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Ramifications of spurious precipitation on MCSs modeled in the WRF

by

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in partial fulfillment of the requirements for the degree of

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ABSTRACT

Spurious precipitation in the Weather Research and Forecasting model (WRF) was analyzed to determine its impact on future forecasts of Mesoscale Convective Systems (MCSs) in the model. Cases were initially identified using output from the National Severe Storms Laboratory (NSSL) WRF model on days where spurious precipitation occurred during the early daytime hours preceding an MCS that was poorly forecasted within the model. These cases were then simulated using a WRF model configuration that was similar to the NSSL WRF model in order to perform sensitivity tests to better understand the role of several atmospheric processes. Additionally, an investigation into WRF Planetary Boundary Layer (PBL) and microphysics schemes sensitivities in producing spurious or false alarm MCSs was performed. These tests involved using model simulations from the NOAA Hazardous Weather Testbed 2010 and 2011 spring experiment datasets.

Four sensitivity tests compared with a control run were performed to examine the role spurious precipitation has in altering the PBL within the WRF model prior to initiation of a MCS. One sensitivity test removed all moisture fields except vapor in order to remove the effects spurious precipitation had on the PBL. A second test removed the latent heating effects caused by the microphysics scheme during the period of spurious precipitation. A third test removed the impacts of spurious precipitation on soil moisture and vegetation content. A final test removed only cloud radiation effects without eliminating clouds like in the vapor-only sensitivity. After spurious precipitation ended in the model runs all sensitivity test runs were halted and returned to their original state and run for completion. Equitable Threat Score (ETS) analyses, the factor separation method, and a qualitative analysis were
performed in order to determine the impact of each of the sensitivities, and the possible roles played by the various processes in the erroneous forecast of the MCS. It was found that among the sensitivities, the removal of cold pool effects (latent heating) and the removal of soil moisture effects (soil moisture) had the largest positive influence in affecting the main MCS forecast when spurious precipitation occurred. There were no conclusive patterns found in thermodynamic variables examined among the Hazardous Weather Testbed WRF ensemble members that reduced the probability of a false alarm MCS.
CHAPTER 1. INTRODUCTION

Severe weather has significant impacts for residents of the United States. Mesoscale convective systems (MCSs) are among the most poorly forecasted, yet are impactful phenomena and have both positive and negative effects for citizens. MCSs produce over half of the United States’ rainfall in the warm season (Heideman and Fritsch 1984). Rain-fed agriculture in states such as Missouri, Iowa and the Central Plains is possible thanks in part to MCS rainfall. This rainfall can lead to life-saving rain for the bulk of the farmers living in this region, but also life-threatening flooding for residents. From 1996-2005, over 36% of all deadly flooding events were a result of MCS rainfall (Ashley et al., 2008). An MCS can produce severe winds, hail, flash flooding, and tornadoes (Collander et. al, 2006; Doswell et al. 1996; Forbes and Wakimoto, 1983; Gallus et al. 2008; Wakimoto et al. 2006; Wheatley et al. 2006). These threats can lead to significant damage to property and loss of life. In June 2012, a MCS initiated in Iowa and became a large bowing line complex in Illinois and Indiana which raced all the way to the Atlantic through Washington D.C. spanning 800 miles and causing 2.9 billion dollars in damage and 28 fatalities (NOAA).

Forecasting MCS systems remains a significant challenge. Will storms initiate? What will be the impacts of the system? Where will the storm initiate? What will be the storm mode/extent once it forms? These are all critical challenges -- the latter two relate directly to this study. Initially, storm scale weather was believed to be too difficult to predict. One reason for this is that it was, and still is economically unfeasible to establish a network of observing stations to fully capture storm processes due to their spatial size being on the order
of tens of kilometers. However, the observation stations are dense enough to adequately describe the near-storm mesoscale environment, and be used as input into numerical models. Before 1987 due to computational constraints, most numerical models could not resolve convection explicitly; rather, they used convection parameterization. These convective parameterization schemes utilized a convective trigger. One example of a convective scheme is the Zhang and McFarland scheme. In this scheme, convection is only allowed if Convective Area Potential Energy (CAPE) reaches a certain threshold. In 1997, it was determined that a 4 km grid spacing model could initiate convection adequately without the need of convective parameterization (Weisman et al. 1997). Keeping with the Zhang and McFarland example, this meant the model no longer needed to rely on a convective trigger in order to initiate convection. Yet, it was discovered that despite a high resolution model’s ability to allow convection, the model could not fully resolve convection. Only a grid spacing of 100m is sufficient to fully resolve the convection once it initiates (Bryan et al. 2003). Prior to 1997, computing power was insufficient to run 4 km grid spacing across the entire Continental United States (CONUS). In the present day, 4 km grid spacing grids that run in real time are now possible across the CONUS. The problem scientists now face is the fact that models are able to initiate convection without the need of convection parameterization but cannot fully resolve the convective features. This becomes especially problematic when trying to simulate MCSs which have very distinct features such as convective cores, rain-free regions, and stratiform rain regions. For this study, 4 km horizontal grid spacing was utilized.
Insufficient grid resolution is not the only source of error when attempting to resolve convection in the WRF. Initial conditions play a significant role in forecast errors. However, in previous studies using an 8 km convection-parameterizing version of the WRF, differences between the estimated time of arrival (ETA) and Rapid Update Cycle initial conditions beyond 12 hours were not found to be as substantial as dynamics core or physics packages (Gallus and Bresch, 2006).

Planetary Boundary Layer (PBL) schemes in particular have well-known biases and can cause spurious precipitation to trigger in 4 km WRF simulations (Weisman et. al 2008). The reason for some of these errors is the design of the schemes. The Yonsei University Scheme (YSU), one of the many PBL options in the WRF model, diagnoses a boundary layer depth and then mixes through the entire boundary layer (Hong et al., 2006). Entrainment into the free atmosphere is done through a separate step. The Mellor-Yamada-Janjic (MYJ) PBL option (Mellor and Yamada 1982; Janjić 2002) builds the boundary layer based on turbulent kinetic energy (TKE) calculations and directly mixes the boundary layer between grid levels (Weisman et. al, 2008). The YSU scheme was found to have a deeper and drier PBL and also tended to eliminate inversions too quickly compared to the MYJ PBL (Weisman et. al, 2008). The YSU scheme has had a known dry bias of 2 g kg$^{-1}$ (Weisman et al. 2008) and a known 24-h low bias for CAPE as well. The MYJ scheme tends to produce cooler, moister, and more strongly capped PBLs but has been shown to maintain moisture. There are several other schemes, but the two discussed here are the most fundamentally different in structure and with well-known and different biases (Hu et al., 2010). For the purpose of this study, the MYJ scheme was utilized.
Microphysics schemes have been the focus of several past investigations in MCS forecasting and MCSs have been shown to be very sensitive to their use (Gilmore et al., 2004(a); Gilmore et al., 2004(b). The Thompson microphysics scheme was utilized in the present study. Although our use of the Thompson scheme is different from that used by NSSL which uses the WRF Single-Moment 6 class Microphysics Scheme (WSM6) in their quasi-operational WRF run, the Thompson scheme has been used with previous studies that likewise used the MYJ PBL scheme (Clark et al., 2010; Trier and Sherman, 2009; Weissman, 2008). In one particular study which varied the microphysics schemes with MYJ, the Thompson scheme offered similar results to other physics schemes in terms of MCS placement and precipitation totals but had more expansive stratiform rain regions that were more representative of the environment (Weisman et al. 2008). The selection of which microphysics scheme performs the best has been a focus of the Center for Analysis and Prediction of Storms (CAPS) throughout the 2010-2013 NOAA Hazardous Weather Testbed Spring experiments. The control member of the CAPS ensemble utilized Thompson microphysics as well. Regardless of the scheme selected, one of the main problems is with the over-prediction of rainfall and latent heat release from the scheme (Jankov et al., 2006).

In particular, models have a very difficult time with the extent and intensity of the rain regions regardless of which microphysics scheme is utilized (Gallus and Pfeifer, 2008). In a study looking at an MCS case in Germany, five microphysics schemes were compared with dual polarization observations, older version of Thompson (Thompson et al., 2008), the revised Thompson scheme, WRF Single Moment – 6 class ((WSM6; Hong et al., 2004), and WRF Single Moment – 5 class ((WSM5); Hong et al., 2004; Lin et al., 1983; Chen and Sun,
All of the schemes underestimated stratiform rain regions both spatially and intensity wise. In the convective core regions all schemes were found to overestimate the areas of higher reflectivity.

Another aspect that can lead to errors in precipitation is the land surface model (LSM) interaction with the PBL (McCumber 1980; Segal et al. 1988). Thermodynamic stability and simulated convection initiation are affected by the soil moisture distribution (Trier et al., 2004). This is mainly due to the partition of surface heat and moisture fluxes that affects the destabilization of the PBL (Segal and Arritt, 1995; Trier et al. 2004). Studies have confirmed that adding soil moisture perturbations can result in as substantial of differences in rainfall as those of atmospheric perturbations (Chen et al., 2001; Sutton et al., 2004). The effects of soil moisture through dynamical modifications can create mesocirculations through the formation of spatial variations in sensible heat flux (Pielke, 2001; Segal and Arritt, 1995). Clark and Arritt (1995) found that through thermodynamic forcing alone, soil moisture plays a role in convection.

The goal of the present study is to assess how false convection in a model affects the PBL prior to the onset of MCS evening activity and how these impacts might affect the MCS. Spurious precipitation has been a known complaint among forecasters, such that if most see spurious precipitation persist in a model run, the model’s ability to handle subsequent convection is called into scrutiny. The present study investigates how false precipitation affects the environment in the WRF by investigating four sensitivity runs and a control run. The first sensitivity test involved eliminating all spurious precipitation effects. Three individual processes through which false precipitation can alter the PBL were studied
in the remaining three sensitivity tests: latent heating by the microphysics scheme, soil wetting, and cloud radiation effects. Cold pools create baroclinic zones which may initiate convection through low-level convergence and lift. Thus, false precipitation can lead to inaccurate baroclinic zones which could incorrectly initiate convection. Latent heat release, both evaporative cooling effects and condensational heating, can cause errors in MCS initiation. False precipitation should increase soil moisture (Gallus and Segal, 2000). Cloud radiation effects can decrease surface temperatures causing a failure to reach convective temperature.

A secondary goal is to investigate spurious precipitation in the form of a false MCS. In some cases a MCS can be produced in the WRF where none occurred in observations. These false MCSs were investigated utilizing the WRF ensembles utilized in the NOAA Hazardous Weather Testbed Spring Experiment WRF members. Thermodynamic variables such as instability, inhibition and mid-level moisture values were investigated in each of the WRF members to try and see if certain WRF configurations were more prone to result in these false systems.
CHAPTER 2 METHODOLOGY

2.1 Case selection

Cases were selected from a domain within the Contiguous United States (CONUS) that stretched from central Texas to the Canadian border and eastern Colorado to the eastern Ohio border. To select cases, stage IV precipitation data was compared to the National Severe Storms Lab (NSSL) 4 km grid spacing WRF output (http://www.nssl.noaa.gov/wrf/) from 1 June through 31 August in 2010 and 2011. The NSSL WRF model uses the Mellor-Yamada-Janjić (MYJ; Mellor and Yamada, 1982) parameterization for the PBL, the WRF single-moment 6-class microphysics scheme (WSM6; Hong et. al, 2006) for the microphysics scheme, Rapid Radiative Transfer Model (RRTM; Mlawer et. al, 1997) for long wave radiation, and Dudhia shortwave radiation (Dudhia, 1989), and 35 vertical levels. The goal of this study was to analyze sensitivity to spurious convection by focusing on four impacts of that spurious precipitation.

To identify systems for this study, poorly forecasted MCSs preceded by spurious precipitation were identified. An MCS was defined as a continuous area of precipitation that was 150 km in aerial coverage or larger (Duda et. al, 2010). Poorly forecasted MCSs were defined as being those systems having convective initiation 1 hour or more prior to or later than observations and being displaced by over 200 km from an observed MCS (Duda et. al, 2010). Once cases were identified in which an evening MCS was misrepresented, the following criteria were used to further determine if the event was a good example of spurious precipitation harming a forecast: 1) spurious precipitation had to occur within 100 km of an
area where initiation of a second MCS was observed, 2) spurious precipitation had to produce a rain rate of 0.1 inch per hour in the model for a minimum of three hours, and 3) a minimum of two hours had to exist between spurious convection dissipation and the initiation of an observed MCS. After applying these criteria, ten cases remained and were studied in detail by performing several sets of WRF model runs.

Additionally, an investigation into spurious or false alarm MCSs was performed. A MCS in this case was defined as simulated or observed convection that was 100 km or greater in diameter and produced 0.1 an inch of rainfall per hour for a minimum of 3 hours. A poorly forecasted MCS was defined as a simulated MCS that either occurred 200 km or more from an observed MCS or initiated 1 hour before or after an observed MCS. A false alarm was defined as a simulated MCS with no observed convection occurring within 200km for more than three hours. There are other ways of identifying an MCS specifically through vertical motion, cloud water mixing ratio, and rain water mixing ratio. However, these processes depend on the microphysics scheme and are not well resolved on a 4k m grid (Bryan, 2003). The Hazardous Weather Testbed WRF ensemble was used to investigate false alarm MCSs (Kong et. al, 2011). The Advanced Research WRF (ARW) control member was used to identify the cases of false alarm MCSs from the Hazardous Weather Testbed WRF ensemble. The ARW control member’s failure to capture convection was usually accompanied by most of the other members in any given day also failing to capture convection and was thus used to determine events.
2.2 Model configuration

Simulations utilized the WRF v 3.3.1 model using the ARW dynamics core (Skamarock et al. 2008). The model was initialized using North American Mesoscale (NAM) model analyses at a grid spacing of 12 km at 00 UTC and was integrated for 30 hours. Lateral boundary conditions were ingested every three hours from the NAM data. A single 1800 x 1800 km domain at 4 km horizontal grid spacing was used to cover the Central Plains. The Thompson microphysics scheme was selected (Thompson et al. 2008). For a PBL scheme, the MYJ was coupled with the Turbulent Kinetic Energy (TKE) boundary layer option. The Unified Noah Land Surface Model (LSM; Ek et al. 2003) was selected from the list of LSMs. For radiation schemes, the Rapid Radiation Transfer Model (RRTM) longwave and Dudhia shortwave radiation schemes were utilized.

In order to investigate how false precipitation alters the WRF model PBL, (via latent heat release in the microphysics, soil wetting, and deep cloud cover), the control run, three individual sensitivity runs, and the vapor-only runs were analyzed. The sensitivities were examined individually during the restart period, which is the period of time from where spurious precipitation initiated to dissipation in the control run. The first sensitivity test, known as the vapor-only run, changed all moisture species except for water vapor (Qvapor) to zero allowing for no spurious precipitation to form. The second sensitivity, known as the latent heat run, removed all latent heating effects from the microphysics scheme. The third sensitivity test, known as the soil moisture run, removed all precipitation from entering the LSM. The final sensitivity, known as the deep cloud run, removed all radiation effects caused by clouds. Upon completion of the restart period, all the processes removed in the sensitivity
tests were reactivated. This was accomplished through the use of WRF restart files and namelist options.

Additionally, the WRF’s susceptibility to produce false alarm MCSs was investigated. Simulations were conducted as part of the NOAA Hazardous Weather Testbed 2010 Spring Experiments WRF ensemble using WRFV3.1.1. There were 19 WRF-ARW, 5 WRF NMM, and 2 ARPS members in the ensemble (Kong et. al, 2011). All but three members included full resolution radar data integration from the WSR-88D radar network into the initial conditions using ARPS 3DVAR and cloud analysis found in (Xue, 1995). These simulations were integrated for 30 hours and initialized at 00 UTC. A variety of initial conditions were used including NAM 12 km analyses, Short Range Ensemble Forecasts with perturbations, and ARPS 3DVAR and cloud analysis (Kong et. al, 2011). For more information on ARPS 3DVAR and cloud analysis configurations refer to Xue et al. (2009). Table 1 taken from (Kong et. al, 2011) states the various members, their initial condition, microphysics, boundary conditions, LSM, and PBL schemes used. Cn are the control members while c0 is the same as the control member but with no radar data analyzed. NAMa and NAMf refer to the 12 km NAM analysis and NAM forecast. ARPSa is the ARPS 3DVAR and cloud analysis using the NAMa as the background (Kong et. al, 2011). M5~14 ARW and m3-m5 NMM are perturbed members where the initial conditions consist of a mixture of Ensemble Transform (ET) perturbations and bred from the 21 UTC SREF members: 4 WRF-em(ARW), 4 WRF-nmm(NMM), 2 ETA-KF, 2 ETA-BMJ, and 1 RSM-SAS. M15-19 of the ARW are extra physic-perturbation-only members and m3-m5
ARW are 3 random perturbation members that were added to the 2010 spring experiment (Kong et. al, 2011).

2.3 Analysis of model output

Both quantitative and qualitative evaluations of quantitative precipitation forecast (QPF) skill for each of the runs were performed. The quantitative evaluations were done using the equitable threat score (ETS; Schaefer 1990) and bias where

\[
ETS = \frac{CFA - CHA}{F + O - CFA - CHA} \quad (1)
\]

\[
CHA = O \frac{F}{V} \quad (2)
\]

\[
bias = \frac{F}{O} \quad (3)
\]

In (1)-(3) \( V \) represents the total number of evaluated grid points, \( CFA \) is the number of grid points where both forecast and verification are greater or equal than the threshold, that is, “hits;” \( O \) at a number of grid points is rainfall where the observed is to exceed the threshold, and \( F \) is the number of grid points where rainfall forecasted to exceed the threshold. CHA is a measure of the number of grid points where a correct forecast would occur by chance. This was evaluated at all grid points comparing with the National Center for Environment Prediction’s (NCEP) stage IV gridded precipitation data (Baldwin and Mitchell, 1997). Both ETS and bias were used to examine quantitatively and objectively the sensitivity of QPF to the changes made in the model. In all cases there were other forms of convection that had no association with spurious precipitation. In order to evaluate the role of spurious precipitation in MCS development solely, a smaller domain was selected over which to perform the verification based on a) where spurious precipitation occurred and subsequent MCS initiation
and b) where the MCS that initiated in the spurious precipitation region resided at the end of the run. This way, errors associated with the run changes on convection that wasn’t affected by spurious precipitation were not taken into account.

Factor separation analysis was used to quantify how varying two of the sensitivities impacted hourly rainfall and total rain volume (Stein and Alpert, 1993). The methodology is as follows:

\[ f_{xy} - f_0 = (f_x - f_0) + (f_y - f_0) + \bar{f}_{xy} \] (4)

where \( f_{xy} \) represents the rainfall simulated by a run with two changes made, \( f_0 \) represents the control run, \( f_x \) represents the rainfall produced by a run that has one sensitivity change, \( f_y \) represents the rainfall with a different single sensitivity change, and \( \bar{f}_{xy} \) represents the synergistic term given as:

\[ \bar{f}_{xy} = f_x - (f_x + f_y) + f_0 \] (5)

The synergistic term accounts for rainfall added due to the non-linear interaction between the two processes examined in the sensitivity runs. The term accounts for differences if the impact of individual changes added together do not equal differences in a run in which both changes were made. In order to evaluate the nonlinear interactions between the changes made during the sensitivity tests, 3 additional model runs were performed where two of the possible three sensitivity changes were performed during the restart period (latent heat removed and soil moisture removed, soil moisture removed and cloud radiation effects removed, and cloud radiation effects and latent heat). These runs were used in order to evaluate the synergistic term. If the synergistic term is equal to zero, there is no rainfall that
is caused by the interaction of the two changes. In addition, to better understand the reasons for the impacts on precipitation, qualitative analysis of each case was performed.

For false alarm MCS cases, Rapid Update Cycle (RUC) analyses were used to compare the differences in thermodynamic parameters one hour prior to initiation of the false alarm MCS. The thermodynamic parameters that were used were surface-based CAPE, 500m CIN, surface potential temperature and surface equivalent potential temperature. A Gaussian filter was applied to the WRF data to eliminate waves of smaller scales than could be produced in the RUC data. The filtering allows better comparison of output having differences in grid spacing (20km for the RUC, 4km for the WRF). In every case, there was upwards of 300 km spatial variability in the location of initiation of a false alarm MCS amongst the members. In order to account for this variability, three 0.5 by 0.5 latitude/longitude grid box were used to average the WRF member values over the site(s) of initiation of convection in the model. A fourth 0.5 by 0.5 latitude/longitude grid box was used centered over the closest RAOB station that the false MCS passed over in order to compare the environment of the members to the 00 UTC RAOB. In the case of the false alarm MCSs, this location of initiation varied. Fig.1 is an example of a case where MCS initiation varied across western NE.
Chapter 3 Results and Analysis

3.1 Case classification

Ten cases were selected that had readily identifiable spurious precipitation at 12 UTC. The spurious precipitation duration varied by case but the longest duration was from 12-21 UTC. Following the spurious precipitation, an observed MCS initiated where spurious precipitation occurred prior in the model. The observed MCS initiation times varied by case but were between the hours of 21-03 UTC. In addition, cases were selected if the simulated MCS in the control run fit the criteria of a poorly forecasted MCS when compared to observations. Large-scale forcing in all of the cases was weak or non-existent (not shown). For instance, in no case were there any upper level height falls or any jet streaks. All of the cases occurred in June, July, and August and all were dominated by large scale ridging over this portion of the CONUS. Therefore, the primary triggers for convection in all of the cases tended to be surface features such as outflow boundaries or upslope-flow and were primarily driven by favorable thermodynamic fields. For verification, 20km RUC analyses were used to represent observations. It should be noted that the WRF output was on a 4 km grid in the spurious precipitation study in order to maintain the sub 20km grid effects of spurious precipitation. The RUC output was only used for a qualitative comparison.

It appeared that these ten cases could be subdivided into four categories based on the primary forecast deficiency. The first category was where spurious precipitation occurred but incorrect placing of an MCS in the WRF in the 0-18 hour forecast played the main role in the incorrect development of the main MCS. Of the ten cases, four failed to accurately represent
the main MCS because of improper initialization and propagation of an MCS at the start of
the runs. Several of the cases evidenced were not situations where spurious precipitation
affected the MCS. Rather, the model failed to represent actual convection in the early stages
of the run which is what led to the erroneous forecasts.

The second category was where false precipitation occurred and played a role in the
development of the main MCS in the model; but an incorrect forecast of a second MCS in the
18-36 hour forecast directly played a larger role. Only one case was found to fit this category.

The third category refers to where observed precipitation occurred in the restart
period within a 100 km location of spurious precipitation but directly influenced the
development of the main MCS. Spurious precipitation formed west of MCSs in most of these
cases and propagated to the east during the afternoon. However, the spurious precipitation
initiated and was close to observed precipitation that was ongoing in the area of CI later in
the period. By running during the restart period, the effects of both the correctly simulated
and spurious precipitation were removed in the CI area of the main MCS. This made analysis
of the impacts of spurious precipitation on the PBL impossible to distinguish from the
removal of correctly simulated precipitation effects on the PBL. Three cases were found in
this category.

The fourth category was where false precipitation played the major role in the
incorrect development of the main MCS. Three cases were found to fit this category and are
the focus of discussion below.
3.1.1 ETS and bias

Equitable Threat Scores (ETS) and bias values were used to ascertain the impacts that spurious precipitation had in the 21-30 forecast hour period in the control run by comparing ETS and bias scores to those valid for the runs during that time period. Comparisons made to the control run are meant to stress the importance of a sensitivity’s impact, not advocate the implementation of the sensitivity in a forecast scenario. Table 2 through Table 5 shows the various effects the sensitivities had on the ETS and bias compared to the control run. The time period ranged from the end of the restart period through the remainder of the run for the control and all sensitivities: vapor-only run (VP), latent heat run (LH), soil moisture run (SM), and deep cloud run (SH). Overall, each of the sensitivities experienced higher scores at lower thresholds when compared to higher thresholds (Fig. 2a). In many cases, these low scores in the higher thresholds were due to displacement errors. At the lowest threshold, averaged over three cases, both the vapor-only and the soil moisture runs exhibited a “good” forecast (Table 3), where a good forecast is defined as an ETS value one standard deviation or more above the median of the 5 runs on that case day. At every other threshold, the vapor-only run was the only run to exhibit an ETS value that was one standard deviation value over the median (see Table 3). This indicates the impact spurious precipitation had on the evolution on convection from after the restart period and suggests that all processes examined played some role in harming the later forecast of the MCS. The vapor-only run in two cases had the highest ETS at the lowest threshold. The removal of all spurious precipitation effects should improve ETS scores the most at this threshold since all convection inhibiting factors in areas where spurious precipitation altered the environment
are removed. In one case, the soil moisture run had the highest ETS at the lowest threshold which indicates that soil moistening due to spurious rain played the largest role in accurately producing 0.01 inch rainfall in that case. At all other thresholds, the vapor-only run had the lowest bias and highest ETS scores followed by the latent heat run indicating an important impact of cold pools on heavier precipitation. These results show that although the soil moisture test had a higher ETS at the 0.01 inch threshold, the soil moisture also had the highest bias indicating an overproduction of rainfall compared to the other runs (Table 6). The high bias is most likely related to the soil moisture run creating a drier deeper PBL that caused convective temperature to be achieved faster than any other run. The result was an over production of rainfall that led to the high bias. This indicates that soil moistening caused by spurious precipitation reduced ETS scores by suppressing precipitation later in the model run. The control run and deep cloud run had the lowest ETS compared to the other three runs in most cases due to large displacement errors of the main MCS related to spurious precipitation during the restart period.

When all cases were averaged together, the vapor-only run exhibited the highest equitable threat scores (Table 3). These high scores might be related to the fact that the vapor-only run allowed for the reduction of cold pools, and enhanced heating that initiated convection in areas where it was suppressed by spurious precipitation effects. The vapor-only run in all three cases had no precipitation measured during the restart period which resulted in no soil wetting. The elimination of all of these factors produced favorable conditions for proper initiation. The results were on average lower biases and higher ETS scores compared to the control run and all other runs in the 3 cases (Table 5; Fig. 2b).
The latent heat run on average had higher scores than the control run with similar ETS scores in the higher thresholds as compared to the soil moisture run. The latent heat run had lower scores compared to the soil moisture run at the 0.01 threshold. For higher thresholds in two cases, the latent heat run tended to have the most similar progression to the vapor-only run which led to the higher ETS scores and lower biases at the higher thresholds. Thus, the two biggest impacts of spurious precipitation can be attributed to the cold pool production and added moisture to the soil by the spurious precipitation based on ETS and bias scores. Condensational heating effects were ignored as it became apparent that evaporative cooling was more dominant by the strength of the cold pools (-10 to -15 C). The latent heat run tended to have lower values of Convective Inhibition (CIN) (~50 J kg\(^{-1}\)) and lower LCL heights (800m) over the spurious precipitation region than those present in the control run, which may have led to more precipitation later, increasing the ETS scores. The lower ETS scores and low bias in the 0.01 inch threshold compared to the soil moisture and deep cloud runs may be related to the low LCL and low CIN values, causing precipitation to initiate in the wrong areas compared to observations especially in later forecast periods without increasing the bias. The latent heat run generated a low bias in the lower thresholds in this case which corresponded to the lower ETS scores. In two of the three cases, at the 0.1 and 0.5 in thresholds, the latent heat run had an ETS score one standard deviation above the median.

For all thresholds, the soil moisture run had the largest positive bias compared to all the other runs (Fig. 2a-b). The deeper PBL (~+400 m) compared to the control run over the spurious rainfall area resulted in surface temperatures increasing faster than the control run
due to the drier soil (Pan and Mahrt, 1987). This may have led to increased precipitation over the spurious rain region due to convective temperature being reached and steep low level lapse rates due to mixing compared to the control run. These factors might have led to the high ETS scores at the low thresholds. For heavier thresholds, the soil moisture run had lower ETS scores compared to the vapor-only run but similar to the other runs. The errors in the heavier thresholds are most likely associated with displacement errors of the heavier precipitation regions. The soil moisture removal during the restart period played a role in increasing precipitation more than the other runs (highest bias at the 0.01 inch threshold) but the result were lower ETS scores at higher thresholds due to the amount of high precipitation produced.

The deep cloud run had the lowest ETS value out of any run but the control. By removing cloud radiation effects across the entire domain, precipitation tended to initiate in more areas than what occurred in the control run due to the higher sensible heat fluxes (~+100 W m$^2$). However, due to the cold pools remaining in the deep cloud run, precipitation did not occur in areas where the cold pool lingered due to spurious precipitation. The result was a higher bias and more widespread precipitation but in the wrong. This would explain the similarities in terms of ETS in all the cases in the deep cloud run when compared to the control run.

3.1.2 Factor separation analysis of rain rate and domain total rain volume.

The factor separation method was used from the end of the restart period to the end of the run to evaluate the sensitivity of rain rate and rain volume to the various processes tested
in the sensitivity runs. Table 6 shows the change in domain total rainfall with individual changes in the sensitivities \((f_x-f_0)\). The synergistic interactions between the two sensitivities were expressed with \(f_{xy}\). In every threshold but the 0.01 inch threshold in the latent heat run, domain total rain volume increased when compared to the control run. In the 0.5 inch threshold, the increase in domain total rain volume in the latent heat and vapor-only runs combined with the low bias and high ETS scores indicates how the removal of cold pools from spurious precipitation resulted in the greatest change in the model runs implicating cold pools as the most important factor in degrading the forecasted MCS. At the lightest threshold (0.01 in.), the soil moisture run had the largest increase in domain total rainfall (18%) with a modest increase in the 0.5 inch threshold (2%). By removing precipitation from entering the land surface model, interactions between the land surface model and the WRF can have as large of an impact as altering the microphysics scheme in the context of spurious precipitation. This result agrees with previous studies on the importance of the land surface model interaction (Chen et al., 2001; Sutton et al., 2004). The deep cloud run had the same increase in the 0.01 threshold as the vapor only (11%) but a more modest increase of 4% in the 0.5 inch threshold. The synergistic terms indicate the highest increase in rain total volume due to nonlinear interactions occurred when soil moisture and latent heating effects were both neglected, at 16% and 9% at the 0.01 and 0.5 inch threshold.

Table 7 shows the impact on rain rate for the various sensitivities with thresholds at 0.01 in/hr and 0.5 in/hr. The vapor-only run had the largest impact on average at the 0.5 inch/hour threshold (86%), the highest among any other run. The latent heat run had a 4% decrease at the 0.01 inch/hour threshold, the largest decrease out of any sensitivity. The
decrease was most likely due to the restart period ending at the same time as initiation in this case. All model members except the latent heat and vapor-only run produced precipitation immediately after the restart period ended. The latent heat and vapor-only run did not produce precipitation until 1 hour after the restart period ended as seen in Table 4 where these two runs had the lowest rainfall volume amongst the sensitivities. The result was reduced ETS scores caused by the lack of precipitation produced by these two members. This was the only case that had this lag in precipitation production and for continuity of the runs; this hour was included in the analysis despite the failure to produce precipitation during this hour. The soil moisture run had the largest impact on the 0.01 inch/hour threshold with a 33% increase on average. The soil moisture also had a high increase at the 0.5 inch/hour threshold at 49%. Lastly, the deep cloud run had a 16% and 42% increase in hourly rain rate on average across all cases. The soil moisture and latent heat synergistic term again had a large impact with a 17% and 36% increase at the 0.01 inch/hour and the 0.5 inch per hour rates. This indicates that the soil moisture and latent heating effects had the largest positive contribution to increasing rain rates from the control run confirming the importance of these two effects.

ETS scores and the factor separation method (Stein and Albert, 1993) indicated a larger sensitivity to changes in the vapor-only run, soil moisture run, and latent heat run when compared to the deep cloud run. The latent heat and soil moisture runs had the highest ETSs out of any sensitivity change excluding the vapor-only which is a summation of all possible spurious precipitation effects. Although the soil moisture run had a large impact on domain total rain volume and on ETS scores at the 0.01 inch threshold, the soil moisture run also had the highest bias and a decrease in ETS scores from the latent heat and vapor-only
runs at high thresholds. The high bias indicates the soil moisture run is producing more precipitation on average but not necessarily correct with observations (low ETS). The latent heat run had a lower 0.01 inch (~10%) and 0.01 inch/hour threshold (~20%) and a low bias compared to the other runs, but had high ETS and large impacts at the heavier thresholds. This indicates that by removing latent heating effects, a slight decrease in light precipitation occurs compared to the control run but a more accurate representation of the main MCS due to the high ETS scores.

3.2 Case studies

3.2.1 Case 0000 UTC 03 August 2010 to 0600 UTC 04 August 2010

i. Synopsis

At 10 UTC on 03 August 2010 in observations, an MCS was ongoing in IA while convection formed an E-W line that bowed out and moved northeast into SW NE. By 12 UTC (Fig.3a), the storms had moved into central NE before dissipating at 14 UTC. CI began in NW SD at 18 UTC associated with an embedded shortwave from a positively tilted trough (Fig.3b). This formed a bowing line segment that propagated E-SE into northern NE by 23 UTC on 03 August 2010. At the same time, a supercell fired in central NE where strong moisture convergence and Warm Air Advection (WAA) existed at 700 and 850 mb. At 02 UTC on 04 August 2010, scattered convection fired along this front in SW NE and formed an E-W broken line from SW NE to SW IA (Fig.3c) through 06 UTC (Fig.3d).

ii. Run comparison
In this particular case, the control run developed spurious precipitation at 12 UTC in far SW NE that extended into south central NE. The spurious precipitation formed on the nose of a theta e ridge that was lower (-4 K) in observations. The spurious precipitation remained in NW KS/SW NE through 19 UTC. By 23 UTC, the control member failed to initiate convection in NW NE and in SW NE/NE CO where an MCS had initiated in observations. The control member initiated an MCS in NW KS at 23 UTC on 3 August 2010 and propagated to Central KS by 06 UTC on 04 August 2010. This placed the simulated MCS over 200km to the south of the observed MCS.

The progression of the convection after the restart period confirms the influence spurious precipitation had on the control run. The incorrect convection in far NW KS initiated due to an upslope flow caused by a 10-15 knot easterly flow along a stalled warm front. In comparison, the observations at the same time indicated weak surface winds at 5 knots. The upslope convection in the control member produced a strong cold pool (-20°F compared to observations) that surged into far western KS by 01 UTC on 04 August 2010 (Fig. 4a-b), cooling surface temperatures to 68°F as compared to 80°F in observations. The cold pool produced convection from 00 to 03 UTC on 04 August 2010 in NW KS which was further south by over 150 km compared to observations. By 03 UTC on 04 August 2010 the cold pool became more diffuse (-5°F) and convection weakened in KS, whereas, convection was ongoing in SW NE in observations. The surface low position subsequently differed from observations with the low being centered in north central KS in the control run as compared to west KS in observations due to this cold pool surge. The eastern portion of the warm front was subsequently pushed into central NE in the control run due to this northward propagation
of the surface low. Meanwhile, observations still had the warm front located in far NW KS on the KS/NE border. Air rose over the warm front as lifting was occurring on the nose of an 850 mb jet in northeast NE. The control member initiated convection north of the warm front but due to its incorrect position and developing 850 mb jet, storms initiated in northern NE instead of just north of the KS/NE border as observed (Fig. 5a-b). The convective system evolved by 06 UTC in the WRF to be centered in northern NE and not in southern NE like in observations (Fig. 6a-b). The evolution of convection and its poor performance compared to observations is confirmed by the low ETS and bias scores for this case (Table 2; Table 4).

Results previously presented indicated that the vapor-only run resulted in the highest ETS scores at the 0.01 in threshold. In this particular case, this can be explained by the vapor-only run producing the warmest temperatures in eastern CO Rockies with temperatures reaching 90°F by 23 UTC on 03 August 2010 (Fig. 7a-d) compared to 85°F in other runs including the control run one hour after the restart period. The results were higher instability (+2500 J kg\(^{-1}\)) over the spurious precipitation area of SW NE by 23 UTC on 03 August 2010 and correct convection in that area. For low ETS thresholds, the correct initialization of the upslope convection in CO/W. NE is evident in the domain total volume having extensive 0.01 inch rainfall totals in W. NE (Fig. 8a-b) compared to the control run. An 8% increase in the 0.01 inch domain total rainfall verifies this difference compared to the control run. For the heavier thresholds, the ETS scores for the vapor-only were the highest amongst all the runs, but low overall. The low overall scores could be due to the high amounts of instability (+4000 J kg\(^{-1}\)) and low CIN (~25 J kg\(^{-1}\)) that formed in each run (Fig. 9a-d). The combination of high CAPE and low CIN in the run led to the production of a MCS in eastern NE, but not
in observations. The latent heat run had the highest 0.1, 0.25, and 0.5 in threshold ETS score most likely due to this run having the lowest heavy rainfall totals across eastern NE from the 02-06 UTC timeframe where the MCS was ongoing in NE. There was 0.01 inches of precipitation widely measured in eastern NE which may have been the cause of the lower ETS score at the 0.01 inch threshold. The factor separation analysis correlates with this decreased precipitation across Nebraska with 1% and 3% decrease in the domain total rainfall value at the 0.01 and 0.5 inch threshold. The vapor-only and latent heat runs had the highest ETS scores in all threshold categories in this case due to the more accurate depiction of precipitation in W and SW NE (Fig. 10a-d) after the restart period. The improved ETS scores in the vapor-only and latent heat runs indicates that spurious precipitations cold pools played the most important role in affecting the main MCS in the control run.

In this case, the latent heat run had more widespread heavy precipitation (>0.1 in) compared to the other runs across NW KS and western NE (wide areas of 0.1-0.5+ inch). Combined with the lightest coverage of heavy precipitation values in eastern NE compared to the runs, these two areas played a role in why the heavy precipitation ETS scores were higher in this case (Fig. 10 a-d). A model sounding in the area where the spurious precipitation occurred during the restart period in NW KS (39.9,-100.55) at 23 UTC on 3 August 2010 indicates a reason why the latent heat run produced higher precipitation values (Fig. 11 a-d). The latent heat run has steep near dry adiabatic surface to 850 mb lapse rates and a more saturated PBL resulting in a low LCL height (~800 m) compared to (~+1000 m) the other sensitivity runs (Fig.12 a-d). More importantly, CAPE (~3500 J kg⁻¹) and Convective
Inhibition (CIN; 5 J kg$^{-1}$) are the most conducive out of all the sensitivities for sustained deep convection.

The soil moisture run in this case had an uncapped but distinctively drier profile as noted by the higher LCL heights of 1500m compared to the other sensitivity runs (Fig. 12a-d.). The dry PBL may have contributed to the lighter precipitation values across the SW NE/NW KS area at 23 UTC which may have led to lower ETS scores. The main contributing factor to why the soil moisture run had a lower ETS is the intensification of convection that entered south central NE at 01 UTC. The cells had initiated along the stalled outflow boundary produced by the spurious precipitation in NW KS at 21 UTC on 03 August 2010. Increased rain rates at a 40% and 47% increase at the 0.01 in/hr and 0.5 inch/hr threshold indicate the presence of these cells when compared to the control run. High amounts of CAPE (~4000 J kg$^{-1}$) stretched from NW KS into south central NE. This environment was highly unstable but lacked a forcing mechanism to initiate cells in the vapor-only and latent heat runs. This spurious precipitation cold pool/outflow boundary can be attributed to causing the low ETS values in the control, soil moisture, and deep cloud runs. The deep cloud run had almost identical progression as the control run. The 0% and 4% increase in rain rates at the 0.01 and 0.5 inch/hour thresholds combined with the 3% and 4% increase in domain total volume verify the similarities between the control and deep cloud run in this case. There were very little differences between the control run and deep cloud runs on all model sounding comparisons as well.

The latent heat run resulted in the highest ETS values at the 0.1, 0.25, and 0.5 thresholds due in part to the correct placement of convection over the area where spurious
precipitation occurred. A contributing factor to the latent heat run’s higher ETS value, when compared to the vapor-only run, was the least amount of heavy precipitation falling in the eastern NE MCS from 01-06 UTC. This case highlighted the importance of eliminating the cold pools during the restart period. The PBL was able to recover to reach convective temperature by 23 UTC on 03 August 2010 in western NE. Unlike the control, soil moisture and deep cloud runs, convection did not initiate along a cold pool in NW KS produced by the spurious precipitation at 21 UTC. Rather convection initiated properly in the latent heat and vapor-only runs over the area where spurious precipitation fell earlier in western NE in the control, soil moisture, and deep cloud runs. The soil moisture run did recover as evidenced by the domain total precipitation values over NW KS/W. NE. However, the production of convection along the outflow boundary in NW KS at 21 UTC caused by the spurious precipitation earlier led to the lower ETS values (Table 3). The higher rain rate percentages in the factor separation and increased domain total rain volume confirms the impact of the cells that fired off the spurious precipitations outflow boundary in NW KS in the soil moisture run (Table 7).

It should be noted that all runs produced a MCS in E. NE and not across the W. KS/NE border from 01-06 UTC that affected ETS scores in this case. The reason for this error was due to the incorrect placement of an outflow boundary produced by a MCS in SD at 19 UTC being in W. SD in all the runs vs. the central NE/SD border in observations. The outflow boundary initiated convection in observations at 23 UTC in W. NE. In the runs, the warm front that stretched across NE and into KS was what initiated the MCS. Regardless of the mechanism, the fact that the vapor-only and the latent heat runs in this case were able to
produce precipitation highlights the effect cold pools caused by spurious precipitation can have on the future development of precipitation affecting the extent of the MCS and the ETS.

3.2.2 Case 06 July 2011 0000 UTC- 07 July 2011 0600 UTC

i. Synopsis

A broad ridge at 500 mb was centered over the Four Corners region at 00 UTC 06 July 2011. At 700 mb, a strong area of WAA and moisture convergence existed in a NW to SE line from NE CO into KS at 00 UTC on 06 July 2011. Subsequently, a large MCS initiated at 02 UTC in central NE and propagated into KS at 12 UTC (Fig. 13a) and dissipated at 21 UTC. Meanwhile, strong upslope flow (~20 knot easterly winds) existed across the Central Plains and ignited convection in eastern CO and WY at 21 UTC. These storms became more concentrated at 22 UTC and formed an E-W line segment across central NE (Fig. 13b). By 04 UTC, a large MCS that extended from SE NE through central NE merged with a line coming off the Colorado Rockies in W. KS forming a MCS with a large stratiform precipitation region (Fig. 13c). By 06 UTC the MCS had propagated into western MO (Fig. 13d).

ii. Run comparison

By 12 UTC, the control run began to have spurious precipitation as it produced and propagated a convective cell 50 km in width in western NE through 21 UTC (Fig. 14a-b). The cell had initiated along a weak surface convergence along the eastern slopes of the Rockies in WY and propagated east through 21 UTC. By 21 UTC, the WRF control member had no precipitation in W NE, unlike observations where cellular convection producing in
excess of 0.5 inches of rainfall (not shown). The spurious convection had created cooler temperatures across western NE (~75°F) compared to observations (~85°F). Most likely no convection developed in that area due to this cold pool caused by spurious precipitation unlike in observations where the convective cells merged into an MCS that propagated across NE from 21-06 UTC. The focus of this case will be with the observed MCS that formed in NE. All sensitivity runs were higher than the control run in terms of ETS scores.

The vapor-only run in this case had ETS scores that were higher than the control run at all thresholds but the third lowest ETS scores of all the runs. The vapor-only run did produce convection in the area after spurious precipitation occurred in the control run in western NE that more closely represented observations. However, the vapor-only run did not convect the extent of precipitation in Kansas by 06 UTC which resulted in low ETS scores (Fig. 15a-d). The reason for the improvement in western NE is due to the elimination of cold pools as evidenced by the surface temperatures at 21 UTC and the high sensible heat flux in excess of 250 W m⁻² (Fig. 16a-d) compared to the control run. This area in all other sensitivity runs failed to produce the amount of precipitation (0.3-1.25 inches) that more closely matched observations (Fig. 15a-d). This is the same area where spurious precipitation occurred from 12-21 UTC. At 21 UTC, CAPE values across this area remained high as well (~2750 J kg⁻¹) compared to (~ 1500 J kg⁻¹) in other sensitivities. The low CIN values (5J kg⁻¹) compared to (~50 J kg⁻¹) led to a reduced cap and the initiation of cells at 22 UTC. In this particular case, this was the only run that produced any precipitation over the spurious precipitation region.
The latent heat runs impact in this case on ETS was lower than the vapor-only, soil moisture and deep cloud runs in all but the lowest threshold (Table 2). This corresponded with a 16% reduction at 0.01 inch/hour rain rate threshold and a 22% reduction at the 0.5 inch/hour rainfall rate threshold. An explanation for the poor performance in terms of ETS scores is that the latent heating effects were only deactivated at 12 UTC, however, the spurious precipitation had initiated at 09 UTC on 6 July 2011. Due to the restraints of the experiment in investigating daytime contributions of spurious precipitation, the latent heating effects were turned off only during the daylight hours. The cloud cover from the spurious precipitation had already formed prior to 12 UTC on 06 July 2011 (not shown). The radiative effects combined with the cold pool that had weakly formed prior to 12 UTC on 06 July 2011 (-10 degrees) made an impact prior to the restart period unlike the previous two cases where spurious precipitation initialized at 12 UTC. These factors may explain why the temperatures never increased above 75°F across western and central NE despite latent heating effects being turned off during the restart period as evidenced by surface temperatures and sensible heat fluxes between the latent heating and vapor-only at 21 UTC (Fig. 15a-d; Fig. 16a-d). In the spurious precipitation area in the latent heat run, only 0.01 inches of rain fell across W. Nebraska and low sensible heat flux was evident with the area being in the 80-100 W m² compared to 300 W m² in the other sensitivity runs. A high bias at the 0.01 inch threshold of 2.06 which was similar to the control run at 2.086 the poor scores at 0.01 inch threshold seem to be related with the high amount of 0.01 inch precipitation noted on the domain total rainfall in W. NE (Fig. 15b).
In this case, the soil moisture run exhibited the largest positive impact on ETS. A comparison of domain total rainfall between the vapor-only and soil moisture runs from the end of the restart period at 21 UTC through 06 UTC on 06-07 July 2011 offers some explanation to why the soil moisture runs ETS scores were the highest amongst the sensitivity runs (Fig. 15a,c). One area where the soil moisture run had more accurate rainfall was in north central NE. Northern NE had widespread 0.1-0.5 inch rainfall in the soil moisture run compared to all other sensitivity runs (Fig. 15a-d). The surface sensible heat flux was higher at 21 UTC on 06 July 2011 in this area at a value of 300 Wm$^{-2}$ compared to 100 Wm$^{-2}$ in the same area in the latent heat and control run (Fig. 16a-d). The contribution of drier soil led to the surface temperatures increasing to 80°F across much of NE which was similar to the vapor-only run by 21 UTC on 06 July 2011. By reducing the soil moisture in the soil moisture and vapor-only runs, the drier ground allowed for increased surface heating. The sensible heat flux resulted in temperatures reaching the 85°F compared to ~ 70°F in the control run, latent heat, and deep cloud runs at 21 UTC on 6 July 2011 (Fig. 16a-d). This led to the cold pool being reduced in size to roughly 80 km in diameter by 21 UTC (Fig. 17a-d).

This is the only case in which the deep cloud run had a higher score than the vapor-only and latent heat runs. The deep cloud run had similar scores to soil moisture run in all categories. The high score corresponds with a 47% increase in 0.01 inch per hour rain rate and a 111% increase in the 0.5 inch rainfall. Sensible heat flux changed at the hour prior to initiation in the sensitivity runs that removed radiation effects due to clouds were higher (250-300 W m$^{-2}$) across most of NE than the control run and latent heat run (100 W m$^{-2}$; Fig. 16a-d). In this case, the area where spurious precipitation fell earlier did not record any
precipitation in the 21-06 UTC timeframe in the deep cloud run. The cold pool did have a negative effect on precipitation falling in western NE centered of LBF as evidence by the 240km diameter 0 inch precipitation hole (Fig. 15d) over SW NE. However, equally as important was that the deep cloud run did not alter the microphysics which in the latent heat and vapor-only runs induced a cap with CIN values over KS−50 J kg$^{-1}$ higher than the soil moisture and deep cloud runs at 21 UTC on 06 July 2011. The soil moisture run in the domain total rainfall had higher totals compared to the deep cloud run across NE and KS (3% and 10% domain wise at 0.01in and 0.5 in) which may have led to the slightly higher ETS scores between the two. In the soil moisture run there was a 90 km diameter area of 0 inch rainfall compared to a 240 km diameter of 0 inch rainfall in the area of spurious precipitation in the deep cloud run. This is the area that had the largest impact in terms of ETS scores between the soil moisture and deep cloud runs. The deep cloud run was affected by the spurious precipitation cold pool as evident by the sounding taken at 21 UTC (41.5, -101.3) (Fig. 18 a-d). The vapor-only run had steep near dry adiabatic lapse from the surface to 750 mb and an uncapped environment compared to the deep cloud run which was largely dry and capped as evidenced in the soundings.

As the forecast evolved, it became apparent how cold pools and cloud cover caused by spurious precipitation influenced the evolution of this MCS. Both aspects contributed to the sensitivity runs having a reduction in domain total rainfall related to an MCS. The sensitivity run that had the greatest impact on MCS development was the soil moisture run. Factor separation in this case had a 38% increase in the 0.01inch threshold and 41% increase in 0.5 inch threshold in domain total volume for the soil moisture run. ETS scores were the
highest with every single category being 1 standard deviation over the mean scores. In comparison, the vapor-only run at the 0.05 and 0.5 thresholds had an ETS one standard deviation over the mean but successfully depicted precipitation where spurious precipitation occurred. The latent heat run fell susceptible to the cloud cover that was produced by the spurious precipitation prior to the 12 UTC timeframe and caused significant errors resulting in low ETS and an 11% reduction at 0.01 in threshold, and a 20% reduction in rainfall at the 0.5 inch threshold in factor separation.

3.2.3 Case 3 0000 UTC 07 August 2011 to 0600 UTC 08 August 2011

i. Synopsis

Synoptically, zonal flow across the northern third of the CONUS existed with a broad ridge centered over northern TX at 00 UTC on 07 August 2011. By 12 UTC cells initiated on the nose of an 850 mb WAA advection region in SW NE (Fig. 19a). By 16 UTC, these cells merged into an E-W MCS line from central KS into NE KS. At 21 UTC, the outflow produced by these storms had pushed into central KS and initiated cells (Fig. 19b). At the same time, convection fired in SW KS along the front range of the Rockies. At 03 UTC, CI occurred on the MCS of interest in northern KS where an E-W line of storms that stretched across the eastern 2/3 of the state from 02-06 UTC (Fig. 19c-d).

ii. Run comparison

At 12 UTC, the control member initiated spurious convection in north central KS and propagated the convection E-SE into east central KS from 12 UTC through 18 UTC on 07 August 2011. The spurious precipitation was falling at the heaviest rate at 15 UTC on 07
August 2011 (Fig. 20a-b). The convection fired falsely along the north side of a stationary front at 12 UTC. The control member showed an outflow boundary produced by the spurious precipitation at 15 UTC (Fig.20c). By 22 UTC, convection initiated west of Wichita, KS as weak scattered convection in line with observations due to an upslope flow. At the same time, convection initiated in SD and moved E-SE through 05 UTC due to the same mechanism. The error in the main MCS resulted in scattered precipitation across central-south central Kansas instead of along a warm front in north central KS like in observations by 03 UTC on 08 August 2011 (Fig. 21a-b). The control run again had the lowest ETS in this case than any of the runs due to the spurious precipitation.

The domain total precipitation indicated why the vapor-only and latent heat runs had the highest ETS (Table 2). The vapor-only and latent heat runs were the only runs that produced precipitation in north central Kansas compared to the control, deep cloud, and soil moisture runs (Fig. 22a-d). The result was the vapor-only and latent heat runs having an increase of 20 and 12% respectively in the 0.5 inch threshold of domain total rainfall. The vapor-only and latent heat runs had a 157% and 98% increase in the 0.5 inch/hour threshold in rainrates compared to the control run as well. The precipitation in north central Kansas was the only significant change in domain total precipitation outside of the north central KS precipitation that occurred in the vapor-only and latent heat runs. The vapor-only and latent heat runs produced the precipitation in north central KS due to the elimination of the outflow boundary spawned by the spurious precipitation earlier that had progressed into south central Kansas. The outflow boundary initiated convection in ICT in the control, soil moisture, and
deep cloud runs and due to cold pool production from this precipitation, northern Kansas
remained precipitation free from 19-06 UTC on 07-08 August 2011.

The vapor-only run had the greatest impact on improving ETS with significant
increases in scores in every category compared to the control and other sensitivity runs. The
cold pools that had been produced in the control run, soil moisture, and deep cloud runs at 12
UTC in northern Kansas were nonexistent by 15 UTC. In the vapor-only and latent heat runs,
surface temperatures in this area climbed to 82 F compared to 75 F in the control run
occurred by 19 UTC on 07 August 2011. The result was ample instability (4000 J kg$^{-1}$) and
little CIN (~25 J kg$^{-1}$) in the vapor-only and latent heat runs by 02 UTC on 08 August 2011.
In comparison, the control and soil moisture runs had ample instability at similar values but a
more substantial cap (~125 J kg$^{-1}$) in northern Kansas. In this case, 02-06 UTC was a time in
which the vapor-only and latent heat runs differed greatly from the control, soil moisture, and
deep cloud runs. The vapor-only and latent heat runs were able to sustain convection in west
central Kansas from 02-06 UTC on 8 August 2011 where the other sensitivity runs failed to
do so. At 03 UTC as convection intensified collocated over where the vapor-only and latent
heat runs had the highest surface temperatures (~+5; Fig. 23a-d). The model sensitivity run
soundings taken at 02 UTC one hour prior on 08 August 2011 in central Kansas (38.57, -
99.2) indicated a possible explanation as to why convection never fully developed in this area
in the soil moisture and deep cloud runs (Fig. 24 a-d). A strong cap was only evident in the
soil moisture run due to the inversion at 800 mb. As a result, CIN values at (~125J kg$^{-1}$) were
the highest in the soil moisture run which may be a reason for why the soil moisture run had
no convection in the vicinity. The soundings also indicated that the latent heat and vapor-
only runs had noticeably drier profiles from 800-600 mb than the soil moisture and deep cloud runs and steeper 700-500 lapse rates near dry adiabatic than the soil moisture run. The deep cloud run had sufficient CAPE and CIN ($\sim +3000 \text{ J kg}^{-1}$, $25 \text{ J kg}^{-1}$) and steep 700-500 mb lapse rates to sustain convection but lacked a forcing mechanism to initiate convection.

This case was unique due to the fact that over 8 hours elapsed between the spurious precipitation impacting north central Kansas and the initiation of convection in that area making direct correlations more difficult. To complicate matters further, the ability to point directly to spurious precipitation being the cause of error was obscured by the observed precipitation that fell over northeast Kansas from 20-01 UTC on 07 August to 08 August. No sensitivity captured the observed rainfall which was another component that could have contributed to the production of a MCS in observations. RUC analysis failed to capture the initiation of the MCS until 2 hours after the observed which made using the sounding from the RUC as a direct comparison difficult.

One feature that pointed to spurious precipitation directly influencing the forecast of a simulated MCS was the cold pool and outflow boundary produced by the spurious precipitation in the control, deep cloud, and soil moisture runs. At 20 UTC on 07 August 2011, the stalled outflow boundary caused by spurious precipitation at 15 UTC on 07 August 2011 initiated convection over Wichita, KS. The restart period would have been extended to 22 UTC on 07 August 2011 to incorporate the precipitation that fell over Wichita, KS at 20 UTC, but observed convection formed at 23 UTC within 200 km which violated the experiments’ conditions. The convection produced a cold pool that stalled the lifting of the warm front into north central KS in the control run, soil moisture, and deep cloud runs.
(Fig. 2a-c). The latent heat and deep cloud runs had no such boundary causing the warm front and surface low to lift into north central KS by 02 UTC. In this case, an outflow boundary and cold pool produced by spurious precipitation led to the incorrect initiation of convection over Wichita, KS at 20 UTC in the deep cloud and soil moisture runs. This was the only noticeable difference as to why precipitation initiated in north central KS at 02 UTC and led to increased rain total volume, increased ETS, and increased rain rates in the vapor-only and latent heat runs.

### 3.3 False alarm MCSs

Four false alarm MCS cases were identified in the 2010 and 2011 spring experiment out of the 52 days of the experiment. Roughly 75 simulated convective systems (cases) progressed through the domain of the Plains states. Thus, 5% of all of these cases simulated by the ensemble, 5% of all MCS cases resulted in the production of a false alarm MCS. The domain of the spring experiment is given in Fig. 25.

An individual case was selected to highlight an example of a false alarm MCS. From 22-06 UTC on 24-25 May 2010, the state of NE recorded no precipitation in observations. A sounding from SPC sounding analysis taken at LBF at 00 UTC on the 24 May indicates a stout cap with (~212 J kg⁻¹) of CIN (not shown). The convective inhibition combined with the inversion located at 800 mb indicated a strong cap that kept the area rain free. At 00 UTC 19 of the 24 members of the CAPS ensemble suite produced a false MCS that propagated across south central NE from 00-05 UTC on 25 May 2010. Fig. 26 shows one member’s reflectivity output taken at 05 UTC of the FAR MCS that was observed. The 19 members
varied on the specific site of initiation with most members (~15) initiating in the central grid box (Fig.27). Consistently higher CAPE and lower CIN values were associated with members that produced a false alarm MCS than non-members. No other thermodynamic parameter exhibited a distinct pattern between false alarm and non-false alarm members. The other three cases of false alarm MCSs indicated no pattern between higher CAPE and low CIN values or any other thermodynamic variables investigated among the members. One possible explanation for the lack of a pattern in the high CAPE/low CIN is the time of year each case occurred. One case that occurred on 29 April 2010 had CAPE values that were on average significantly lower (~1000 or less J kg\(^{-1}\)) compared to the end of May/June cases (~3000 J kg\(^{-1}\)). In the 29 April 2010 case, large scale forcing was much stronger than the May and June cases and may have played a larger role than thermodynamic variables in determining if a false alarm MCS occurred. In the early spring, large scale vertical motion is stronger than in the early summer months. The early summer months are more dominated by higher values of CAPE that account for the weaker large scale forcing to occur.

On average, 19-21 members falsely produced a MCS making it difficult to determine if certain perturbations were more likely to produce accurate results. The lack of a pattern among thermodynamic variables indicated that other factors must play a role in why a false alarm MCS occurs in the WRF members. The investigation of false alarm MCSs with the Hazardous Weather Testbed Dataset became a challenge due to restrictions on computing resources. Surface data from the WRF members alone were barely able to be stored with current resources. Due to the limited number of cases, restrictions on computing space, and
lack of any pattern amongst thermodynamic variables, the expansion of this experiment to include other variables was halted.
Chapter 4: Conclusions

Four sensitivity runs and a control run were performed using a 4km horizontal grid spacing version of the WRF-ARW model across ten cases to investigate spurious precipitation’s role in the upscale evolution of MCSs across the United States. A subjective detailed analysis was performed on three particular cases that showed the direct impact of spurious precipitation on MCS evolution. A quantitative analysis was performed to evaluate the sensitivity runs accuracy in convection involving ETS, bias, and factor separation techniques.

The vapor-only run which eliminated all aspects of spurious precipitation improved ETS the most, followed by the soil moisture and latent heat runs. The elimination of increased soil moisture had the greatest impact in improving ETS across all cases at low thresholds. Latent heating and soil moisture had the highest ETS scores at higher thresholds although none by a significant amount with this sample size. The sample size was small which advises caution when determining the statistical significance of the ETS scores. What was important qualitatively is the induction of soil moisture through precipitation is as important as cold pool formations in improving ETS in these three cases. The highest biases out of all the runs did occur in the soil moisture run compared to the latent heat run which had the lowest bias other than the vapor-only run. Thus qualitatively, the cold pool formation had the greatest impact on improving ETS and bias scores. Radiation effects due to clouds caused by spurious precipitation had less of an effect than the soil moisture and latent heat runs in terms of ETS.
Using the factor separation analysis, it was found that all sensitivity runs increased rain total volume compared to the control run. Rain rates offered some insight into how each sensitivity run affected the forecast against a base run (the control run). The soil moisture run had the highest increase in the 0.01 inch per hour rain rate. The vapor-only run had the highest increase in the 0.5 inch per hour rain rate followed by the soil moisture and latent heat runs. The highest increased rain rates at the 0.5 inch/hour and increased rain volume at 0.5 inches were found in the vapor-only and latent heat runs. Combined with the ETS scores and low biases, it is reasonably assumed that these two runs had the highest impact to the control run. The cold pool caused by spurious precipitation is the leading cause to deficiencies in the control run and is what led to the control runs low ETS, high bias, and decreased rainfall totals/rain rates at all thresholds.

This spurious precipitation study focused on several cases and demonstrated the complex interactions that can lead to spatial errors associated with convective initiation and morphology. Fields such as surface temperature, mean sea level pressure and dew point show how slight variations can alter convective initiation in a large nonlinear way. There is great importance on future work in convective initiation, particularly in the resolving of small scale features both surface based and upper level shortwaves. Improvements in cloud microphysics, PBL schemes, and integration of observations are all necessary to improve forecast accuracy in the model. Particular focus in the future should be in finding ways to improve cold pool propagation from MCSs in the model. Four of the ten cases failed to accurately produce convection in the 0-18 hour forecast which resulted in poorly placed cold pools that led to MCS CI errors in the 21-30 hour forecast periods. Improvements in the
computing power to be able to run at higher resolutions (less than 1km) integrating observational data at a rate more frequent than 24 hours are critical.

A brief investigation was done into comparing microphysics and PBL schemes to one another when a false alarm MCS occurred. In only one case during the 2010 and 2011 did any surface based parameter indicate a correlation of the ability to produce a false alarm (FAR) MCS. It was found in one case that low CIN and high CAPE (~3500) one hour prior to the FAR MCS initialization indicated the occurrence in a model sensitivity of a false alarm MCS. The occurrence of a FAR MCS was rare in the experiment. Four cases out of 75 MCSs observed were FAR MCSs. When a FAR MCS was identified, an average of 2/22 members failed to produce a FAR MCS and two members varied amongst the members indicating no pattern.

It appears that sensitivity of WRF model rainfall forecasts where spurious precipitation impacted the production of a MCS was dependent upon the production of cold pools. Cold pool production confirms the theory as being the leading cause to forecast deficiencies when spurious rainfall occurs. If MCS rainfall and rain rate prediction is to improve, the reduction of spurious precipitation’s formation and cold pool strength must be investigated. The land surface model interaction proved to have as great an impact on MCS forecasts in this experiment as the cold pool contribution from the microphysics scheme, especially in the 06 July 2011 case. This finding confirms with previous studies that investigated land surface model interaction (Chen et al., 2001; Sutton et al., 2004). Knowledge of these sensitivities respective contribution to where spurious rainfall occurs can
allow for improvements to the initialization of rapid refresh models and their respective MCS rainfall forecasts.

ACKNOWLEDGEMENTS

I would like to thank my co-advisers William Gallus and Moti Segal for their guidance in this work, Adam Clark of NSSL for his assistance in gathering the NSSL WRF and CAPs datasets, Chris Karstens and Justin Schultz of CIMMS, Daryl Herzmann of Iowa State, and Luke Madaus of the University of Washington for their help in Python coding, WRF troubleshooting, and general computer support. This work was supported by NSF grant ATM-0848200, with funds from the American Recovery and Reinvestment Act of 2009.

Although not directly involved in the study, I would also like to thank my parents for their generous love and support as well as my friends while I spent time working on the thesis. This work in no way, shape, or form would have been able to be accomplished without them.
Table 1: Configurations for each individual member with the 2010-2011 NOAA Hazardous Weather Testbed Spring experiment CAPS ensemble. NAMa and NAMf refer to the 12-km NAM analysis and forecast, respectively. ARPSa refers to ARPS 3DVAR and cloud analysis. Members in orange are used in producing probabilistic ensemble products (Kong et al., 2011)

<table>
<thead>
<tr>
<th>member</th>
<th>IC</th>
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<th>microphysics</th>
<th>LSM</th>
<th>PBL</th>
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<td>RRTM</td>
<td>Dudhia</td>
<td>RUC</td>
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<tr>
<td>nmm_m5</td>
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<td>21Z SREF em-n1</td>
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<td>Chou/Suarez</td>
<td>TKE</td>
<td>3D TKE</td>
<td>2-layer</td>
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Table 2: Equitable Threat Scores for all three case studies from the time the restart period ended within the model through the remainder of the run. The domains used to calculate ETS were determined on a case by case basis of where an MCS occurred that was impacted by spurious precipitation. Thresholds are in in. Values highlighted in **bold** represent ETS scores with values more than 1 standard deviation over the median. VP stands for the vapor-only run, LH for the latent heat run, SM for the soil moisture run, and SH for deep cloud run.

<table>
<thead>
<tr>
<th></th>
<th>Sensitivity</th>
<th>0.01 in</th>
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<th>0.25 in</th>
<th>0.5 in</th>
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<td>20100803</td>
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<td>0.076</td>
<td>0.03</td>
<td>0.009</td>
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<tr>
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<td>0.142</td>
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<td></td>
<td>LH</td>
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Table 3: As in Table 1 but for ETSs averaged over all cases.

<table>
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Table 4: Bias values for all three case studies from the time the restart period ended within the model through the remainder of the run. Areas were calculated and determined on a case by case basis of where an MCS occurred that was impacted by spurious precipitation. Thresholds are in in. Values highlighted in **bold** represent ETS scores with 1 standard deviation value over the median. VP stands for the vapor-only run, LH for the latent heat run, SM for the soil moisture run, and SH for deep cloud run.

<table>
<thead>
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<th>0.5 in</th>
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<td>1.94</td>
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<tr>
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Table 5: Same as Table 4 but averaged over all cases

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Table 6: Factor Separation values for changes (expressed as a percentage) in system rain volume for each case due to the processes tested in sensitivity runs (f₁ represents rainfall in the vapor-only run, f₂ represents rainfall in the latent heat run, f₃ represents rainfall in the soil moisture run, f₄ represents rainfall in the deep cloud run) averaged over all points where rainfall exceeded specific thresholds (0.01 in or 0.5 in.). f₀ represents rainfall in the control run. f₂₃, f₂₄, and f₃₄ represent the corresponding synergistic terms. Case 1 refers to the 03 August 2010, Case 2 06 July 2011, Case 3 07 August 2011. Average refers to the mean value over all 3 cases.

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<td>-2</td>
<td>-2</td>
<td>-2</td>
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<td>(f₃-f₀)/f₀ (%)</td>
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<td>(f₂-f₀)/f₀ (%)</td>
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<td>(f₃-f₀)/f₀ (%)</td>
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<td>11</td>
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<tr>
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<td>(f₄-f₀)/f₀ (%)</td>
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<td>6</td>
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<td>4</td>
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<tr>
<td></td>
<td>f₂₃/f₀ (%)</td>
<td>-1</td>
<td>-9</td>
<td>36</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>f₂₄/f₀ (%)</td>
<td>1</td>
<td>-11</td>
<td>16</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>f₃₄/f₀ (%)</td>
<td>-4</td>
<td>-10</td>
<td>46</td>
<td>11</td>
</tr>
</tbody>
</table>
Table 7: Same as Table 6 but with hourly rain rates.

<table>
<thead>
<tr>
<th>Threshold</th>
<th>Sensitivity</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>0.01</strong></td>
<td>(f₁-f₀)/f₀ (%)</td>
<td>21</td>
<td>10</td>
<td>18</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>(f₂-f₀)/f₀ (%)</td>
<td>-7</td>
<td>0</td>
<td>-4</td>
<td>-4</td>
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<tr>
<td></td>
<td>(f₃-f₀)/f₀ (%)</td>
<td>40</td>
<td>58</td>
<td>1</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>(f₄-f₀)/f₀ (%)</td>
<td>0</td>
<td>47</td>
<td>1</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>f₂₃/f₀ (%)</td>
<td>27</td>
<td>-13</td>
<td>38</td>
<td>17</td>
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<tr>
<td></td>
<td>f₂₄/f₀ (%)</td>
<td>27</td>
<td>-28</td>
<td>29</td>
<td>9</td>
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<tr>
<td></td>
<td>f₃₄/f₀ (%)</td>
<td>-13</td>
<td>-43</td>
<td>49</td>
<td>2</td>
</tr>
<tr>
<td><strong>0.5</strong></td>
<td>(f₁-f₀)/f₀ (%)</td>
<td>20</td>
<td>80</td>
<td>158</td>
<td>86</td>
</tr>
<tr>
<td></td>
<td>(f₂-f₀)/f₀ (%)</td>
<td>-11</td>
<td>58</td>
<td>99</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td>(f₃-f₀)/f₀ (%)</td>
<td>47</td>
<td>119</td>
<td>-20</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td>(f₄-f₀)/f₀ (%)</td>
<td>5</td>
<td>111</td>
<td>10</td>
<td>42</td>
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<tr>
<td></td>
<td>f₂₃/f₀ (%)</td>
<td>28</td>
<td>-40</td>
<td>122</td>
<td>37</td>
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<tr>
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<td>f₂₄/f₀ (%)</td>
<td>33</td>
<td>-16</td>
<td>75</td>
<td>31</td>
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<td>f₃₄/f₀ (%)</td>
<td>-6</td>
<td>-132</td>
<td>144</td>
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</table>
Figure 1. Example of the grid that was used in the false alarm MCS cases. The blue, green, and black boxes represents the spread of where all members initiated the false alarm MCS.
Figure 2. Average (a) ETS scores and (b) biases for all cases. Control represents the control run, VP represents vapor-only, LH represents the latent heat, SM represents the soil moisture, and SH represents the deep cloud run.
Figure 3. Observed reflectivity from 03-04 August 2010 (UTC) at (a) 1200, (b) 1800, (c) 0200, and (d) 0600.
Figure 4. (a) Surface plot taken from the control WRF member at 01 UTC on 4 August 2010 with temperature (colored, °F), 10 meter wind (wind barbs, half staff 5 knots, full staff 10 knots), and mean sea level pressure (contoured, mb). (b) Surface plot taken from the 20 km RUC at 01 UTC on 4 August 2010 with temperature (colored, °F), 10 meter wind (wind barbs, half-staff 5 knots, full staff 10 knots), and mean sea level pressure (contoured, mb).
Figure 5. (a) Surface plot taken from the control WRF member at 03 UTC on 4 August 2010 with temperature (colored, F), 10 meter wind (wind barbs, half staff 5 knots, full staff 10 knots), and mean sea level pressure (contoured, mb). (b) 850 mb wind speed (colored, knots), 850 mb heights (contoured, dm), and 850 mb wind barbs (half staff 5 knots, full staff 10 knots, 50 flag).
Figure 6. (a) Precipitation (colored, in) in the hour ending at 06 UTC 4 August 2010 taken from the WRF control run member. b) Observed precipitation over 24 hours from 12-12 UTC on 03-04 August 2010 (water.weather.gov).
Figure 7. Surface plots taken at 21 UTC on 03 August 2010 with temperature (colored, °F), 10 meter wind (wind barbs, half staff 5 knots, full staff 10 knots), and mean sea level pressure (contoured, mb) for the (a) vapor-only, (b) latent heat, (c) soil moisture, and (d) deep cloud runs.
Figure 8. Precipitation (colored, in) taken from 19 UTC on 03 August 2010 to 06 UTC on 04 August 2010 for the (a) control and (b) vapor-only runs.
Figure 9. Model derived surface based Convective Available Potential Energy (CAPE, colored, J kg$^{-1}$) taken at 23 UTC on 03 August 2010 for the (a) vapor-only, (b) latent heat, (c) soil moisture, and (d) deep cloud runs.
Figure 10. Precipitation (colored, in) totals taken from 19 UTC on 03 August 2010 to 06 UTC on 04 August 2010 for the a) vapor-only, b) latent heat, c) soil moisture, and d) deep cloud runs.
Figure 11. Sounding analysis taken at 23 UTC on 03 August 2010 with temperature (solid red, Celsius), dew point (solid green, Celsius), dry adiabats (dashed red, °C km⁻¹), pressure (solid black, mb), isotherms (dashed red above 0 °C, dashed blue below 0 °C), wind barbs (black, knots), surface temperature and surface dew point (black text, °F), and mean sea level pressure (black text, mb) plotted for the (a) vapor-only, (b) latent heat, (c) soil moisture, and (d) deep cloud runs.
Figure 12. Model derived LCL heights (colored, m) taken at 23 UTC on 03 August 2010 for
the a) vapor-only, b) latent heat, c) soil moisture, and d) deep cloud runs.
Figure 13. Observed reflectivity from 06-07 July 2011 (UTC) at (a) 1200, (b) 2200, (c) 0400, and (d) 0600.
Figure 14. (a) Precipitation (colored, in) at 12 UTC 6 July 2011 taken from the control WRF member. (b) Surface plot taken from the control WRF member at 12 UTC on 6 July 2011 with temperature (colored, F), 10 meter wind (wind barbs, half staff 5 knots, full staff 10 knots), and mean sea level pressure (contoured, mb).
Figure 15. Precipitation (colored, in) taken from 21 UTC on 06 July 2011 to 06 UTC on 07 July 2011 for the (a) vapor-only, (b) latent heat, (c) soil moisture, and (d) deep cloud runs.
Figure 16. Surface sensible heat flux (colored, W m$^{-2}$) at 21 UTC on 06 July 2011 for the (a) vapor-only, (b) latent heat, (c) soil moisture, and (d) deep cloud runs.
Figure 17. Surface plot taken from the WRF runs at 21 UTC on 6 July 2011 with temperature (colored, °F), 10 meter wind (wind barbs, half staff 5 knots, full staff 10 knots), and mean sea level pressure (contoured, mb) for the (a) vapor-only, (b) latent heat, (c) soil moisture, and (d) deep cloud runs.
Figure 18. Sounding analysis taken at 21 UTC on 06 July 2011 from model sensitivities with temperature (solid red, Celsius), dew point (solid green, Celsius), dry adiabats (dashed red, °C km⁻¹), pressure (solid black, mb), isotherms (dashed red above 0°C, dashed blue below 0°C), wind barbs (black, knots), surface temperature and surface dew point (black text, °F), and mean sea level pressure (black text, MSLB, mb) for the (a) vapor-only, (b) latent heat, (c) soil moisture, (d) deep cloud runs.
Figure 19. Observed reflectivity taken from 07-08 August 2011 (UTC) at (a) 1200, (b) 2100, (c) 0300, and (d) 0600.
Figure 20. (a) Precipitation (colored, in) taken from the control WRF member at 15 UTC on 7 August 2011. (b) Surface plot taken from the control WRF member at 15 UTC on 7 August 2011 with temperature (colored, F), 10 meter wind (wind barbs, half staff 5 knots, full staff 10 knots), and mean sea level pressure (contoured, every 2 mb). (c) 10 meter wind speed at 15 UTC on 7 August 2011 from the control WRF member, wind speed (colored, knots), wind barbs (half staff 5 knots, full staff 10 knots), and mean sea level pressure (contoured, every 4 mb).
Figure 21. Precipitation (colored, in) taken at 03 UTC on 08 August 2011 for (a) observations (http://www.srh.noaa.gov/ridge2/RFC_Precip/) and (b) control run.
Figure 22. Precipitation (colored, in) taken from 18 UTC on 07 August 2011 to 06 UTC on 08 August 2011 for the (a) vapor-only, (b) latent heat, (c) soil moisture, and (d) deep cloud runs.
Figure 23. Surface plot taken at 03 UTC on 08 August 2011 with temperature (colored, F), 10 meter wind (wind barbs, half staff 5 knots, full staff 10 knots), and mean sea level pressure (contoured, mb) for the (a) the vapor-only, (b) latent heat, (c) soil moisture and (d) deep cloud runs.
Figure 24. Sounding analysis taken at 02 UTC on 08 August 2011 with temperature (solid red, Celsius), dew point (solid green, Celsius), dry adiabats (dashed red, °C km⁻¹), pressure (solid black, mb), isotherms (dashed red above 0°C, dashed blue below 0°C), wind barbs (black, knots), surface temperature and surface dew point (black text, °F), and mean sea level pressure (black text, mb) for the (a) vapor-only, (b) latent heat, (c) soil moisture, and (d) deep cloud runs.
Figure 25: Domain used for the FAR MCS study using the NOAA Hazardous Weather Testbed spring experiment dataset.
Figure 26. Reflectivity (a) simulated at ground level reflectivity in the control member of the ARW WRF (s4cn_arw) at 05 UTC on 22 May and b) Observed reflectivity taken at 05 UTC on 22 May 2010.
Figure 27: 500m CIN (J kg$^{-1}$) and surface based CAPE (SBCAPE, J kg$^{-1}$) of the CAPS 2010 NOAA hazardous weather spring experiment in the area of initiation of a false alarm MCS (red, false alarm; blue, no false alarm). Values are averaged over the grid box in which members initiated convection at 2200 UTC on 24 May 2010.
REFERENCES


Duda, J.D, Gallus, W.A., and Segal, M. 2010: WRF model skill of MCSs as a function of large-scale forcing at 3km resolution.


