ABSTRACT

BLANK, LINDSAY ROSE. Operational Predictability of Explicit High Shear, Low CAPE Convection. (Under the direction of Dr. Gary Lackmann).

High Shear, Low CAPE (HSLC) environments pose a difficult challenge for National Weather Service (NWS) forecasters. These environments primarily occur in the cool season (autumn – winter) during evening and overnight hours. These low instability environments most often occur in the Southeastern U.S., Mississippi Valley, and Ohio Valley. These environments can be accompanied by severe weather, including significant tornadoes, but forecasting HSLC convection is difficult. The aim of this study is to determine numerical weather prediction (NWP) model operational resolution requirements with regards to the explicit prediction of HSLC rotating convection.

The Weather Research and Forecasting (WRF) model was run at varying convective-permitting resolutions for two different HSLC cases, one event case and one null case. All three of the convective-allowing domains tested were able to provide operationally useful information about explicit low instability severe convection at varying degrees of detail. Between the three convective-permitting model domains, the severe proxy metrics were overall more similar between domains with a horizontal grid spacing of 1.2-km and 400-m than between the 3.6-km and 1.2-km domains. The results of this study indicate that operational numerical weather prediction models run for low instability prediction can be run with a minimum grid spacing of 3.6-km. Overall, the event case and the null case are statistically significantly different. The 3.6-km domain performs the best of the three convection allowing domains in distinguishing between the event and null cases.
Operational Predictability of Explicit High Shear, Low CAPE Convection

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BIOGRAPHY

Lindsay grew up in Brookeville, MD. She wanted to be an architect until she saw her first tornado, an F1, on May 27, 2001 in her neighborhood. That day, Lindsay asked her parents for a NOAA weather radio and her fascination with the weather began. She graduated from Millersville University of Pennsylvania with a Bachelor of Science in Meteorology and a Bachelor of Science in Computer Science in May 2014. While studying at Millersville University, Lindsay completed her Ernest F. Hollings Internship at the National Severe Storms Laboratory in Norman, Oklahoma. There, she discovered her dual love of atmospheric science and computer science in the form of numerical weather prediction. Lindsay pursued this interest further by attending North Carolina State University to obtain her Master of Science in Atmospheric Science with Dr. Gary Lackmann, beginning in August 2014.
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Chapter 1: Background

1.1 Introduction

High Shear Low Convective Available Potential Energy (HSLC) environments are defined when an environment meets the following parameters: 0-6 km bulk shear vector magnitude $\geq 18$ m/s, surface-based CAPE (SBCAPE) $\leq 1000$ J/kg, and most unstable CAPE (MUCAPE) $\leq 1000$ J/kg (Sherburn and Parker 2014; Davis and Parker 2014; King 2016). This convection can produce severe weather such as tornadoes (including EF2s and EF3s on the Enhanced Fujita scale), significant severe winds, and significant hail (Guyer et al. 2006; Schneider and Dean 2008; Clark 2009, 2011; Guyer and Dean 2010; Sherburn and Parker 2014; Davis and Parker 2014; King 2016; Sherburn et al. 2016). HSLC convective events most often occur in the Southeastern United States and the Ohio Valley, however, such events occur in all parts of the country and, indeed, worldwide (Guyer et al. 2006; Smith et al. 2008, Clark 2009, 2011; Davis and Parker 2014, Sherburn and Parker 2014, King et al. 2017, in press). These weak CAPE severe weather events most often occur during the cool season and overnight, when the environment is generally considered unfavorable for severe weather, thus increasing public risk (Konarik and Nelson 2008; Kis and Straka 2010; Brotzge et al. 2011).

High Shear Low CAPE convection poses a predictive challenge to forecasters. One difficulty is determining whether or not a HSLC environment will produce severe weather, leading to higher false-alarm rates (FARs) and lower probability of detection (POD) (Guyer and Dean 2010; Brotzge et al. 2011; Sherburn and Parker 2014; Sherburn et al. 2016). Traditional environmental parameters, such as the Significant Tornado Parameter (STP) and the Supercell Composite Parameter (SCP), may not indicate the existing convective potential of weak CAPE environments (Guyer and Dean 2010; Sherburn and Parker 2014). Another difficulty arises when
detecting and warning severe weather if a HSLC environment does indeed produce it. This issue arises from the fact that HSLC convective storms do not present like classic Great Plains (high shear, high CAPE; HSHC) supercells, starting with the fact that they are characterized by weak instability (Smith et al. 2008; Clark 2009; Guyer and Dean 2010). The radar climatology compiled by Davis and Parker (2014) shows that the storms produced in low instability environments are of a smaller width and depth than classic HSHC supercells thus making these storms difficult to detect until they are within close proximity to the radar. This makes it difficult for forecasters to issue warnings.

Operational forecasters, such as those in the National Weather Service (NWS) often utilize Numerical Weather Prediction (NWP) models for guidance (e.g. Clark et al. 2012a). The purpose of this study is to investigate how well NWP models handle HSLC convection. This research seeks to shed some light on this by pursuing the following research questions: 1) at what horizontal grid spacing, if any, does an NWP model provide operationally useful\(^1\) information about explicit low instability severe convection?, and 2) can a NWP model properly differentiate between HSLC event case and HSLC null event case environments (see Chapter 2) given the proper initial conditions? A synopsis of previous HSLC research and a discussion of NWP models are first necessary to fully understand the problem and context of this research.

1.2 High Shear, Low CAPE Environments

1.2.1 Spatial and Temporal Distribution

HSLC environments occur largely in the Southeastern United States and the Ohio Valley, including the Gulf Coast states and the lower and middle Mississippi Valley (Figure 1.1) (Guyer

\(^1\) Operationally useful, in this study, is defined as what can be used by a forecaster to predict severe convection and what can distinguish between a low instability event and a low instability null event.
et al. 2006; Smith et al. 2008; Guyer and Dean 2010; Davis and Parker 2014; Sherburn and Parker 2014; Sherburn et al. 2016; King et al. 2017, in press). Furthermore, HSLC significant tornadoes exhibit clear maximum in the lower Mississippi Valley and Tennessee Valley (Figure 1.2) (Guyer and Dean 2010; Sherburn and Parker 2014).

These low instability environments overwhelmingly occur during the cool season, although they can occur at any time of year (Figure 1.3 and 1.4; Smith et al. 2008; Konarik and Nelson 2008; Guyer and Dean 2010; Clark 2011; Davis and Parker 2014; Sherburn and Parker 2014; Sherburn et al. 2016). The cool season is defined as autumn and winter, approximately October – March (Guyer et al. 2006; Smith et al. 2008). Sherburn and Parker (2014) diagnosed the following HSLC environmental climatology: HSLC severe weather exhibits an early spring peak and secondary October peak. Alternatively, HSLC null events are more prominent between July and December and an annual minimum in weak CAPE tornadoes occurs in the summer (Figure 1.4).

Low instability environments and associated severe weather exhibit a diurnal pattern. Although HSLC severe events can occur at any time of day, they are most likely to occur overnight (Figure 1.3; Davis and Parker 2014; Sherburn and Parker 2014; Sherburn et al. 2016). HSLC tornadoes specifically feature a late afternoon peak throughout the evening hours into overnight (Guyer et al. 2006; Smith et al. 2008; Glass and Britt 2010; Guyer and Dean 2010; Sherburn and Parker 2014). In terms of the frequency of HSLC environment, these environments are a more common occurrence than HSHC environments (Schneider and Dean 2008; Sherburn et al. 2016). Low CAPE tornadoes are also more common than previously estimated (Schneider and Dean 2008). Schneider and Dean (2008) found that nearly half of all tornadoes (between 2003 and 2007) occurred in environments with MLCAPE < 1000 J/kg. Indeed, HSLC convective
environments produce a significant portion of tornadoes annually and produce more significant tornadoes than typical Great Plains HSHC environments (Konarik and Nelson 2008; Sherburn and Parker 2014).

1.2.2 Convection and Associated Hazards

HSLC convection presents in a variety of convective modes, including supercells, QLCS, and others (Smith et al. 2008; Smith et al. 2010; Kis and Straka 2010; Davis and Parker 2014). Figure 1.5 illustrates the temporal and spatial diversity with respect to convective mode and severe weather type. HSLC vortices are shallow and this translates to the size of the associated supercells (Table 1.1). These so-called “mini-supercells” have the similar lifespan and structure as their higher-CAPE counterparts (Davies 1990; Davis and Parker 2014).

A variety of severe weather is associated with low instability convection. These include tornadoes, severe winds, and hail (Guyer et al. 2006; Schneider and Dean 2008; Smith et al. 2008; Glass and Britt 2010; Smith et al. 2010; Smith et al. 2012). Indeed, the majority of tornadoes ranked EF1+ and significant severe winds between the winter months and mid-spring occur in low-CAPE environments (Sherburn et al. 2016). Schneider and Dean (2008) found that 39% of all significant tornadoes (F2 – F5) from 2003-2007 occurred in low CAPE environments (defined in that study as MLCAPE < 1000 J/kg).

1.2.3 Synoptic and Thermodynamic Environments

HSLC environments that yield severe convection are strongly synoptically forced (Sherburn et al. 2016; King et al. 2017, in press). They are generally associated with strong upper-level troughs, surface cyclones, and cold fronts (Guyer and Dean 2006; Sherburn et al. 2016). Additionally, some case studies have detailed dry intrusions aloft associated with the
development of low instability convection and a strong low-level jet (Guyer et al. 2006; Clark 2009, 2011; Kis and Straka 2010; Sherburn et al. 2016). Traditional synoptic predictors of a severe weather event, i.e. a deep 500mb and/or 850mb trough are not always present (Konarik and Nelson 2008). Severe events tend to be produced in unseasonably moist environments, especially in the lower levels (Figure 1.6; Smith et al. 2008; Sherburn et al. 2016). Surface dew points generally range from the upper 50s – mid-60s°F and surface temperatures range between the 60s – upper 70s°F (Guyer et al. 2006; Guyer and Dean 2010).

1.3 Numerical Weather Prediction Models

NWP models are an indispensable forecasting tool, allowing operational forecasters an increase in convective forecasting ability (Lilly 1990; Weisman et al. 1997; Kain et al. 2010; Clark et al. 2012a). Convection-allowing high resolution models, such as the 3-km High Resolution Rapid Refresh (HRRR) model, provide explicit representations of convective modes and convective overturning thus greatly increasing the ability to forecast convective activity (Kain et al. 2010; Clark et al. 2012a).

The ability to successfully predict convection is heavily determined by the ability of a mesoscale model to do the same (Weisman et al. 1997). A key determinant of how well a NWP model will handle convection is its grid spacing (e.g. Weisman et al. 1997; Bryan et al. 2003; Clark et al. 2012a). An ongoing research question is at what grid length do NWP models need to be run in order to resolve severe weather (e.g. Weisman et al. 1997; Bryan et al. 2003). The answer to this question depends on the scale of the severe weather being forecast. One of the earliest resolution sensitivity studies, Weisman et al. (1997), found that horizontal grid spacing of 4-km was sufficient to reasonably represent squall-lines. Bryan et al. (2003) found that
minimum horizontal grid spacing on the order of 100m is necessary to adequately resolve convection for research purposes.

A key question resulting from these two studies and studies like them is what grid spacing is reasonable, that is, how fine of a grid do NWP models need to represent convection for operational purposes? The main concern for operations is the computational and temporal expense of finer resolution NWP models. NWP models need to generate forecasts quickly enough to be used for operational guidance, yet they need to reasonably predict convection (Clark et al. 2012a). Therefore, trade-offs between operational utility and resolution are necessary (Potvin and Flora 2015). For example, Bryan et al. (2003) admits that even though 1-km grid spacing gets characteristics of convection wrong, it may yield enough detail for forecasting purposes. In another example, Kain et al. (2008) found that the benefits gained from running convection-allowing models at 2-km grid spacing as opposed to 4-km do not outweigh the associated computational expense.

For the purposes of this research, specifically in answering question 1 under section 2.1, the results of the aforementioned resolution studies are used as guide for selecting what grid lengths to run simulations of HSLC convection (see Chapter 2) even though it is on a smaller scale than the deep moist convection used in the previous studies. The range of 4-km to $O(100m)$ horizontal grid spacing provides a useful starting point.

1.3.1 Operational Convection Permitting Models

At the present, there are convection permitting models run operationally. Some of these models include the aforementioned NOAA HRRR run with a grid spacing of 3-km (https://rapidrefresh.noaa.gov/hrrr/), the NCEP High-Resolution Window Forecast System run with grid spacings of 3 – 4-km (http://www.emc.ncep.noaa.gov/mmb/mmbpll/nestpage/), the
SPC Storm-Scale Ensemble of Opportunity (SSEO) with ensemble members run with grid spacings of 3.6 – 4.2-km (http://www.spc.noaa.gov/exper/sseo/), and the NCAR Ensemble Prediction System (EPS) with ensemble members run with a grid spacing of 3-km (http://www.image.ucar.edu/wrfdart/ensemble/index.php; Schwartz et al. 2015).

These models are capable of producing forecasts that are operationally useful for predicting severe weather. Examples include forecasts of measures of rotation, such as updraft helicity (see Section 2.4) and storm relative helicity, measures of instability, such as CAPE and the Significant Tornado Parameter (STP), lightning threat, and radar reflectivity (see Section 2.4). These models are capable of forecasting the mesoscale environment, the factors that contribute to convection, and the timing, coverage, and convective mode of the convection, among other useful products. Examples of what these models are incapable of include explicitly predicting tornadoes, tornado location, tornado intensity, and whether or not there will be damage due to severe weather.

1.4 Thesis Outline

The thesis is organized as follows: Chapter 2 details the real-world HSLC cases simulated, model configuration, and metrics used to measure. Chapter 3 presents the analysis of the simulated cases. Chapter 4 contains conclusions and suggestions for future work.
Figure 1.1: a) all tornadoes associated with < 500 J.kg MLCAPE for 2003 – 2009, and b) same as a), but for E(F)2+ (significant) tornadoes. Taken from Guyer and Dean 2010.
Figure 1.2: All significant wind reports (blue dots) and all EF1 or greater tornado reports (red dots) occurring in HSLC environments from 2006-2011. The shading represents a kernel density estimation of significant severe reports; darker colors correspond to a higher density of reports (probability density function estimate contoured every 0.001). Taken from Sherburn et al. 2016.
Figure 1.3: Fraction of EF1 or greater tornadoes and significant wind reports from 2006-2011 that occurred in HSLC environments by month and hour (shaded). Total number of EF1 or greater tornadoes and significant wind reports for the given hour/month are listed in each box. Taken from Sherburn et al. 2016.
Figure 1.4: Distribution of tornado reports for 2003-2007, binned by values of ML CAPE and 0-6 km bulk shear. Values are computed by associating each report with the appropriate hourly surface analysis grid values. Taken from Schneider and Dean 2008.
Figure 1.5: a) all right-mover (RM) tornado events in the fall (September – November); b) the same as a) but for the winter (December – February); c) the same as a), but for QLCS tornado events; d) the same as b) but for QLCS tornado events; e) the same as c) but for significant wind events; and f) the same as d) but for significant wind events. Taken from Smith et al. 2012.
Figure 1.6: Regional comparisons of (panels a, d, and g) 300 hPa winds (shaded, kt), wind barbs (kt), and geopotential heights (black contours, every 120m); (panels b, e, and h) 500 hPa absolute vorticity (shaded $10^{-5}$ s$^{-1}$), wind barbs (kt), geopotential heights (black contours, every 60m), and 700 hPa omega (blue contours, μbars s$^{-1}$); (panels c, f, and i) 2-m dew point (shaded, °C), mean sea level pressure (black contours, every 2hPa), and 10-m wind barbs (kt). Plots for the southeast region are in panels a)-c), northeast region are in panels d)-f), and western region are in panels g)-i). Maps are shown for a reference scale, with the white dot depicting the event-relative composite center point and the average latitude and longitude of each subset. The number of times in each composite is shown in a), d), and g) at bottom right. Taken from Sherburn et al. 2016.
Table 1.1: Summary of median values of characteristics of vortices within 60 km from the radar, including azimuthal shear at the 0.5°-elevation scan at the time of the tornado/warning, vortex lifetime, detection lead time (how long a vortex existed prior to the tornado) for tornadic vortices, vortex depth, and diameter (distance between velocity peaks) at the 0.5°-elevation scan at the time of the tornado/warning. Taken from Davis and Parker 2014.

<table>
<thead>
<tr>
<th>Vortex type</th>
<th>Base-scan azimuth shear (s⁻¹)</th>
<th>Lifetime (min)</th>
<th>Detection lead time (min)</th>
<th>Depth (km)</th>
<th>Base-scan diameter (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tornadic supercell vortex</td>
<td>0.013</td>
<td>65</td>
<td>25</td>
<td>3.82</td>
<td>2</td>
</tr>
<tr>
<td>Non-tornadic supercell vortex</td>
<td>0.011</td>
<td>50</td>
<td>—</td>
<td>2.77</td>
<td>1.8</td>
</tr>
<tr>
<td>Tornadic nonsupercell vortex</td>
<td>0.016</td>
<td>30</td>
<td>10</td>
<td>3.11</td>
<td>2.1</td>
</tr>
<tr>
<td>Non-tornadic nonsupercell vortex</td>
<td>0.011</td>
<td>20</td>
<td>—</td>
<td>2.01</td>
<td>3.1</td>
</tr>
</tbody>
</table>
Chapter 2: Data and Methods

2.1 Case Studies

In order to determine the operational resolution requirements of HSLC rotating convection, real-world cases were simulated. There were two categories of cases simulated: an event case and a null case. An event case is a case in which the severe HSLC convection occurred; multiple Storm Prediction Center (SPC) reports of tornadoes (of any strength), significant severe winds, and/or hail (King 2016). Following King (2016) and the methodology of Trisha Palmer, a null case is a case in which the SPC issued a slight or greater Day 1 Convective Outlook and/or the SPC issued a tornado or severe thunderstorm watch for an area featuring a HSLC environment yet no local storm reports were recorded. A more detailed description of each category is defined below in the respective subsections.

2.1.1 Event Case

This study is the second iteration in a Collaborative Science, Technology, and Applied Research (CSTAR) grant investigating HSLC. One event case was simulated in this study. This event case was chosen because it was identified as “high priority” by the participating WFOs in the previous CSTAR iteration. Additionally, this case was successfully simulated by King (2016). This last factor was an important one for case selection as other high priority cases were simulated and produced erroneous solutions. Both the event and null case simulated in this study underwent the evaluation process described in Section 2.3 and a successful simulation is one that meets the criteria described therein. Selecting an HSLC event case that was already successfully simulated reduced the amount of time and the chance of a poor simulation, thus allowing more energy to be spent on analysis. A brief summary of the event case synoptic environment, convection, and severe impacts is detailed in Chapter 3. The start and end times of the event case
were determined by the nearest hour of the first and last storm report with guidance from the HSLC Master Case List, an internal document. The Master Case List is a collection of HSLC cases compiled by participating NWS WFOs. It includes HSLC events that occurred in their respective County Warning Areas (CWAs) that occurred within the time period of fall 2006 to spring 2011 (Sherburn and Parker 2014). The information regarding the severe weather produced by this event is from NOAA’s National Centers for Environmental Information (NCEI)’s Storm Events Database (http://www.ncdc.noaa.gov/stormevents/).

2.1.2 Null Case

One null case was simulated in this study: December 25 – 26, 2009. This case was chosen because it was in the HSLC null event database compiled by CSTAR participant Trisha Palmer. The purpose of running a null event case is to investigate a goal of this research, that is, can NWP models successfully differentiate between an event and a null case given the appropriate initial conditions.

2.2 Data and Model Configuration

The Weather Research and Forecasting (WRF) model version 3.7.1 was used to conduct the case studies described above (Skamarock et al. 2008). This model was compiled using an Intel compiler and run on the University Corporation for Atmospheric Science (UCAR) and National Center for Atmospheric Research (NCAR)’s Computational and Information Systems Lab (CISL)’s Yellowstone high performance computing system (CISL 2012). The model was run with 256 MPI tasks with 16 tasks per node. The model was most commonly run with a wall clock time of 8 hours.
North American Mesoscale Forecast System (NAM) NOAA grid number 218 12-km forecast data were used for the initial conditions and lateral boundary conditions. These data were obtained from NOAA’s National Center for Environmental Information’s (NCEI) National Operational Model Archive and Distribution System (NOMADS). NAM was used over the other available forecast models, the Global Forecast System (GFS) and Rapid Refresh Model (RAP), for a number of reasons. Firstly, of the readily available models, the NAM has the finest grid spacing at 12-km as opposed to the GFS with 1 degree and the RAP with either 20-km or 13-km grid spacing (Information about these NWP models can be found at the following address: https://www.ncdc.noaa.gov/data-access/model-data/model-datasets). A finer resolution is desired when simulating mesoscale features (Weisman et al. 1997, Bryan et al. 2003). Additionally, the NAM has data for both case studies whereas the newer mesoscale models do not.

The two cases were simulated using four nested domains. The horizontal grid spacing of these domains is as followed: 10.8-km, 3.6-km, 1.2-km, and 400-m (Figure 2.1). Davis and Parker (2014) found that the median low instability tornadic supercell vortex has a diameter of 2000 meters. To fully resolve a feature, a horizontal grid spacing of 8-10Δx is required and a minimum resolution of 4Δx is required (Grasso 2000). A minimum horizontal grid spacing of 500 meters is therefore required to resolve the parent mesocyclone of a typical HSLC tornadic supercell vortex. The finest grid spacing of 400-m (5Δx) was chosen because it is a reasonable order of resolution and computationally feasible in terms of operational forecasting capabilities (Clark et al. 2012a; Kain et al. 2008). The other three gridlengths were determined by multiplying 400-meters by 3 in order to fulfill the best practice of having nested domains in WRF be related by a 3:1 nest ratio (http://www2.mmm.ucar.edu/wrf/users/namelist_best_prac_wps.html). Excluding the 10.8-km
domain, all domains allow for explicit convection, that is, the convection in the model is not parameterized (Weisman et al. 1997). These models are known as “convective allowing” models (CAMs) (Kain et al. 2010).

The domains for each case are placed in such a way that they fulfill the following four criteria. Firstly, the outer domain is designed to capture the synoptic environment and synoptic influences, such as moisture from the Gulf of Mexico. This domain is in the same location for all runs. The first nested domain (Δx = 3.6-km) is designed to capture the bulk of the convection. The location of the convection is determined by SPC Storm Reports and observed radar reflectivity. The second nested domain (Δx = 1.2-km) is placed over the area with the largest cluster of storm reports. Finally, the third nested domain (Δx = 400-m) is located over the area with the largest number of tornado reports (Figure 2.1). The outer three domains for each case were started from nearest NAM analysis 24 hours before the severe convection began until the severe convection ended, approximately 42 to 48 hours. The finest domain (Δx = 400-m) began six hours prior to the convection start time and ended three hours before the convective end time. This adjustment in run time is due to the aforementioned focused area of domain 4; it is computationally unnecessary to run the model at 400-m grid spacing when no severe activity is occurring. The computational expense is illustrated by the model time step for each domain and the resulting size of the model output files for each domain as resolution decreases. The model time step is the amount of time (in seconds) for integration. The smaller the domain, the more frequent the integration interval. For example, the 400-m domain time step was 2 seconds. This means that more data is being written to the output file. The larger the data file, the more time it takes to write out which slows down the process. For example, the null case domain 1 output
files were 322 megabytes, the domain 2 output files were 1.6 gigabytes, the domain 3 files were 3.7 gigabytes, and the domain 4 files were 4.0 gigabytes.

The namelist options are listed in Table 2.1. These choices were informed by experience and by the namelist choices for the HRRR model. The HRRR model was chosen as a guide because it is an operational convection-allowing model with 3-km grid spacing and is used by the NWS for severe weather prediction (see Section 1.3.1; Clark et al. 2012a). More information about the HRRR can be found at the following address: http://ruc.noaa.gov/hrrr/.

The Twice Digital Filter Initialization (TDFI) is used to balance the initial model environment (Lynch 2003). One-way nesting is used because, as previously mentioned, the goal of this study is to determine what benefits are gained at the different resolutions. Two-way nesting allows for the nested domains to send information about their solutions back and forth. This allows for the model solution on coarser domains to benefit from the higher resolution domains nested within them (NCAR 2016). The Rapid Update Cycle (RUC) land-surface model (LSM) is used because it is used in the HRRR. The YSU planetary boundary layer (PBL) scheme (Hong et al. 2006) is used because this scheme has been proven to represent low instability severe convection well (Cohen et al. 2015). The HRRR uses the Mellor-Yamada-Nakanishi-Niino 2 (MYNN2) PBL scheme (Nakanishi and Niino 2006). To make sure that there were no glaring differences between using the RUC and the Noah LSM as well as the YSU scheme instead of the MYNN2 scheme, a four member ensemble was performed (Table 2.2). The spatial distribution and magnitudes of two-meter temperature, 24-hour total precipitation accumulation, and the vertical wind component (w) at 700mb were compared and no glaring differences were found (not shown).
The Thompson microphysics scheme (Thompson et al. 2008) is used for multiple reasons. Firstly, for the model version used, it is the only WRF microphysics scheme that communicates directly with the radiation schemes (Thompson and Eidhammer 2014). A six member ensemble was run to determine if HSLC convection was especially sensitive to microphysics choices. The ensemble members only differed by which microphysics scheme was used. The microphysics schemes used were: Kessler (Kessler 1969), Lin (Lin et al. 1983), WRF Single Moment 6-Class (Hong and Lim 2006), WRF Double Moment 6-Class (Lim and Hong 2010), Thompson, and NSSL (+CCN) (Mansell et al. 2010). Comparisons were made among composite radar reflectivity, total accumulated precipitation, maximum positive vertical motion, and maximum negative vertical motion. While there were minor differences between the ensemble members, there were no drastic differences (not shown). The Rapid Radiative Transfer Model-GCM (RRTMG) scheme is used for both longwave radiation and for shortwave radiation. These schemes communicate with the Thompson microphysics scheme and are used in the HRRR model. The Kain-Fritsch cumulus parameterization scheme is used for the outermost domain ($\Delta x = 10.8$-km). Vertical damping is in place with a damping layer of 5000m.

2.3 Verification of Cases

A comparison was made between a preliminary simulation and observations for each case prior to conducting a full four domain simulation and analysis. A preliminary simulation is defined as a run with only the two outer domains (10.8-km and 3.6-km grid spacing). This was conducted in order to ensure that the model was producing an adequate simulation of the corresponding real world case. It follows that if the model did not produce an accurate simulation of the overall synoptic environment or of the convective mode, it will not accurately represent the rotating convection.
The comparison was made using the SPC Mesoscale Analysis also known as the SFCOA (http://www.spc.noaa.gov/exper/ma_archive/index2.html) as well as the UCAR Image Archive (http://www2.mmm.ucar.edu/imagearchive/). Five metrics were used for this comparison: sea-level pressure (SLP), 10-meter wind speeds, surface based CAPE (SBCAPE), surface frontogenesis, and composite radar reflectivity. At this stage, this comparison is qualitative ("eyeballing") and quantitative as opposed to purely quantitative (Kain et al. 2008).

The simulated SLP field was considered an adequate representation of the observed SLP field if it was in approximately the same position and had approximately the same magnitude (Figure 2.2). Similarly, the simulated 10-meter wind speed field was considered an adequate representation of the archived 10-meter wind speed field if it produced similar wind barb positions speed and direction (Figure 2.2). The simulated SBCAPE field was considered an adequate representation, not only if it met the similar placement and magnitude requirements, but also if the maximum value of SBCAPE met the definition of a HSLC environment (SBCAPE < 1000 J/kg) (Figure 2.3). Frontogenesis was also compared (Figure 2.4).

Simulated composite radar reflectivity was calculated during post processing with the Unified Post Processor version 2.2 (UPP). Observed composite radar reflectivity was obtained from the UCAR Image Archive. Simulated composite radar reflectivity was considered an adequate representation of the observed convection if it simulated the observed composite radar reflectivity convective mode, if the maximum magnitude was close to the observed maximum magnitude, and if the model produced the convection in approximately the same time and general location as the observed convection (Figure 2.5).
2.4 Intra-domain Metrics

Four metrics were used to compare the three convection-allowing domains: half-hourly maximum updraft helicity, half-hourly maximum updraft speed, half-hourly maximum 10-meter wind speed, and composite radar reflectivity. The first three metrics were calculated using the namelist option “nwp_diagnostics”.

Updraft helicity (UH) is the measure of rotation in the updraft of a storm (Kain et al. 2008). It is the product of the vertical wind and vorticity integrated over height:

\[ UH = \int_{z_0}^{z_t} w\zeta dz \]  
(Equation 2.1)

UH is an excellent analog for severe rotating convection, including supercells and tornadoes, although it is not a direct comparison (Kain et al. 2010; Clark et al. 2012b; Guyer and Jirak 2014). For classic high-plains severe convection, this integral is calculated over the 2-5 km layer. This configuration is not necessarily appropriate for the shallow convection observed in these low instability environments. Davis and Parker (2014) found that the average depth of a tornadic supercell vortex is 3.82-km and the average depth of a non-tornadic supercell vortex is 2.77-km (Table 1.1). Calculating updraft helicity over the 1-4-km layer is therefore better suited to HSLC convection. In order to achieve updraft helicity for this layer, the bounds of integration were changed in the WRF subroutine that calculates UH and then the model was recompiled.

Half-hourly maximum updraft helicity is calculated by recording the maximum value at each model time step for each grid point over a 30 minute period, thus resulting in swaths of UH (Kain et al. 2010; Clark et al. 2012a; Clark et al. 2013). Half-hourly maximum fields (HHMFs) allow for the examination of convective features which occur on time scales less than the hourly or half-hourly output intervals without needing to output every model time step, thus reducing computational expense and storage requirements (Kain et al. 2010; Clark et al. 2012a; Clark et
Prior research of CAM produced maximum field UH swaths have found that it is a good indicator of severe weather (Clark et al. 2013; Guyer and Jirak 2014), including system development and convective mode evolution (Kain et al. 2010) and supercells and their associated hazards (Clark et al. 2012b).

Updraft speed is the measure of upward vertical motion in a storm. This metric is indicative of the severity of the convective overturning (Kain et al. 2010; Clark et al. 2012a). Stronger updrafts are associated with severe weather. Like the UH HHMF, the half-hourly maximum updraft speed is calculated by recording the maximum value of this quantity at each grid cell at each model time step over a 30 minute period. Only vertical velocity below 400-mb was considered (Kain et al. 2010).

10-meter wind speed is a measure of the horizontal wind speed at 10-meters above ground level (AGL). As with the previous half-hourly maximum metrics, half-hourly maximum 10-meter AGL wind speed is the maximum value of this quantity at each model time step for each grid cell over a 30 minute time period (Kain et al. 2010). This metric is useful for evaluating severe weather because strong surface winds are associated with severe weather, for example, outflow boundaries and gust fronts. Wind speeds at 10m AGL are a useful analog and predictive tool for predicting severe surface wind gusts and damaging winds (Kain et al. 2010; Clark et al. 2012b).

Composite radar reflectivity is the maximum value of radar reflectivity at any height measured by the radar. Radar reflectivity is a representation of the number and size of particles present in a given volume (Rinehart 2010). It is useful for evaluating severe weather because higher values of radar reflectivity indicate larger amounts of particles and/or large particles, such as hail (Rinehart 2010). Higher values of radar reflectivity are associated with severe weather,
although it is important to note that model simulated radar reflectivity is more of an analog for observed reflectivity than an equivalent (Kain et al. 2008; Kain et al. 2010). Radar reflectivity is a widely used tool by forecasters to analyze and observe convective systems (Kain et al. 2008). Composite radar reflectivity is useful because it does not matter at what height the scan was taken. In the case of model radar reflectivity, it is simulated since there are no radars in the model. It is computed from microphysical information in each grid cell during post processing.

### 2.5 Analysis Techniques

The aforementioned metrics in section 2.4 were analyzed to investigate the similarities and differences of the model solutions across the three convective-allowing domains in order to determine what benefit is gained from running the model at higher resolution. This section details how this analysis was performed. The results of this analysis can be found in the next chapter (Chapter 3).

#### 2.5.1 Post-Processing

After each simulation, the model output was post-processed using UPP (see Section 2.3). This resulted in GRIB2 files which were then converted to GEMPAK grid files. After this conversion, the conforming process occurred. There are a few methods to analyze the different domains. The one utilized in this study is to calculate the analysis metrics on the native domain and then conform the output to the same grid. In this study, the word conform is to have all of the domains on the same grids (same number of grid points and same horizontal grid spacing). This is effectively sub-sampling the higher resolution domains. In this manner, the number of grid

---

2 A second method is to use the native domain data and normalize the number of grid points that meet the severe threshold by dividing by the number of grid points on that domain. A third method is to examine the areal coverage of values of a certain metric that exceed a certain threshold across the native domains.
points that exceed certain severe thresholds (see Chapter 3) can be compared since the data is on the same grid. In order to analyze and compare the three convective-allowing domains to one another, the sampling differences needed to be accounted for. Sampling differences arise due to the different horizontal grid-spacing which creates more grid points on the higher resolution domains. As such, using the GEMPAK bi-linear interpolation function (gdbiint), a new grid was created that had the horizontal grid spacing of domain 2 (3.6-km) and covered the same area as domain 4 (400-m; see Figure 2.1).

2.5.2 Histogram Analysis

Once the post-processing and conforming process was complete, the binning and histogram process began. The newly conformed fields were run through a Fortran program that sorted the value of a specified metric into a previously determined bin value. This was done for the 12 hour time period during which the most severe weather occurred. For example, if the metric was composite radar reflectivity, the program would read in the conformed grid file and loop over the grid points (1 to ix-1 and 1 to iy-1), reading the value of composite radar reflectivity. If the given composite reflectivity value was greater than the bin value (i.e. 50 dbZ), but less than or equal to the next bin value (55 dBZ) the program would add “1” to value of the bin array, indicating that one grid point fit the constraints of this bin. Plotting these bins results in a histogram which allows for the nature and behavior of the data to be examined without dealing with $O(100,000)$ data points.
Figure 2.1: WRF model domain set up for event case 02/24/2011.
Figure 2.2: Mean Sea-Level Pressure and 10-meter wind speeds for event case 02/24/2011 at 18 UTC on 02/24/2011 for a) the model simulation and b) same as a), but SFCOA. The red box corresponds to the model domain shown in a); c) as in a, but for 02/24/2012 at 00 UTC; and d) as in b), but for 02/24/2012 at 00 UTC. This case is a null case that was tested but did not pass the verification process. Note the isobar displacement between c) and d).
Figure 2.3: a) SBCAPE and 10-meter wind speeds for event case 02/24/2011 at 18 UTC for the model simulation; b) as in a) but SFCOA SBCAPE and with CIN shaded. The red box corresponds to the model domain shown in a); c) as in a), but for 02/24/2012 at 00 UTC; and d) as in b), but for 02/24/2012 at 00 UTC. As in Figure 2.2, note the northeastern displacement of SBCAPE.
Figure 2.4: a) Surface frontogenesis and 10-meter wind speeds for null event case 12/25/2009 at 12 UTC for the model simulation. b) SFCOA surface frontogenesis, temperature, pressure, and winds at the same time as a). The red box corresponds to the model domain shown in a).
Figure 2.5: a) Model composite radar reflectivity for event case 02/24/2011 at 06 UTC on 02/25/2011; b) NEXRAD 2km observed composite radar reflectivity for the same time as a). The red box corresponds to the area shown in b); c) as in a), but for 02/24/2012 at 00 UTC; d) NEXRAD 1km observed composite radar reflectivity for the same time as c). Note the linear structure apparent in the model solution compared to the observed radar.
Table 2.1: Namelist configurations for all simulations in this study.

<table>
<thead>
<tr>
<th>Namelist Option</th>
<th>Choice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digital Filter Initialization</td>
<td>Twice DFI and Dolph filtering</td>
</tr>
<tr>
<td>Feedback</td>
<td>None</td>
</tr>
<tr>
<td>Microphysics</td>
<td>Thompson</td>
</tr>
<tr>
<td>Radiation (Longwave)</td>
<td>Rapid Radiative Transfer Model- GCM (RRTMG)</td>
</tr>
<tr>
<td>Radiation (Shortwave)</td>
<td>RRTMG</td>
</tr>
<tr>
<td>Surface Layer Physics</td>
<td>Monin-Obukhov Similarity scheme</td>
</tr>
<tr>
<td>Land Surface</td>
<td>Rapid Update Cycle (RUC)</td>
</tr>
<tr>
<td>Boundary Layer Scheme</td>
<td>Yonsei University (YSU)</td>
</tr>
<tr>
<td>Cumulus Scheme</td>
<td>Kain-Fritsch (for outer domain); none for all nested domains</td>
</tr>
<tr>
<td>W Damping</td>
<td>Yes</td>
</tr>
<tr>
<td>Damping Layer</td>
<td>5000 m</td>
</tr>
</tbody>
</table>

Table 2.2: Ensemble members comprising the LSM-PBL sensitivity test.

<table>
<thead>
<tr>
<th>Member Name</th>
<th>LSM</th>
<th>PBL Scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td>MYNN_RUC</td>
<td>RUC</td>
<td>MYNN2</td>
</tr>
<tr>
<td>YSU_RUC</td>
<td>RUC</td>
<td>YSU</td>
</tr>
<tr>
<td>MYNN_Noah</td>
<td>Noah</td>
<td>MYNN2</td>
</tr>
<tr>
<td>YSU_Noah</td>
<td>Noah</td>
<td>YSU</td>
</tr>
</tbody>
</table>
Chapter 3: Results

3.1 February 24 – 25, 2011

This convective event occurred from approximately 14 UTC on February 24 to approximately 08 UTC on February 25, 2011. This produced severe weather across the Central Mississippi Valley and parts of the Southeast, particularly in Arkansas, Tennessee, Mississippi, and Alabama (Figure 3.1a) (http://www.spc.noaa.gov/climo/reports/110224_rpts.html). A quasi-linear convective system (QLCS) produced 20 tornadoes, including 6 EF2s and severe winds in excess of 80 knots. A deepening mid-level shortwave trough in combination with an amplifying surface low provided a synoptic environment favorable for severe weather (Figure 3.1b-c). The surface warm front associated with the surface cyclone ushered in warm and moist air into the region supporting the development of severe weather (Figure 3.1c-d) (http://www.spc.noaa.gov/exper/archive/event.php?date=20110224).

As discussed in Section 2.3, the model produced environment was verified for accuracy against observations. Comparisons between observations and the simulated mean sea-level field and 10-meter wind speeds (Figure 3.2), the simulated surface-based CAPE (Figure 3.3), the surface simulated frontogenesis (Figure 3.4), and the simulated composite radar reflectivity (Figure 3.5) were conducted. The model adequately represented the case environment per the standards outlined in Section 2.3.

3.1.1 Half-Hourly Maximum Updraft Helicity

As previously mentioned in Section 2.4, half-hourly maximum fields are swaths of UH. These swaths illustrate the tracks of rotating updrafts over the previous 30 minute period at each model time step. The three convective-permitting domains exhibit different swath behavior. Overall, the model produced severe threshold exceeding values of updraft helicity, 25 \text{ m}^2/\text{s}^2.
when rotation was observed. As the horizontal grid spacing decreases, the values of half-hourly maximum updraft helicity increase, as expected. This is due in part to the dependence of updraft helicity has on horizontal and vertical spacing (see Equation 2.1). While there are no available one-to-one observations for maximum updraft helicity, a proxy observation is the NWS Mesoscale Detection Algorithm (MDA) product. The MDA is a NEXRAD Level III product which derives information about a thunderstorm’s mesocyclone from the radar data (https://www.ncdc.noaa.gov/swdiws/csv/nx3mda).

In order to demonstrate model behavior, the half-hourly maximum updraft helicity field for three example time periods is displayed. Only values that exceed 25 m²/s² are shown, indicating that the rotation surpassed the severe threshold suggested for cool season severe weather by Guyer and Jirak (2014). These three example time periods were chosen because tornadoes were reported at corresponding times in the 400-m domain area. The aforementioned domain UH differences are highlighted in Figure 3.6 which displays the UH swaths for the time period 22:30 – 23:00 UTC on 02/24/2011. An EF1 tornado touched down in Lonoke County, Arkansas (Figure 3.1a) during this time period. It caused an estimated $75,000 worth of damage and remained on the ground for an estimated 3 minutes (Table 3.1). According to the MDA, mesocyclones were detected in the area during the 90-minute time period that encapsulates 22:30 – 23:00 UTC (Figure 3.7).

During the time period 00:30 – 01:00 UTC, an EF1 tornado touched down in Fulton County, Kentucky and remained on the ground for 14 minutes, travelling across two more counties (Figure 3.1a and Figure 3.8). It caused an estimated $80,000 worth of damage (Table 3.1). The 400-m domain was the closest in terms of showing severe threshold values of UH in the area where mesocyclones were observed (Figure 3.9) although the fact that all of the domains
showed severe threshold values is promising. As previously stated in chapter 2, a one-to-one matchup between the model and observations is not the goal. During the time period 02:30 – 03:00 UTC, an EF2 tornado touched down in Decatur County, Tennessee and remained on the ground for 15 minutes (Figure 3.1a and Figure 3.10). It caused an estimated $1.5 million worth of damage (Table 3.1). Again, the 400-m domain was the closest in terms of showing severe threshold values of UH in the area where mesocyclones were observed and all three domains produced severe threshold exceeding values of updraft helicity (Figure 3.11).

The time period during which the majority of severe weather was reported for this event occurred between 18:00 UTC on 02/24/2011 to 06:00 UTC on 02/25/2011. In order to evaluate how each domain represented the severe proxy parameters during this time period, the distribution of half-hourly maximum updraft helicity values over the conformed domains is calculated (Figure 3.12). The distribution of half-hourly maximum updraft helicity is similar across the three conformed domains. In each domain, there are a larger number of grid points with lower values of updraft helicity and the number of grid points with higher values of updraft helicity decreases at each threshold. In order to determine how similar the domains are to one another, the differences between the conformed distributions are calculated (Figure 3.13). The largest overall differences are between the 400-m and 3.6-km domains. This is expected due to the previously mentioned resolution dependence of UH on horizontal grid length and due to the difference in horizontal resolution. The smallest overall difference is not apparent from this graph therefore a deeper investigation into the data is required to determine how different the domains are. The Wilcoxon signed-rank difference test is performed on the distributions. This test is a non-parametric test that examines non-normal dependent populations and tests for the null hypothesis that the median of the population differences are 0, that is, that the difference
between the two data sets tested have about an equal amount of positive differences and negative differences (Wilcoxon, 1945; Wilkes, 142-143). This test does not depend on the distribution of the data and is robust in regards to outliers (Wilkes, 142). Since domain 3 is nested in domain 2 and domain 4 is nested in domain 3, the distributions are inherently dependent. The results of this test are that all three domains have median differences that are not 0, that is, the distributions are statistically significantly different at the 95th significance interval (Table 3.3).

This study is most concerned with how WRF handles explicit severe rotating convection, represented by the severe proxy parameters, therefore, the distribution of half-hourly maximum updraft helicity that exceeds the 25 m^2/s^2 severe threshold is investigated (Figure 3.14). The difference between 3.6-km to 1.2-km features and the difference between 1.2-km to 400-m is approximately the same. The difference between the conformed 3.6-km and 1.2-km distributions’ third quartile and the maximum values are less than the differences than those between 1.2-km and 400-m. The difference between the conformed 1.2-km and 400-m distributions’ first quartile and median are closer than those between 3.6-km and 1.2-km (Table 3.4). The minimum value is the same across all three distributions.

3.1.2 Half-Hourly Maximum 10-Meter Wind Speed

Half-hourly maximum 10-meter wind speed is a half-hourly maximum field metric. It yields swaths of 10-meter wind speed over a 30 minute time period, using each model time step. 10-meter wind speed is examined during the same three time periods as in Section 3.1.1. Only values that exceed the 16 m/s surface wind threshold for severe HSLC convection (King 2016) are shown. King (2016), using a 3-km grid, found that this threshold is skillful in differentiating between severe and non-severe wind speeds for low instability convection.
Four severe wind reports were observed in the area encompassed by the 400-m domain during the time period 22:30 – 23:00 UTC on 02/24/2011 (Figure 3.1a; Figure 3.15; Figure 3.16). These reports occurred in three separate counties in Arkansas and caused a combined $27,000 worth of damage (Table 3.2). During the time period 00:30 – 01:00 UTC on 02/25/2011 (Figure 3.17), three severe wind reports were observed (Figure 3.1a and Figure 3.18). These reports occurred in three separate counties in Arkansas (Table 3.2). The amount of property damage caused by these reports is unknown. The 400-m domain has the largest area of severe winds and higher maximum wind speed values than the other two domains, as expected. During the time period 02:30 – 03:00 UTC on 02/25/2011, all three convective permitting domains again 10-meter wind speeds that exceed the 16 m/s severe threshold with (Figure 3.19). One severe wind report was observed in the area encompassed by the 400-m domain during this time period (Figure 3.1a and Figure 3.20). This report occurred in Henry County, Tennessee and caused $150,000 worth of damage (Table 3.2).

The Wilcoxon signed-rank test is performed on the full half-hourly maximum 10-meter wind speed distribution across all domain pairs (Table 3.5). The results of this test are that all three domains have median differences that are not 0, that is, the distributions are statistically significantly different at the 95\textsuperscript{th} significance interval (Table 3.5).

The distribution of half-hourly maximum 10-meter wind speed is calculated for the same time period as in section 3.1.1 (Figure 3.21). Unlike half-hourly maximum updraft helicity, the number of grid points with higher values of 10-meter wind speed does not decrease at each threshold. When looking at the differences between the distributions, again, it is clear that the largest difference is between distributions at 3.6-km and 400-m grid spacing, as expected due to the disparity in resolution (Figure 3.22). The smallest overall difference appears to be between
1.2-km and 400-m, however, a closer look at the distributions is necessary to determine this. Since this study focuses on severe high shear, low CAPE convection, the distributions of 10-meter wind speed that exceeds the severe proxy threshold of 16 m/s are calculated (Figure 3.23). These distributions are for the grid points in all of the convection permitting domains that exceed the 16 m/s threshold. The greatest difference is between 3.6-km and 1.2-km domains (Table 3.6). The minimum is the same across all domains. The differences between all other distribution markers (quartile 1, median, quartile 3, and maximum) are smaller between 1.2-km and 400-m than between 3.6-km and 1.2-km.

### 3.1.3 Half-Hourly Maximum Updraft Speed

Half-hourly maximum updraft speed (UVV) is another half-hourly maximum field metric. Like the previous two half-hourly maximum metrics, this metric yields swaths composed of maximum values across all time steps during the interval. These swaths are of the maximum value of updraft speed over the previous 30 minute period. This field therefore illustrates the tracks of updrafts. UVV is examined during the same three time periods as in Section 3.1.1. As the horizontal grid spacing decreases, the larger the values of half-hourly maximum updraft speed are. With each increase in resolution, the larger the values of UVV and the more area covered (Figures 3.24 – 3.26).

The Wilcoxon signed-rank test is performed on the full half-hourly maximum updraft speed distribution across all domain pairs (Table 3.7). The results of this test are that all three domains have median differences that are not 0, that is, the distributions are statistically significantly different at the 95th significance interval.

The distribution of half-hourly maximum updraft speed over the conformed domains is calculated for the same time period as in Sections 3.1.1 and 3.1.2, the time period during which
the majority of severe weather was reported for this event (Figure 3.27). The behavior of the all three domain distributions of UVV is similar to those of UH. In each domain, there are more grid points with smaller values of UVV. There are fewer grid points with larger values of UVV as the threshold of UVV increases. The number of grid points yielding higher values of UVV increases with domain resolution. In order to determine how similar the domains are to one another, the differences between the conformed distributions are calculated (Figure 3.28). The largest overall difference in UVV distribution is again between the 400-m and 3.6-km domains. This is expected because of the greatest difference in grid spacing. The smallest overall difference is, again, not apparent from this figure therefore an investigation into the distributions is required.

There is no previously determined threshold of severe updraft speed for HSLC convection. In light of the shallow nature of HSLC convection and with previous studies indicating that lower overall values of typical severe predictors (e.g. CAPE; Sherburn and Parker 2014), the severe proxy updraft speed values for HSLC convective environments is based on the 99th percentile of data. The 99th percentile of data contains the largest values of updraft speed and larger values of updraft speed are associated with severe weather (Kain et al. 2010; Clark et al. 2012a). The difference between the 3.6-km and 1.2-km distributions is larger than that between the 1.2-km and 400-m distributions (Figure 3.29). The differences between all distribution markers (minimum, quartile 1, median, quartile 3, and maximum) were closer between the 1.2-km and 400-m domain distributions (Table 3.8).

3.1.4 Composite Radar Reflectivity

Unlike the previous three metrics, composite radar reflectivity is not a half-hourly maximum field and is therefore not a swath. It is an instantaneous display of the composite radar reflectivity every 30 minutes in the environment at the time period shown. Overall, all three
domains feature a slower system progression and a northwestern shift in position as compared to the observed event. The 1.2-km and 400-m domains better represent the convective mode and magnitude of dBZ than the 3.6-km domain. This is illustrated when examining the three sample comparisons between the domains (Figures 3.30, 3.32, and 3.34). These display the composite radar reflectivity during the same three time periods shown in the previous three sections. It is apparent that there is more detail, that is, finer radar signatures are more defined as resolution increases. The native composite radar reflectivity fields are compared to the observed to determine how well the domains represented the shape and spread of the convection (Figures 3.31, 3.33, and 3.35). As previously mentioned, the model is not evaluated for a one-to-one match with the observations. Instead, the model is evaluated for similarity in convective mode, magnitude, timing, and spatial position.

The Wilcoxon signed-rank test is performed on the full composite radar reflectivity across all domain pairs (Table 3.9). The results of this test are that all three domains have median differences that are not 0, that is, the distributions are statistically significantly different at the 95th significance interval.

The distributions of conformed composite radar reflectivity were calculated for the time period 18:00 UTC on 02/24/2011 to 06:00 UTC on 02/25/2011. The distribution behavior is similar across all three domains (Figure 3.36). There are fewer grid points with larger values of composite radar reflectivity as the thresholds of composite radar reflectivity increase. The differences between the distributions of composite radar reflectivity are calculated (Figure 3.37). The largest difference between the domains is, again, between 3.6-km and 400-m. The smallest difference appears to be between 1.2-km and 400-m. A more in-depth look at the distributions is needed to determine which domain pairing is more similar. Like the previous three metrics, only
the severe values of composite radar reflectivity are of interest since higher values are traditionally associated with more severe weather (see Section 2.5). There are no official definitions of radar reflectivity for representing severe weather, but nevertheless large values of simulated reflectivity can be associated with strong convection in a qualitative sense. In light of the shallow nature of HSLC convection, and in line with previous studies indicating lower overall values of typical severe predictors (e.g. CAPE; Sherburn and Parker 2014), the severe proxy composite radar reflectivity values for HSLC convection are defined as the top 99\textsuperscript{th} percentile of the data. The 99\textsuperscript{th} percentile of data contains the largest values of composite radar reflectivity and larger values of composite radar reflectivity are associated with severe weather (Kain et al. 2008; Kain et al. 2010). The difference between the 3.6-km and 1.2-km domain severe distributions is larger than that between the 1.2-km and 400-m data (Figure 3.38). All distribution metrics between 1.2-km and 400-m, except for the minimum, are closer in value (Table 3.10).

3.1.5 Case Summary

The model convection was slower than the observed convection and the convective mode and coverage was well simulated, especially by the 1.2-km and 400-m domains. All possible pairs of full domain distributions are statistically significantly different from one another. Three out of the four severe metric distributions, half-hourly maximum 10-meter wind speed, half-hourly maximum updraft speed, and composite radar reflectivity, exhibit smaller differences between the 1.2-km and 400-m severe distributions than the differences between the 3.6-km and 1.2-km severe distributions. The half-hourly maximum updraft helicity severe distribution illustrates a similar gain in detail when increasing the grid-spacing from 3.6-km to 1.2-km as when increasing from 1.2-km to 400-m.
3.2 December 25 – 26, 2009

This case was given a slight convective outlook, including a maximum 5% chance of isolated tornadoes and a maximum 15% threat of severe winds across parts of the Southeast (Figure 3.39; http://www.spc.noaa.gov/products/outlook/archive/2009/day1otlk_20091225_1300.html).

As discussed in Section 2.3, the model forecast environment was verified for accuracy against observations. Comparisons between observations and the simulated mean sea-level pressure and 10-meter wind speeds (Figure 3.40), the simulated surface-based CAPE (Figure 3.41), the surface simulated frontogenesis (Figure 3.42), and the simulated composite radar reflectivity (Figure 3.43) indicate that these simulations represent the case environment per the standards outlined in Section 2.3.

3.2.1 Half-Hourly Maximum Updraft Helicity

As previously mentioned in Section 3.1.1, we expect that the magnitude of half-hourly maximum updraft helicity will generally increase with resolution; this relationship is also evident in the three convective permitting domains in the null event. Overall, the null event yielded values of updraft helicity that exceeded the severe threshold. This is especially true for the 1.2-km and 400-m domains and these two domains produces swaths that do not necessarily indicate a null event. This idea is explored further in Chapter 4.

There were no tornadoes that occurred during this case therefore the three sample time periods examined were chosen based on the maximum number of MDA detected mesocyclones in the 400-m domain region. These time periods are 13:30 – 14:00 UTC on 12/25/2009 (Figure
3.44), 15:00 - 15:30 UTC on 12/25/2009 (Figure 3.46), and 16:00 - 16:30 UTC on 12/25/2009 (Figure 3.48). All three convection permitting domains display severe values of updraft helicity in the region where mesoscyolones were observed (Figure 3.45, Figure 3.47, and Figure 3.49). None of these mesoscyolones were associated with severe weather (Figure 3.39a). This indicates that WRF may be overproducing severe threshold values of updraft helicity or that the 25 m²/s² threshold is not an appropriate proxy for HSLC convection (see Section 4.3).

The time period evaluated for this case is 12:00 UTC on 12/25/2009 to 00 UTC on 12/26/2009. This time period was selected based on the methods for identifying a null case mentioned in Section 2.1. As in Section 3.1.1, the distribution of conformed HHMUH was calculated (Figure 3.50). In order to determine how similar the half-hourly maximum updraft helicity distributions are at the different resolutions, the distribution differences were calculated (Figure 3.51). The largest difference, as expected, was between the 400-m and 3.6-km domains. The severe threshold updraft helicity distributions were investigated (Figure 3.52). The smallest difference is between the 1.2-km and 400-m conformed severe distributions with three out of five distribution metrics being closer than those between the 3.6-km and 1.2-km distributions (Table 3.11). The Wilcoxon signed-rank test is performed on the full half-hourly maximum updraft helicity distribution across all domain pairs (Table 3.12). The results of this test are that all three domains have median differences that are not 0, that is, the distributions are statistically significantly different at the 95th significance interval (Table 3.12).

3.2.2 Half-Hourly Maximum 10-Meter Wind Speed

There was minimal to no severe threshold exceeding winds in the land-mass region encompassed by the 400-m domain during the time periods when there were no severe wind reports (Figure 3.53 – 3.55). There was one severe wind report recorded for the entire case and it
occurred outside of the 400-m domain. All three domains yield severe proxy wind speeds
(greater than or equal to 16 m/s) off the East Coast, but there are no local storm reports in the
Atlantic so comparison to observations cannot be made in this region.

The distribution of conformed half-hourly maximum 10-meter wind speed was calculated
(Figure 3.56). This null event distribution has a peak at the 6 m/s threshold for all domains. The
distribution differences were calculated and the largest differences were between 400-m and 3.6-
km, as expected (Figure 3.57). The severe proxy distribution (all grid points exceeding the 16
m/s severe threshold) differences are calculated and the smallest difference is between the 1.2-
km and 400-m conformed severe distributions with four out of five distribution metrics being
closer than those between the 3.6-km and 1.2-km distributions (Figure 3.58; Table 3.13). The
Wilcoxon signed-rank test is performed on the full half-hourly maximum 10-meter wind speed
distribution across all domain pairs. The results of this test are that all three domains have
median differences that are not 0, that is, the distributions are statistically significantly different
at the 95th significance interval (Table 3.14).

3.2.3 Half-Hourly Maximum Updraft Speed

Half-hourly maximum updraft speed was examined during the same three time periods as
in Section 3.2.1 and Section 3.2.2. As the horizontal grid spacing decreases, the larger the values
of updraft speed are. With each increase in resolution, the larger the values of UVV and the more
area covered (Figures 3.59 – 3.61).

The distribution of conformed half-hourly maximum updraft speed was calculated
(Figure 3.62). The distribution differences were calculated and the largest difference was
between the 400-m and 3.6-km domain distributions (Figure 3.63). The top 99th percentile of
data was again calculated for each conformed domain distribution as in Section 3.1.3 as a means
to represent the largest values of UVV. The smallest difference is between 400-m and 1.2-km with all five distribution metrics being closer than those between the 3.6-km and 1.2-km distributions (Figure 3.64; Table 3.15). The Wilcoxon signed-rank test is performed on the full composite radar reflectivity distribution across all domain pairs (Table 3.16). The results of this test are that all three domains have median differences that are not 0, that is, the distributions are statistically significantly different at the 95th significance interval.

### 3.2.4 Composite Radar Reflectivity

Three sample comparisons between the domains are shown (Figures 3.65, 3.67, and 3.69). These display the instantaneous composite radar reflectivity during the same three times shown in Section 3.2.1. The native composite radar reflectivity fields are compared to the observed fields to determine how well the domains represented the shape and spread of the convection (Figures 3.66, 3.68, and 3.70). All three domains produce the same maximum magnitude of radar reflectivity. For all three domains, the two lines are closer to one another in the model than observed. The model produced a stronger line than what was observed with more coverage of larger values of composite radar reflectivity.

The three conformed distributions behavior are similar across all three domains with the main difference being less grid points with higher values of composite radar reflectivity (Figure 3.71). The differences between the domains were calculated with the largest difference between the domains is, again, between 3.6-km and 400-m (Figure 3.72). The severe distributions are examined (Figure 3.73). The differences between the 1.2-km and 400-m severe conformed distributions are less across all five distribution metrics as compared to the differences between the 3.6-km and 1.2-km domains (Table 3.17). The Wilcoxon signed-rank test is performed on the full composite radar reflectivity distribution across all domain pairs (Table 3.18). The results of
this test are that all three domains have median differences that are not 0, that is, the distributions are statistically significantly different at the 95th significance interval.

3.2.5 Case Summary

The model produced swaths of severe threshold exceeding updraft helicity even though the case did not produce severe weather, especially on the 1.2-km and 400-m grids. This is most likely due to the resolution dependence of UH. The model convection was overactive and stronger than observed on all three domains. All possible pairs of full domain distributions are statistically significantly different from one another. Four out of the four severe metric distributions exhibit smaller differences between the 1.2-km and 400-m severe distributions than the differences between the 3.6-km and 1.2-km severe distributions. This indicates that more detail is gained in decreasing the horizontal grid spacing from 3.6-km to 1.2-km than from 1.2-km to 400-m.

3.3 Case Comparison

An aim of this study is to evaluate the ability of numerical forecasts to differentiate between an event featuring severe convective activity and a null event. The forecast distribution characteristics, the maximum and minimum (where applicable) values, and whether or not the distribution differences are significant are explored.

3.3.1 Half-Hourly Maximum Updraft Helicity

The maximum values of conformed UH for the event case are 94.50 m²/s², 849.25 m²/s², and 2159.56 m²/s² for the 3.6-km, 1.2-km and 400-m distributions respectively. The maximum values of conformed UH for the null event case are 48.00 m²/s², 240.00 m²/s², and 1028.16 m²/s². As expected, the event case yields much larger values of updraft helicity which is promising. The
areal extent of severe values of updraft helicity indicate that at a 3.6-km grid spacing, there is a factor of 10 square kilometers more severe threshold exceeding updraft helicity for the event case than the null case. The areal extent between 1.2-km and 400-m are on the same order of magnitude (Table 3.23).

The Wilcoxon rank-sum test is performed on the conformed severe distributions to determine if the differences between the two populations are significant. The null hypothesis for the Wilcoxon rank-sum test is that the two samples are from the same population (Wilkes, 138 – 139). That is, if the null hypothesis is proven false, the data sets are different. The p-value returned from this test at a given significance level determines whether or not the data are statistically significantly different. The results of the Wilcoxon rank-sum right tail test for the event case and null case severe threshold conformed updraft helicity yield statistically significant p-values (Table 3.19). These values of statistical significance imply that there is little to no similarity between the two distributions. The distribution differences are apparent when qualitatively compared side by side and by and when looking at the different distribution metrics (Figure 3.74). This indicates that for these two cases, WRF can skillfully discriminate between the event and null event cases using updraft helicity. The extremely low p-values are most likely due to the number of grid points in each distribution, which are on the order of tens of thousands.

3.3.2 Half-Hourly Maximum 10-meter Wind Speed

The maximum values of the event case conformed half-hourly maximum 10-meter wind speed are 22.70 m/s, 33.76 m/s, 32.83 m/s for the 3.6-km, 1.2-km, and 400-m domains respectively. The maximum values of the null event case are 28.38 m/s, 31.52 m/s, and 33.08 m/s. The maximum values between the two cases are comparable with the null case maximum values being larger than the event case maximum values for the 3.6-km and 400-m distributions.
The Wilcoxon rank-sum test is again performed on the severe conformed half-hourly maximum 10-meter wind speed distributions. The results of the Wilcoxon rank-sum two tailed test for the event case and null case severe threshold conformed half-hourly maximum 10-meter wind speed yield mixed results in terms of statistical significance (Table 3.20). Only the 3.6-km domain distributions are statistically significantly different and this is apparent when examining the distributions alongside one another (Figure 3.75). This implies three conclusions, the first that the 3.6-km domain is a more skillful discriminant between the event and null case in terms of 10-meter wind speed, the second is that the 16 m/s threshold is not a good determinant of severity for these two cases, or, finally, that 10-meter wind speed is not a useful discriminating metric for HSCLC severe convection for these two cases. Previous research by King (2016) indicates that the first and third possibilities are more likely (see Section 2.4).

### 3.3.3 Half-Hourly Maximum Updraft Speed

The maximum values of the event case conformed half-hourly maximum updraft speed are 16.75 m/s, 27.25 m/s, and 35.47 m/s for the 3.6-km, 1.2-km, and 400-m distributions respectively. The maximum values of the null event case conformed half-hourly maximum updraft speed are 18.25 m/s, 24.75 m/s, and 32.39 m/s. Like half-hourly maximum conformed 10-meter wind speed, the values are comparable with greater 1.2-km and 400-m event case maxima.

The Wilcoxon rank-sum test is performed on the severe proxy conformed half-hourly maximum updraft speed distributions. The results of the Wilcoxon rank-sum right tail test for the event case and null case severe threshold conformed updraft speed yield statistically significant p-values (Table 3.21). These values of statistical significance indicate that there is little to no similarity between the two distributions. The distribution differences are apparent when
examined alongside one another and by and when looking at the different distribution metrics (Figure 3.76). This indicates that for these two cases, WRF can skillfully discriminate between the event and null event cases using updraft speed. The extremely low p-values are most likely due to the number of grid points in each distribution, which are on the order of tens of thousands.

3.3.4 Composite Radar Reflectivity

The maximum values of event case conformed composite radar reflectivity are 58.50 dBZ, 64.50 dBZ, and 64.19 dBZ for the 3.6-km, 1.2-km, and 400-m distributions respectively. The maximum values of the null case conformed composite radar reflectivity are 55.75 dBZ, 61.25 dBZ, and 59.52 dBZ. The event case has the larger maximums, as expected, but the differences between the two case maximums are within 10 dBZ of one another.

The Wilcoxon rank-sum test is performed on the severe proxy conformed composite radar reflectivity distributions. The results of the Wilcoxon rank-sum right tail test for the event case and null case severe threshold conformed composite radar reflectivity yield statistically significant p-values (Table 3.22). The distribution differences are apparent when qualitatively compared side by side and by and when looking at the different distribution metrics although the differences do not appear as drastic as those for updraft helicity or updraft speed (Figure 3.77). This indicates that for these two cases, WRF can skillfully discriminate between the event and null event cases using composite radar reflectivity.
Table 3.1: Tornado reports occurring during the time period 18:00 UTC on 02/24/2011 to 06:00 UTC on 02/25/2011 in the area encompassed by the 400-m domain. All report data courtesy of the National Centers for Environmental Information Storm Events Database: https://www.ncdc.noaa.gov/stormevents/.

<table>
<thead>
<tr>
<th>Scale</th>
<th>Begin Date (UTC)</th>
<th>Begin Location</th>
<th>End Date (UTC)</th>
<th>End Location</th>
<th>Deaths/Injuries</th>
<th>Property Damage (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EF1</td>
<td>02/24/2011 22:56</td>
<td>34.7304, -92.0772</td>
<td>02/24/2011 22:58</td>
<td>34.7477, -92.0422</td>
<td>0/0</td>
<td>$75,000</td>
</tr>
<tr>
<td>EF1</td>
<td>02/24/2011 23:03</td>
<td>34.7708, -91.9045</td>
<td>02/24/2011 23:05</td>
<td>34.783, -91.8812</td>
<td>0/0</td>
<td>$400,000</td>
</tr>
<tr>
<td>EF0</td>
<td>02/25/2011 00:15</td>
<td>36.5602, -89.1789</td>
<td>02/25/2011 23:17</td>
<td>36.5625, -89.159</td>
<td>0/0</td>
<td>$30,000</td>
</tr>
<tr>
<td>EF1</td>
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<td>36.5256, -88.889</td>
<td>02/25/2011 00:46</td>
<td>36.55, -88.765</td>
<td>0/0</td>
<td>$80,000</td>
</tr>
<tr>
<td>EF2</td>
<td>02/25/2011 02:30</td>
<td>35.6643, -88.237</td>
<td>02/25/2011 02:45</td>
<td>35.7282, -88.0345</td>
<td>0/0</td>
<td>$1.525 million</td>
</tr>
</tbody>
</table>
Table 3.2: As in Table 3.1, except for thunderstorm wind reports.

<table>
<thead>
<tr>
<th>Magnitude (kts)</th>
<th>Date (UTC)</th>
<th>Location</th>
<th>Deaths/Injuries</th>
<th>Property Damage (USD)</th>
</tr>
</thead>
<tbody>
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<td>$1,000</td>
</tr>
<tr>
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<td>0/0</td>
<td>$10,000</td>
</tr>
<tr>
<td>52</td>
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<td>34.7, -92.1</td>
<td>0/0</td>
<td>$15,000</td>
</tr>
<tr>
<td>52</td>
<td>02/24/2011 22:56</td>
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<td>0/0</td>
<td>$1,000</td>
</tr>
<tr>
<td>52</td>
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<td>34.7633, -91.9942</td>
<td>0/0</td>
<td>$1,000</td>
</tr>
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<td>$1,000</td>
</tr>
<tr>
<td>52</td>
<td>02/24/2011 23:02</td>
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<td>$5,000</td>
</tr>
<tr>
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</tr>
<tr>
<td>56</td>
<td>02/24/2011 23:10</td>
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</tr>
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<tr>
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</tr>
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</tr>
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<td>65</td>
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<td>34.9116, -91.1721</td>
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</tr>
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<td>0/0</td>
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<td>02/24/2011 23:55</td>
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</tr>
<tr>
<td>50</td>
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<tr>
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<td>02/25/2011 00:10</td>
<td>35.0733, -90.8161</td>
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<tr>
<td>74</td>
<td>02/25/2011 00:18</td>
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<td>0/0</td>
<td>$75,000</td>
</tr>
<tr>
<td>70</td>
<td>02/25/2011 00:20</td>
<td>35.6587, -90.2877</td>
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</tr>
<tr>
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</tr>
<tr>
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<tr>
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</tr>
<tr>
<td>74</td>
<td>02/25/2011 00:45</td>
<td>35.2675, -90.1641</td>
<td>0/0</td>
<td>Unknown</td>
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<tr>
<td>54</td>
<td>02/25/2011 00:45</td>
<td>35.6982, -89.9631</td>
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<td>Unknown</td>
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<td>$10,000</td>
</tr>
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<td>02/25/2011 00:58</td>
<td>36.67, -88.52</td>
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<td>$5,000</td>
</tr>
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</tr>
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<td>78</td>
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</tr>
<tr>
<td>65</td>
<td>02/25/2011 04:05</td>
<td>34.22, -88.08</td>
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<td>$15,000</td>
</tr>
</tbody>
</table>
Table 3.3: Results of the Wilcoxon signed-rank test for updraft helicity for 02/24/2011 at the 95th significance interval.

<table>
<thead>
<tr>
<th>Domain Pair</th>
<th>Wilcoxon signed-rank p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6-km and 1.2-km</td>
<td>~0.00</td>
</tr>
<tr>
<td>1.2-km and 400-m</td>
<td>~0.00</td>
</tr>
<tr>
<td>3.6-km and 400-m</td>
<td>~0.00</td>
</tr>
</tbody>
</table>

Table 3.4: Severe threshold half-hourly maximum updraft helicity distribution differences for 02/24/2011.

<table>
<thead>
<tr>
<th>Metric</th>
<th>1.2-km – 3.6-km (m²/s²)</th>
<th>400-m – 1.2-km (m²/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Quartile 1</td>
<td>16.00</td>
<td>-2.00</td>
</tr>
<tr>
<td>Median</td>
<td>43.75</td>
<td>13.97</td>
</tr>
<tr>
<td>Quartile 3</td>
<td>92.75</td>
<td>108.31</td>
</tr>
<tr>
<td>Maximum</td>
<td>754.75</td>
<td>1310.31</td>
</tr>
</tbody>
</table>

Table 3.5: Results of the Wilcoxon signed-rank test for 10-meter wind speed for 02/24/2011 at the 95th significance interval.

<table>
<thead>
<tr>
<th>Domain Pair</th>
<th>Wilcoxon signed-rank p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6-km and 1.2-km</td>
<td>~0.00</td>
</tr>
<tr>
<td>1.2-km and 400-m</td>
<td>~0.00</td>
</tr>
<tr>
<td>3.6-km and 400-m</td>
<td>~0.00</td>
</tr>
</tbody>
</table>
Table 3.6: Severe threshold half-hourly maximum 10-meter wind speed distribution differences for 02/24/2011.

<table>
<thead>
<tr>
<th>Metric</th>
<th>1.2-km – 3.6-km (m/s)</th>
<th>400-m – 1.2-km (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Quartile 1</td>
<td>0.37</td>
<td>0.12</td>
</tr>
<tr>
<td>Median</td>
<td>1.03</td>
<td>0.23</td>
</tr>
<tr>
<td>Quartile 3</td>
<td>2.34</td>
<td>0.20</td>
</tr>
<tr>
<td>Maximum</td>
<td>11.06</td>
<td>-0.93</td>
</tr>
</tbody>
</table>

Table 3.7: Results of the Wilcoxon signed-rank test for updraft speed 02/24/2011 at the 95\(^{th}\) significance interval.

<table>
<thead>
<tr>
<th>Domain Pair</th>
<th>Wilcoxon signed-rank p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6-km and 1.2-km</td>
<td>~0.00</td>
</tr>
<tr>
<td>1.2-km and 400-m</td>
<td>~0.00</td>
</tr>
<tr>
<td>3.6-km and 400-m</td>
<td>~0.00</td>
</tr>
</tbody>
</table>

Table 3.8: Severe proxy half-hourly maximum updraft speed distribution differences for 02/24/2011.

<table>
<thead>
<tr>
<th>Metric</th>
<th>1.2-km – 3.6-km (m/s)</th>
<th>400-m – 1.2-km (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>4.75</td>
<td>3.49</td>
</tr>
<tr>
<td>Quartile 1</td>
<td>5.25</td>
<td>3.99</td>
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<tr>
<td>Median</td>
<td>6.00</td>
<td>4.64</td>
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<tr>
<td>Quartile 3</td>
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<td>5.06</td>
</tr>
<tr>
<td>Maximum</td>
<td>10.50</td>
<td>8.49</td>
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</table>
Table 3.9: Results of the Wilcoxon signed-rank test for composite radar reflectivity 02/24/2011 at the 95th significance interval.

<table>
<thead>
<tr>
<th>Domain Pair</th>
<th>Wilcoxon signed-rank p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6-km and 1.2-km</td>
<td>~0.00</td>
</tr>
<tr>
<td>1.2-km and 400-m</td>
<td>~0.00</td>
</tr>
<tr>
<td>3.6-km and 400-m</td>
<td>~0.00</td>
</tr>
</tbody>
</table>

Table 3.10: Severe proxy composite radar reflectivity distribution differences for 02/24/2011.

<table>
<thead>
<tr>
<th>Metric</th>
<th>1.2-km – 3.6-km (dBZ)</th>
<th>400-m – 1.2-km (dBZ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
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<td>0.98</td>
</tr>
<tr>
<td>Quartile 1</td>
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<td>1.06</td>
</tr>
<tr>
<td>Median</td>
<td>2.75</td>
<td>1.10</td>
</tr>
<tr>
<td>Quartile 3</td>
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<td>1.09</td>
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<tr>
<td>Maximum</td>
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<td>-0.31</td>
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</table>

Table 3.11: Severe threshold half-hourly maximum updraft helicity distribution differences for 12/25/2009.

<table>
<thead>
<tr>
<th>Metric</th>
<th>1.2-km – 3.6-km (m²/s²)</th>
<th>400-m – 1.2-km (m²/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Quartile 1</td>
<td>4.75</td>
<td>2.95</td>
</tr>
<tr>
<td>Median</td>
<td>11.38</td>
<td>9.34</td>
</tr>
<tr>
<td>Quartile 3</td>
<td>25.56</td>
<td>23.07</td>
</tr>
<tr>
<td>Maximum</td>
<td>192.00</td>
<td>788.16</td>
</tr>
</tbody>
</table>
Table 3.12: Results of the Wilcoxon signed-rank test for updraft helicity for 12/25/2009 at the 95\textsuperscript{th} significance interval.

<table>
<thead>
<tr>
<th>Domain Pair</th>
<th>Wilcoxon signed-rank p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6-km and 1.2-km</td>
<td>~0.00</td>
</tr>
<tr>
<td>1.2-km and 400-m</td>
<td>~0.00</td>
</tr>
<tr>
<td>3.6-km and 400-m</td>
<td>~0.00</td>
</tr>
</tbody>
</table>

Table 3.13: Severe threshold half-hourly maximum 10-meter wind speed distribution difference for 12/25/2009.

<table>
<thead>
<tr>
<th>Metric</th>
<th>1.2-km – 3.6-km (m/s)</th>
<th>400-m – 1.2-km (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>-0.03</td>
<td>0.00</td>
</tr>
<tr>
<td>Quartile 1</td>
<td>-0.02</td>
<td>0.04</td>
</tr>
<tr>
<td>Median</td>
<td>-0.05</td>
<td>0.08</td>
</tr>
<tr>
<td>Quartile 3</td>
<td>-0.35</td>
<td>0.22</td>
</tr>
<tr>
<td>Maximum</td>
<td>3.14</td>
<td>1.56</td>
</tr>
</tbody>
</table>

Table 3.14: Results of the Wilcoxon signed-rank test for half-hourly maximum 10-meter wind speed for 12/25/2009 at the 95\textsuperscript{th} significance interval.

<table>
<thead>
<tr>
<th>Domain Pair</th>
<th>Wilcoxon signed-rank p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6-km and 1.2-km</td>
<td>~0.00</td>
</tr>
<tr>
<td>1.2-km and 400-m</td>
<td>~0.00</td>
</tr>
<tr>
<td>3.6-km and 400-m</td>
<td>~0.00</td>
</tr>
</tbody>
</table>
Table 3.15: Severe proxy half-hourly maximum updraft speed distribution difference for 12/25/2009.

<table>
<thead>
<tr>
<th>Metric</th>
<th>1.2-km – 3.6-km (m/s)</th>
<th>400-m – 1.2-km (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>3.15</td>
<td>2.05</td>
</tr>
<tr>
<td>Quartile 1</td>
<td>3.40</td>
<td>2.00</td>
</tr>
<tr>
<td>Median</td>
<td>3.41</td>
<td>2.18</td>
</tr>
<tr>
<td>Quartile 3</td>
<td>3.90</td>
<td>2.01</td>
</tr>
<tr>
<td>Maximum</td>
<td>6.50</td>
<td>7.64</td>
</tr>
</tbody>
</table>

Table 3.16: Results of the Wilcoxon signed-rank test for half-hourly maximum updraft speed for 12/25/2009 at the 95th significance interval.

<table>
<thead>
<tr>
<th>Domain Pair</th>
<th>Wilcoxon signed-rank p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6-km and 1.2-km</td>
<td>~0.00</td>
</tr>
<tr>
<td>1.2-km and 400-m</td>
<td>~0.00</td>
</tr>
<tr>
<td>3.6-km and 400-m</td>
<td>~0.00</td>
</tr>
</tbody>
</table>

Table 3.17: Severe proxy composite radar reflectivity distribution differences for 12/25/2009.

<table>
<thead>
<tr>
<th>Metric</th>
<th>1.2-km – 3.6-km (dBZ)</th>
<th>400-m – 1.2-km (dBZ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>1.25</td>
<td>1.00</td>
</tr>
<tr>
<td>Quartile 1</td>
<td>1.50</td>
<td>0.84</td>
</tr>
<tr>
<td>Median</td>
<td>1.75</td>
<td>0.69</td>
</tr>
<tr>
<td>Quartile 3</td>
<td>1.75</td>
<td>0.37</td>
</tr>
<tr>
<td>Maximum</td>
<td>5.50</td>
<td>-1.73</td>
</tr>
</tbody>
</table>
Table 3.18: Results of the Wilcoxon signed-rank test composite radar reflectivity for 12/25/2009 at the 95th significance interval.

<table>
<thead>
<tr>
<th>Domain Pair</th>
<th>Wilcoxon signed-rank p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6-km and 1.2-km</td>
<td>~0.00</td>
</tr>
<tr>
<td>1.2-km and 400-m</td>
<td>~0.00</td>
</tr>
<tr>
<td>3.6-km and 400-m</td>
<td>~0.00</td>
</tr>
</tbody>
</table>

Table 3.19: Wilcoxon rank-sum p-values at the 95th significance interval between the event case and null case conformed half-hourly maximum updraft helicity severe proxy distributions.

<table>
<thead>
<tr>
<th>Domain</th>
<th>Wilcoxon Rank Sum p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6-km</td>
<td>~0.00</td>
</tr>
<tr>
<td>1.2-km</td>
<td>~0.00</td>
</tr>
<tr>
<td>400-m</td>
<td>~0.00</td>
</tr>
</tbody>
</table>

Table 3.20: Wilcoxon rank-sum p-values at the 95th significance interval between the event case and null case conformed half-hourly maximum 10-meter wind speed severe proxy distributions.

<table>
<thead>
<tr>
<th>Domain</th>
<th>Wilcoxon Rank Sum p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6-km</td>
<td>~0.00</td>
</tr>
<tr>
<td>1.2-km</td>
<td>0.49</td>
</tr>
<tr>
<td>400-m</td>
<td>0.12</td>
</tr>
</tbody>
</table>
Table 3.21: Wilcoxon rank-sum core p-values at the 95th significance interval between the event case and null case conformed half-hourly maximum updraft speed severe proxy distributions.

<table>
<thead>
<tr>
<th>Domain</th>
<th>Wilcoxon Rank Sum p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6-km</td>
<td>~0.00</td>
</tr>
<tr>
<td>1.2-km</td>
<td>~0.00</td>
</tr>
<tr>
<td>400-m</td>
<td>~0.00</td>
</tr>
</tbody>
</table>

Table 3.22: Wilcoxon rank-sum p-values at the 95th significance interval between the event case and null event conformed composite radar reflectivity severe proxy distributions.

<table>
<thead>
<tr>
<th>Domain</th>
<th>Wilcoxon Rank Sum p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6-km</td>
<td>~0.00</td>
</tr>
<tr>
<td>1.2-km</td>
<td>~0.00</td>
</tr>
<tr>
<td>400-m</td>
<td>~0.00</td>
</tr>
</tbody>
</table>

Table 3.23: Areal extent of severe proxy conformed half-hourly maximum updraft helicity.

<table>
<thead>
<tr>
<th>Domain</th>
<th>Event (km²)</th>
<th>Null (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6-km</td>
<td>19,725.12</td>
<td>1,755.52</td>
</tr>
<tr>
<td>1.2-km</td>
<td>85,445.28</td>
<td>48,677.76</td>
</tr>
<tr>
<td>400-m</td>
<td>152,202.24</td>
<td>180,377.28</td>
</tr>
</tbody>
</table>
Figure 3.1: a) SPC storm reports for 02/24/2011; b) SPC 12 UTC 500mb upper air observations valid 02/24/2011. This includes 500mb heights (gray), temperature (dashed red), wind barbs, and observations; c) Weather Prediction Center (WPC, formally Hydrological Prediction Center, HPC) 18 UTC surface analysis valid 02/24/2011. This includes surface pressure isobars (brown), surface fronts, and surface observations, WMO style; and d) SFCOA precipitable water in lowest 400-mb valid 18 UTC 02/24/2011.
Figure 3.2: Mean sea-level pressure and 10-meter wind speeds for the event case 02/24/2011 at 18 UTC for a) the model simulation, and b) SFCOA. Mean sea-level pressure and 10-meter wind speeds for 02/25/2011 at 00 UTC for c) the model simulation, and d) SFCOA. The red box approximately corresponds to the model domain show in a) and c).
Figure 3.3: SBCAPE and 10-meter wind speeds for event case 02/24/2011 at 18 UTC a) for the model simulation and b) for SFCOA with CIN shaded. SBCAPE and 10-meter wind speeds at 00 UTC on 02/25/2011 c) for the model simulation and d) for SFCOA with CIN shaded. The red box approximately corresponds to the model domain shown in a) and c).
Figure 3.4: Surface frontogenesis and 10-meter wind speeds for event case 02/24/2011 at 18 UTC a) for the model simulation and b) for SFCOA surface frontogenesis (red), temperature, pressure and winds. c) the same as in a) for time 00 UTC on 02/25/2011, and d) the same as in b) for time 00 UTC on 02/25/2011. The red box approximately corresponds to the model domain shown in a) and c).
Figure 3.5: a) Model composite radar reflectivity for event case 02/24/2011 at 18 UTC on 02/24/2011, and b) NEXRAD 2km observed composite radar reflectivity for the same time as in a). c) The same as in a) for time 00 UTC on 02/25/2011, and d) the same as in b) but at 00 UTC on 02/25/2011. The red box approximately corresponds to the area shown in b) and d).
Figure 3.6: Half-hourly maximum updraft helicity for the time period 22:30 – 23:00 UTC on 02/24/2011 in m$^2$/s$^2$. Only values of updraft helicity that exceed the severe threshold of 25 m$^2$/s$^2$ are shaded (Guyer and Jirak 2014). Figures a, c, and e are the native domains with horizontal grid spacings of 3.6-km, 1.2-km, and 400-m respectively. The area shown matches that covered by the conformed 400-m domain. Figures b, d, and f are the result of the corresponding native domains conformed to 3.6-km horizontal grid spacing as defined in section 2.5.
Figure 3.7: Native half-hourly maximum updraft helicity for the time period 22:30 – 23:00 UTC on 02/24/2011 in m²/s². Only values of updraft helicity that exceed the severe threshold of 25 m²/s² are shaded (Guyer and Jirak 2014). The diamonds represent observed mesocyclones detected by the NOAA Mesocyclone Detection Algorithm. In order to account for the temporal and spatial differences between the model and the observations, MDA mesocyclones were plotted for the 30 minute time period before the one shown (brown), for the current 30 minute time period (white), and for the next 30 minute time period (fuchsia). Figure a) is the native 3.6-km domain, b) is the native 1.2-km domain, and c) is the native 400-m domain.
Figure 3.8: As in Figure 3.6, but for the time period 00:30 – 01:00 UTC on 02/25/2011.
Figure 3.9: As in Figure 3.7, but for the time period 00:30 – 01:00 UTC on 02/25/2011.
Figure 3.10: As in Figure 3.6, but for the time period 02:30 – 03:00 UTC on 02/25/2011.
Figure 3.11: As in Figure 3.7, but for the time period 02:30 – 03:00 UTC on 02/25/2011.
Figure 3.12: Distribution of conformed half-hourly maximum updraft helicity across the three convection-allowing domains from 18:00 UTC on 02/24/2011 to 06:00 UTC on 02/25/2011. Distribution shows half-hourly maximum updraft helicity values greater than or equal to 50 m$^2$/s$^2$ because the majority of the grid points had less than 50 m$^2$/s$^2$ and dwarfed the rest of the distribution.
Figure 3.13: Differences between the distributions of half-hourly maximum updraft helicity across the conformed three convection-allowing domains from 18:00 UTC on 02/24/2011 to 06:00 UTC on 02/25/2011. The x- and y-axes are the same for each graph.
Figure 3.14: Distribution of severe conformed half hourly maximum updraft helicity from 18:00 UTC on 02/24/2011 to 06:00 UTC on 02/25/2011. Guyer and Jirak 2014 show that 25 m²/s² is a sufficient threshold to diagnose severe weather in low CAPE environments.
Figure 3.15: Half-hourly maximum 10-meter wind speed for the time period 22:30 – 23:00 UTC on 02/24/2011 in m/s. Only values that exceed the severe threshold of 16 m/s are shaded (King 2016). The Figures a, c, and e are the native domains with horizontal grid spacings of 3.6-km, 1.2-km, and 400-m respectively. The area shown matches that covered by the conformed 400-m domain. Figures b, d, and f are the result of the corresponding native domains conformed to 3.6-km horizontal grid spacing as defined in section 2.5.
Figure 3.16: Native half-hourly maximum 10-meter wind speed for the time period 22:30 – 23:00 UTC on 02/24/2011 in $m^2/s^2$. Only values of updraft helicity that exceed the severe threshold of 16 m/s are shaded (King 2016). The stars represent thunderstorm wind reports detailed in the NCEI Storm Event Database. In order to account for the temporal and spatial differences between the model and the observations, reports were plotted for the 30 minute time period before the one shown (brown), for the current 30 minute time period (white), and for the next 30 minute time period (fuchsia). Figure a) is the native 3.6-km domain, b) is the native 1.2-km domain, and c) is the native 400-m domain.
Figure 3.17: The same as figure 3.15, but for the time period 00:30 – 01:00 UTC on 02/25/2011.
Figure 3.18: The same as figure 3.16, but for the time period 00:30 – 01:00 UTC on 02/25/2011.
Figure 3.19: The same as figure 3.15, but for the time period 02:30 – 03:00 UTC on 02/25/2011.
Figure 3.20: The same as figure 3.16, but for the time period 02:30 – 03:00 UTC on 02/25/2011.
Figure 3.21: Distribution of conformed half-hourly maximum 10-meter wind speed across the three convection-allowing domains from 18:00 UTC on 02/24/2011 to 06:00 UTC on 02/25/2011.
Figure 3.22: Differences between the distributions of half-hourly maximum 10-meter wind speed across the three conformed convection-allowing domains from 18:00 UTC on 02/24/2011 to 06:00 UTC on 02/25/2011. The x- and y-axes are the same for each graph.
Figure 3.23: Distribution of severe conformed half hourly maximum 10-meter wind speed from 18:00 UTC on 02/24/2011 to 06:00 UTC on 02/25/2011. The severe threshold for severe HSLC wind speeds is 16 m/s as determined by King 2016.
Figure 3.24: Half-hourly maximum updraft speed for the time period 22:30 – 23:00 UTC on 02/24/2011 in m/s. Figures a, c, and e are the native domains with horizontal grid spacings of 3.6-km, 1.2-km, and 400-m respectively. The area shown matches that covered by the conformed 400-m domain. Figures b, d, and f are the result of the corresponding native domains conformed to 3.6-km horizontal grid spacing as defined in section 2.5.
Figure 3.25: The same as in figure 3.24, but for the time period 00:30 – 01:00 UTC on 02/25/2011.
Figure 3.26: The same as in figure 3.24, but for the time period 02:30 – 03:00 UTC on 02/25/2011.
Figure 3.27: Distribution of conformed half-hourly maximum updraft speed across the three convection-allowing domains from 18:00 UTC on 02/24/2011 to 06:00 UTC on 02/25/2011. Distribution shows values of half-hourly maximum updraft speed greater than or equal to 4 m/s because the majority of grid points had values less than 4 m/s dwarfing the severe distribution.
Figure 3.28: Differences between the distributions of half-hourly maximum updraft speed across the three conformed convection-allowing domains from 18:00 UTC on 02/24/2011 to 06:00 UTC on 02/25/2011. The x- and y-axes are the same for each graph.
Figure 3.29: Distribution of severe conformed half hourly maximum updraft speed from 18:00 UTC on 02/24/2011 to 06:00 UTC on 02/25/2011. The severe proxy half-hourly maximum updraft speed values for HSLC is based off of the top 99% of data for each convective-allowing domain.
Figure 3.30: Composite radar reflectivity at 23:00 UTC on 02/24/2011, shown in dBZ. Figures a, c, and e are the native domains with horizontal grid spacings of 3.6-km, 1.2-km, and 400-m respectively. The area shown matches that covered by the conformed 400-m domain. Figures b, d, and f are the result of the corresponding native domains conformed to 3.6-km horizontal grid spacing as defined in section 2.5.
Figure 3.31: Composite radar reflectivity at 23:00 UTC on 02/24/2011, show in dBZ. Figure a is the observed NEXRAD 2-km radar courtesy of UCAR and the College of DuPage (http://www2.mmm.ucar.edu/imagearchive/). Figures b, c, and d are the native 3.6-km, 1.2-km, and 400-m domains respectively.
Figure 3.32: The same as in figure 3.30, but for 01:00 UTC on 02/25/2011.
Figure 3.33: The same as in Figure 3.31, but for 01:00 UTC on 02/25/2011.
Figure 3.34: The same as in figure 3.30, but for 03:00 UTC on 02/25/2011.
Figure 3.35: The same as in Figure 3.31, but for 03:00 UTC on 02/25/2011.
Figure 3.36: Distribution of conformed composite radar reflectivity across the three convection-allowing domains from 18:00 UTC on 02/24/2011 to 06:00 UTC on 02/25/2011.
Figure 3.37: Differences between the distributions of composite radar reflectivity across the three conformed convection-allowing domains from 18:00 UTC on 02/24/2011 to 06:00 UTC on 02/25/2011. The x- and y-axes are the same for each graph. This plot only shows values of composite radar reflectivity that are greater than or equal to 0.0 dBZ in order to highlight the differences between higher values of dBZ.
Figure 3.38: Distribution of severe composite radar reflectivity from 18:00 UTC on 02/24/2011 to 06:00 UTC on 02/25/2011. The severe proxy composite radar reflectivity values for HSLC is based off of the top 99% of data for each convective-allowing domain.
Figure 3.39: a) SPC storm reports for 12/25/2009; b) SPC Day 1 Convective Outlook issued at 13 UTC on 12/25/2009; c) SPC Day 1 Tornado Outlook issued at 13 UTC on 12/25/2009; and d) SPC Day 1 Wind Outlook issued at 13 UTC on 12/25/2009.
Figure 3.40: Mean sea-level pressure and 10-meter wind speeds for the null event case 12/25/2009 at 12 UTC for a) the model simulation, and b) SFCOA. Mean sea-level pressure and 10-meter wind speeds for 12/26/2009 at 06 UTC for c) the model simulation, and d) SFCOA. The red box approximately corresponds to the model domain show in a) and c).
Figure 3.41: SBCAPE and 10-meter wind speeds for null event case 12/25/2009 at 12 UTC a) for the model simulation and b) for SFCOA with CIN shaded. SBCAPE and 10-meter wind speeds at 00 UTC on 12/26/2009 c) for the model simulation and d) for SFCOA with CIN shaded. The red box approximately corresponds to the model domain shown in a) and c).
Figure 3.42: Surface frontogenesis and 10-meter wind speeds for null event case 12/25/2009 at 12 UTC a) for the model simulation and b) for SFCOA surface frontogenesis (red), temperatures, pressure, and winds. c) the same as in a) for time 00 UTC on 12/26/2009, and d) the same as in b) for time 00 UTC on 12/26/2009. The red box approximately corresponds to the model domain shown in a) and c).
Figure 3.43: a) Model composite radar reflectivity for null event case 12/25/2009 at 12 UTC, and b) NEXRAD 2km observed composite radar reflectivity for the same time as in a). c) The same as in a) for time 00 UTC on 12/26/2009, and d) the same as in b) but at 00 UTC on 12/26/2009. The red box approximately corresponds to the area shown in b) and d).
Figure 3.44: The same as in Figure 3.6, but for the time period 13:30 – 14:00 UTC on 12/25/2009.
Figure 3.45: The same as in Figure 3.7, but for the time period 13:30 – 14:00 UTC on 12/25/2009.
Figure 3.46: The same as in Figure 3.6, but for the time period 15:00 – 15:30 UTC on 12/25/2009.
Figure 3.47: The same as in Figure 3.7, but for the time period 15:00 – 15:30 UTC on 12/25/2009.
Figure 3.48: The same as in Figure 3.6, but for the time period 16:00 – 16:30 UTC on 12/25/2009.
Figure 3.49: The same as in Figure 3.7, but for the time period 16:00 – 16:30 UTC on 12/25/2009.
Figure 3.50: The same as in Figure 3.12, but for the time period 12:00 UTC on 12/25/2009 to 00:00 UTC on 12/26/2009.
Figure 3.51: The same as in Figure 3.13, but for the time period 12:00 UTC on 12/25/2009 to 00:00 UTC on 12/26/2009.
Figure 3.52: The same as in Figure 3.14, but for the time period 12:00 UTC on 12/25/2009 to 00:00 UTC on 12/26/2009.
Figure 3.53: The same as in Figure 3.15, but for the time period 13:30 – 14:00 UTC on 12/25/2009.
Figure 3.54: The same as in Figure 3.15, but for the time period 15:00 – 15:30 UTC on 12/25/2009.
Figure 3.55: The same as in Figure 3.15, but for the time period 16:00 – 16:30 UTC on 12/25/2009.
Figure 3.56: The same as in Figure 3.21, but for the time period 12 UTC on 12/25/2009 to 00 UTC on 12/26/2009.
Figure 3.57: The same as in Figure 3.22, but for the time period 12 UTC on 12/25/2009 to 00 UTC on 12/26/2009.
Figure 3.58: The same as in Figure 3.23, but for the time period 12 UTC on 12/25/2009 to 00 UTC on 12/26/2009.
Figure 3.59: The same as in Figure 3.24, but for the time period 13:30 – 14:00 UTC on 12/25/2009.
Figure 3.60: The same as in Figure 3.24, but for the time period 15:00 – 15:30 UTC on 12/25/2009.
Figure 3.61: The same as in Figure 3.24, but for the timer period 16:00 – 16:30 UTC on 12/25/2009.
Figure 3.62: The same as in Figure 3.27, but for the time period 12 UTC on 12/25/2009 to 00 UTC on 12/26/2009.
Figure 3.63: The same as in Figure 3.28, but for the time period 12 UTC on 12/25/2009 to 00 UTC on 12/26/2009.
Figure 3.64: The same as in Figure 3.29, but for the time period 12 UTC on 12/25/2009 to 00 UTC on 12/26/2009.
Figure 3.65: The same as in 3.30, but for 12/25/2009 14:00 UTC.
Figure 3.66: The same as in Figure 3.31, but for 12/25/2009 14:00 UTC.
Figure 3.67: The same as in Figure 3.30, but for 12/25/2009 15:30 UTC.
Figure 3.68: The same as in Figure 3.31, but for 12/25/2009 at 15:30 UTC.
Figure 3.69: The same as in Figure 3.30, but for 12/25/2009 16:30 UTC.
Figure 3.70: The same as in Figure 3.31, but for 12/25/2009 at 16:30 UTC.
Figure 3.71: The same as in Figure 3.36 but for the time period 12/25/2009 12 UTC – 12/26/2009 00 UTC.
Figure 3.72: The same as in Figure 3.37 but for the time period 12/25/2009 12 UTC – 12/26/2009 00 UTC.
Figure 3.73: The same as in Figure 3.38, but for the time period 12/25/2009 12 UTC – 12/26/2009 00 UTC.
Figure 3.74: The severe proxy conformed half-hourly maximum updraft helicity distributions for the event case and null event case at each convective permitting domain.
Figure 3.75: As in Figure 3.74, but for severe proxy conformed half-hourly maximum 10-meter wind speed distributions.
Figure 3.76: As in Figure 3.74, but for severe proxy conformed half-hourly maximum updraft speed distributions.
Figure 3.77: As in Figure 3.74, but for severe proxy conformed composite radar reflectivity.
Chapter 4: Conclusions and Future Work

High shear, Low CAPE convection poses a predictive challenge to forecasters, both by the difficulty in determining whether or not a HSLC environment will produce severe weather to the difficulty in detecting HSLC convective storms on radar. These environments most often occur in the Southeastern United States and Ohio Valley during the cool season although they can occur in any part of the country during any time of year (Guyer and Dean 2010; Brotzge et al. 2011; Davis and Parker 2014; Sherburn and Parker 2014; Sherburn et al. 2016).

Previous studies have focused on improving environmental parameters for low instability convection such as Sherburn and Parker (2014 and 2016). This study, as well as King et al. (2017, in press), focus on NWP prediction of HSLC and is one of the very few of its kind. Numerical weather prediction models are often utilized in operational forecasting for guidance (e.g. Clark et al. 2012a). Past work on NWP resolving explicit convection indicated that this can be achieved at the proper horizontal grid spacing, the minimum being 4.0-km (Weisman et al. 1997; Bryan et al. 2003).

The aim of this study was to determine how well numerical weather prediction models handle explicit HSLC convection by investigating at what horizontal grid spacing, if any, does an NWP model provide operationally useful information about explicit low instability severe convection and if a NWP model can properly differentiate between a HSLC event case and a HSLC null case. By answering these two questions, recommendations can be made to the operational forecasting community to optimize NWP models specifically for forecasting HSLC convection thereby potentially improving forecasts, warnings, and thereby potential reducing risk to the public.
4.1 Discussion

For the event case severe metric distributions, three out of the four of these metrics, half-hourly maximum 10-meter wind speed, half-hourly maximum updraft speed, and composite radar reflectivity, exhibit smaller differences between the 1.2-km and 400-m severe conformed distributions than between the 3.6-km and 1.2-km severe conformed distributions. The smaller difference between the 1.2-km and 400-m severe conformed domains indicates that more detail, specifically in terms of the spatial extent of the convection and the structure of convection, is gained from decreasing the grid spacing from 3.6-km to 1.2-km. This is especially apparent when looking at the composite radar reflectivity signatures, in particular Figure 3.34. The horizontal structure of the convection becomes finer and finer as resolution increases, allowing for a closer examination of the embedded cells.

In terms of the null event, all four of the severe metric distributions exhibit smaller differences between the 1.2-km and 400-m severe conformed distributions than between the 3.6-km and 1.2-km severe conformed distributions. While there were no tornadoes reported for this event, all three of the convective permitting domains exhibit some severe threshold exceeding values of UH (e.g. Figure 3.44). While updraft helicity is not a direct indication of the presence of tornadoes, no severe weather was reported in the region examined for this case. What is promising is that the maximum values of UH produced by the event case are much higher than those produced by the null event case (see Section 3.3.1).

To determine whether or not WRF, configured specifically for HSLC environments, was able to detect differences in activity level between the event and null case, quantitative comparisons were made between the two for each severe metric distribution. All event case conformed half-hourly maximum updraft helicity severe distributions were statistically
significantly different from one another at the 95% significance level (0.05). The same is true of
the conformed half-hourly maximum updraft speed severe distributions and the conformed
composite radar reflectivity severe distributions. The only difference in event and null case
distributions for which there was not a statistically significant difference were the 1.2-km
conformed severe half-hourly maximum 10-meter wind speed and the 400-m conformed severe
half-hourly maximum 10-meter wind speed. This indicates that for all of the 3.6-km severe proxy
metrics and for almost all of the 1.2-km and 400-m severe proxy metrics, WRF did differentiate
between the event case and the null event case.

4.2 Conclusions

The first research question is at what horizontal grid spacing, if any, does an NWP model
provide operationally useful information about explicit low instability severe convection. Based
on the results of the analysis in Chapter 3 and the discussion in Section 4.1, all tested grid
spacings, 3.6-km, 1.2-km, and 400-m can explicitly represent low instability severe convection.
Based on the statistically significant differences between all 3.6-km event and null case severe
proxy metric conformed distributions and that the areal extent of severe threshold exceeding
values of updraft helicity were different by a factor of 10, the results of this study indicate that
operational numerical weather prediction models run for low instability prediction can be run
with a minimum grid spacing of 3.6-km. In terms of computational expense, 1.2-km grid spacing
incurs an estimated 9 times the computational expense of 3.6-km and 400-m grid spacing incurs
an estimated 27 times (the 400-m domain has three times more grid points in the x, y, and z-
directions) the computational expense of 1.2-km grid-spacing. Running a NWP model at fine
resolutions increases the run time of the model and the storage requirements. For example, the
null event case model output for all four domains is 840 gigabytes (GB) for a 48 hour model run.
The twenty-one hours of domain 4 model output sum to 171 GB. If the 400-m domain was run for the full 48 hours, its domain output would sum to 366 GB. The storage requirements for running the model operationally would be incredibly expense and take more than the 24 – 48 hour time period needed to make a Day 1 or Day 2 Convective Outlook. The time needed to run high resolution NWP models will change as computational power increases over time so it is possible that in the future, NWP models with $O(100m)$ grid spacing can be run operationally. Granted, this study contains a very small sample size, one event case and one null case, therefore these results cannot be applied to make a general recommendation. More event and null cases need to be run. Another caveat is the small size of the 400-m domain (Figure 2.1). Due to computational limitations, the 400-m domain was limited to a grid size of approximately 1000 by 1000 grid points. It is possible that the lack of separation, that is, the smaller distribution differences, between the 1.2-km domain and 400-m domain is due to this spatial limitation. The convection developed prior to moving into the 400-m domain. It is possible that the 1.2-km and 400-m domains would be less similar if the 400-m domain was larger thus capturing more of the convection as it developed.

Based on the results of the comparison between the event case and the null case, the answer to the second research question, can a NWP model properly differentiate between a HSLC event case and HSLC null event case given the proper initial conditions, is yes. Again, more event and null event cases need to be run and compared in order to make a broader conclusion. There is a difference between the ability to differentiate and to distinguish between an event and null case. Given the model simulation of the null case and within the limited two case sample size, WRF cannot distinguish between an event and null in an operationally useful manner at 1.2-km and 400-m. Severe proxy thresholds previously defined for HSLC and cool
season convection were exceeded in the null case. This is particularly apparent in the null case updraft helicity (e.g. Figure 3.48b-c). One reason for these swaths of threshold exceeding UH is due to the resolution dependence of UH (see Equation 2.1). Even when the thresholds are adjusted for the resolution (Figure 4.1), the resulting swaths, while smaller, do not clearly indicate a null event. The only domain that was able to distinguish between the event and null was the 3.6-km domain (e.g. Table 3.22) indicating that the finer resolutions do not do a better job in distinguishing between an event and a null. All three domains produced stronger convection than observed in the null case.

4.3 Future Work

Due to the small sample size, one event case and one null case, these results cannot be generally applied to all of HSLC cases. Therefore, analyzing additional event and null cases would be very advantageous to determine if running NWP models at 3.6-km grid spacing is broadly operationally useful. Testing a variety of horizontal grid spacing values between 3.6-km and 1.2-km could prove beneficial. It is possible that more detail in terms of the convective mode and coverage of the convection is gained between 3.6-km and another value coarser than 1.2-km while still accurately representing the convective environment and distinguishing between an event and null. The event case 1.2-km and 400-m domains excelled in this study in terms of accurately representing the convection, which is operationally useful to forecasters. In terms of representing the convection, an investigation into why WRF was overactive in the null case would be beneficial. Some possible reasons for this over activity include: the model did not accurately produce enough convective inhibition (CIN), the model did not capture the cold pool, and/or the inability of the model to capture entrainment. Determining the cause and correcting the bias would improve the ability of WRF to better represent null cases.
An investigation into scaling the updraft helicity threshold for cool season severe weather (Guyer and Jirak 2014) for the grid spacing could prove beneficial. By taking into account the resolution dependence of updraft helicity, areas forecasted to experience severe rotation may be more specified and accurate by reducing the areas considered severe threshold exceeding (Figure 4.1). Also, comparing the native NEXRAD radar data to the model output would provide a more quantifiable measure of what the different model grids are capturing in terms of the convection. Additional focus on the convective processes captured by the different domains and comparing the vertical structure of low instability severe convection across the different model grids could provide more insight into the ability of the model to explicitly represent HSLC severe convection.
Figure 4.1: Half-hourly maximum updraft helicity for the time period 16:00 – 16:30 UTC on 12/25/2009. a) is the 3.6-km native domain with values of UH that exceed the original threshold of 25 m²/s² are shown, b) is the 1.2-km native domain with values of UH that exceed the resolution adjusted threshold of 75 m²/s² shown, and c) is the 400-m native domain with values of UH that exceed the resolution adjusted threshold of 225 m²/s².
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