e.g., implementation of NEXRAD WSR-88Ds (Crum and Alberty 1993)]. Also, during the past few decades, forecasters have gained a much better understanding of the environment (Schneider and Dean 2008) and storm structures favorable for severe weather and tornadoes (Lemon 1980; Forbes 1981). In recent years, the average lead-time for tornado warnings has increased to 14 minutes (NOAA 2011). While this lead time allows individuals time to get to a safe shelter, increased lead time of an hour or more would aid those who do not have immediate access to a shelter to move to a safer location. To accomplish this feat, the National Oceanic and Atmospheric Administration (NOAA) National Severe Storms Laboratory (NSSL) has developed a program called Warn-on-Forecast (Stensrud et. al 2009). Within the next 5 to 10 years, this convective-scale probabilistic hazardous weather forecast system is expected to provide several hours of reliable probabilistic information on the approximate time, location, and intensity of hazardous weather, including tornadoes. For this goal to be fulfilled, accurate high-resolution storm-scale models are required.

The Warn-on-Forecast system will build upon some of the ideas and lessons learned from an experimental realtime modeling system. The experimental modeling system NSSL uses is the Weather Research and Forecasting (WRF) and is known as the NSSL-WRF. This model currently provides storm-scale guidance to SPC forecasters and is also a testing ground for the development of storm-scale model forecast products. The NSSL-WRF and several other storm scale models were used extensively throughout the five week 2013 NOAA/Hazardous Weather Testbed (HWT) Spring Forecasting Experiment (SFE). The HWT SFE pulls together forecasters, researchers and academia to work side-by-side to test the applicability of cutting-edge tools in a simulated forecasting environment. Also, the output from the storm-scale models is examined daily and experimental severe weather outlooks are created and verified. The forecast and model output are also evaluated. The evaluations of specific storm-scale products, derived from both ensembles and deterministic models, provide focused feedback to model developers so improvements can be made, and the relevance and usefulness to operational forecasters are determined. While severe weather occurred on most days during the experiment, 19 and 20 May presented a unique opportunity to see how well the NSSL-WRF performed on backto-back days when a violent tornado occurred.

II. Description of NSSL WRF

NSSL and the SPC starting exploring the usefulness of convection WRF during the 2004 NOAA HWT SFE (Kain et al. 2006). Forecasters were impressed by the output and especially the ability of the WRF simulations to depict realistic convective-scale storm structures associated with mesoscale convective systems and discrete supercells. These successful tests motivated NSSL scientists to establish a more permanent experimental modeling framework to provide storm-scale guidance to SPC forecasters and to develop new storm-scale model products.

The NSSL-WRF uses a 4-km grid-spacing and is run twice daily at 0000 and 1200 UTC. The forecast output are generated hourly out to 36 hours, and covers the full CONUS domain using NOAA's high performance computing resources. MYJ is the boundary layer scheme that is employed, while the WRF single-moment six-class is used for the microphysics scheme. The initial and lateral boundary conditions are interpolated from the latest run of the North American Mesoscale (NAM) model. Some of the unique products generated from the NSSL-WRF and not available from operational models include: Simulated Reflectivity, Hourly Maximum

Updraft Helicity (UH), Lightning, and Max Updraft/Downdraft speeds. The NSSL-WRF also outputs other traditional environmental parameters such as surface temperatures, dewpoints, and winds as well as instability and hourly precipitation.

III. Synoptic Environment

The 12z soundings for 19 and 20 May are shown in Figure 1. Similarities on the two soundings include strong instability with steep mid-level lapse rates, a capping inversion around 850 mb and sufficient deep layer shear for supercells. The more notable differences between the two days includes stronger low level winds/shear as well as a stronger capping inversion on 19 May than 20 May.



Figure 1a. The 19 May 1200 UTC Norman, OK sounding.



Figure 1b. The 20 May 1200 UTC Norman, OK sounding

The synoptic pattern did not change much during the two days with a broad upper trough at 500 mb located over much of the plains states westward into the intermountain west. (Fig. 3). At the surface, a weak cold front was located in northwest Oklahoma, with a dry line extending southward from the front in northwest Oklahoma into southwest Texas. Temperatures in the 70s and 80s with dewpoints in the 60s resulted in the strong instability ahead of the front and dryline on both days.



Figure 2. Analyzed 500 mb and surface chart for 21 May 0000.

The SPC mesoanalysis products in (Fig. 3) show some of the mesoscale parameters near the time of violent tornado events (2300 UTC on 19 May and 2000 UTC on 20 May). While both days were strongly unstable, instability was greater on the 20^{th} (~3000 J/KG MLCAPE) than the 19^{th} (~2000-2500 J/KG MLCAPE). Due to the northerly surface winds, the strongest effective shear was located in northern Oklahoma north of the cold front. However, 40 to 50 knots of effective shear, sufficient for supercells, was located in the warm sector across central Oklahoma. Due to strong low level winds, the 0-1 km SRH was stronger on the 19^{th} (around 150 m²/s²) than the 20^{th} (50 to $100 \text{ m}^2/\text{s}^2$). While Thompson et. al (2013) found that the lowest 1 km SRH alone is not necessarily a good discriminator between weak and significant right-moving plain states tornadoes, it appears locally enhanced shear was present near the intersection of the cold front and dry line. However, the smaller scale features and their relevance to the tornado development on this day are beyond the scope of this paper.



Figure 3. The SPC mesosanalysis products showing various derived products near the time of the violent tornado occurrences on 19 and 20 May (2300 and 2000 UTC, respectively).

IV. A comparison between the NSSL-WRF and the EF3 and EF4 tornado event on 19 May

Figure 4 shows a comparison between the NSSL-WRF simulated reflectivity (top) and the radar observations (bottom) from 2100-0000 UTC. From 2100-2300 UTC, the northern storm ("1" on the graphic) is remarkably well forecast, and even displayed hooked-shaped echoes, which closely resemble the radar observations. Except for the NSSL-WRF forecasting the location of the storm slightly north and west of the actual storm location, the accuracy of the Simulated Reflectivity 21 to 24 hour in advance was extremely impressive. The northern storm produced a couple of weak tornadoes in the northern Oklahoma City suburbs between 2100-2200 UTC and an EF3 tornado northeast of Oklahoma City around 2200 UTC.

The second and southern storm ("2" on graphic) was evident from 2200-000 UTC and produced an EF4 tornado east of Norman around 2300 UTC. The storm at 2200 UTC appears to be a non-descript northwest-southeast oriented storm on both the NSSL-WRF and radar observation. The storm shape changes at 2200 and 2300 UTC with both depicting strongly rotating storms, as evidenced by the hook echoes. The important low level

reflectivity features with the NSSL-WRF forecast and radar observations were remarkably similar in both the number of storms and location.



Figure 4. The 19/0000 UTC NSSL-WRF Simulated Reflectivity output (top) and the Twin Lakes (Norman) radar at 2100, 2200 2300 and 0000 UTC.

Figure 5 shows a comparison between the NSSL-WRF forecast surface winds and dewpoints and the SPC mesoanalysis of surface winds and dewpoints from 2100-0000 UTC. The dry line is depicted by the tight dewpoint gradient to the west of the Oklahoma City metro ("O" on graphic). While the mesoanalysis shows a slightly more bowed dryline than the NSSL-WRF, the location is fairly similar. The exception is at 0000 UTC as the mesoanalysis shows the dry line retrograding faster westward than forecast by the NSSL-WRF. Also, note the expansive storm outflows (both in wind fields and lower dewpoints) in the NSSL-WRF that were not observed on the SPC mesoanalysis. This is likely due to the storm outflows being much smaller in size (storm-scale) than forecast by the WRF. However, the micro-scale storm environment was not stabilized, so the model was able to maintain the supercells without interruption from other storm outflows.



Figure 5. The 19/0000 UTC NSSL-WRF dewpoints and surface winds (top) and the SPC dewpoint mesoanalysis and surface winds at 2100, 2200 2300 and 0000 UTC.

The Hourly Max Updraft Helicity (UH) is a calculation of the vertical velocity and vertical vorticity integrated through the 2-5 km layer of the storm's updraft. Units are in m2/s2 and values at or above 100 m2/s2 have been a good predictor for supercell tornadoes (Clark et. al 2012). In Figure 6, the NSSL-WRF Simulated Reflectivity (top) and UH values are displayed from 2100-0000 UTC. To help compare the hourly graphics, an "O" and "N" are plotted on the graphics to represent the cities of "Oklahoma City" and "Norman", respectively. Also note that while the Simulated Reflectivity is a snapshot of the forecast reflectivity at the time noted, the displayed UH values are calculated with each radar scan (every 5 minutes) for the entire hour. As an example, the 2100 UTC represents UH computed from each radar scan between 2000 and 2100 UTC. In this case, UH greater than 175 m^2/s^2 indicated locations of where two long tracked tornadoes (rated EF3 and EF4) occurred. The tornado tracks are noted on the graphic at 2300 and 0000 UTC. The high UH values were not only excellent at indicating the threat for stronger tornadoes, but also longer lived tornadoes.



Figure 6. The 19/0000 UTC NSSL-WRF Simulated Reflectivity (top) and UH output (bottom) at 2100, 2200 2300 and 0000 UTC.

V. A comparison between the NSSL-WRF and the EF5 Moore Tornado on 20 May

On 20 May, the NSSL-WRF Simulated Reflectivity showed echoes developing at 1800 UTC (Fig. 7), but no such echoes were observed at the same time. The number of storms increased on the NSSL- WRF at 1900 UTC, near the dry line and cold front. The radar observation at this time showed only one stronger storm was located about 50 miles southwest of Moore, OK ("M" on graphic) and weak convection just west of Moore. At 2000 UTC, a large hook echo was evident on radar and an EF5 tornado was moving into Moore. At this same time, the NSSL-WRF Simulated Reflectivity depicted the highest reflectivity storm about 30 miles southeast of Moore with strong outflow occurring with this storm. While numerous other weaker storms were forecast by the NSSL-WRF by 2000 UTC, observations showed the storms were more discrete and intense than forecast. By 2100 UTC, the NSSL- WRF had organized the storms into an eastward moving band or line, while the radar observations showed the storms remained discrete and also further west than the NSSL-WRF forecast.



Figure 7. The 20/0000 UTC NSSL-WRF Simulated Reflectivity (top) and radar observations (bottom) at 1800, 1900, 2000 and 2100 UTC.

A comparison between the NSSL-WRF dewpoint forecast and the SPC mesoanalysis page explains meteorologically why the NSSL-WRF forecast did not forecast the evolution of the Moore storm and consequent EF5 tornado (Fig. 8). The NSSL-WRF dry line location closely resembled the SPC mesoanalysis, however, the NSSL-WRF spread stable storm outflows across the Oklahoma City metro, including Moore, by 2000 UTC. The outflow from the storms congealed and organized the convection into an outflow dominant band or line of storms, which then pushed more rapidly eastward than the discrete supercells did on this day.

Obviously, the EF5 Moore tornado would have observationally generated large UH values. The NSSL-WRF (Fig. 9) showed the values were very low at the EF5 tornado location (UH values less $55 \text{ m}^2/\text{s}^2$). The WRF forecast initiated too many weaker storms early on and this resulted in numerous outflows that undercut the storms and inhibited stronger updrafts and more intense rotation. The outflows eventually congealed and organized the storms more into a line instead of keeping them as discrete storms. These outflow generated storms consequently lowered the UH values as strong and persistent updrafts generally could not be maintained. Since the NSSL-WRF was not able to replicate the small-scale near storm environment that was present at 2000 UTC in Moore, the model was not able to accurately forecast the storm or tornado evolution.



Figure 8. The 20/0000 UTC NSSL-WRF dewpoints (top) and SPC dewpoint mesoanalysis at 1800, 1900 2000 and 2100 UTC.



Figure 9. The 20/0000 UTC NSSL-WRF Dewpoints and UH at 1800, 1900, 2000 and 2100 UTC.

VI. Summary

The NSSL-WRF on 19 May was highly accurate in predicting the initiation, number, and location of supercells, including hook-shaped echoes, in central Oklahoma, 21 to 24 hours in advance. The model also forecast tracks of UH with values greater than $100 \text{ m}^2/\text{s}^2$. The longer tracked UH values at or greater than $175 \text{ m}^2/\text{s}^2$ closely

resembled the location of the EF3 and EF4 tornadoes occurrences. Despite an apparent overexpansion of storm outflows, the outflows did not disrupt the storm updrafts, so the model was able to closely mimic the actual storm micro-scale environment and consequent storm evolution.

On 20 May, the NSSL-WRF developed more numerous and weaker storms than actually occurred. This resulted in storm outflows being dominant and undercut the updrafts, which inhibited strong updrafts from being maintained. Since strong updrafts were not able to develop in the model, the UH output values for this day were generally weak. Also, the outflows organized the storms into a weakly disorganized line, which shifted the storms eastward much quicker than actually occurred. At the time of the Moore tornado, the model had forecast the atmosphere to be stabilized over Moore, due to outflow from a forecast of a storm being located 30 miles southeast of Moore. The Moore EF5 tornado was not forecast by the NSSL-WRF as the model was not able to replicate the small-scale, near storm environment near Moore, OK.

VII. Future Research

On both 19 and 20 May, the outflow from storms became too expansive and too dry, as compared to nearby surface observations and analysis. More model tweaking may be needed to decrease the strength of the downdrafts. Also, although the environments were similar, the NSSL-WRF forecast discrete supercells on 19 May, but weaker and more numerous storms on May 20. Discrete supercells were the dominant storm mode on both days. An investigation into why discrete supercells were forecast one day and not the next should aid in model performance for the future.

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IX. References

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