Revisiting the 1976 Jordan Iowa F5 Tornado: A Case of Subtle Forcing with Extreme Sensitivity of WRF Simulations to Initial Conditions

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1. Introduction

The development of reanalysis datasets in recent years is allowing for fine grid simulations of important historical weather events, with the possibility of enhanced understanding of mechanisms that played a role in these events. Some examples include the April 1974 Super outbreak of tornadoes (Locatelli et al. 2002), and a series of F5 Iowa tornado events (Jungbluth 2008).

The 13 June 1976 Jordan Iowa F5 tornado event was unique in several aspects, and is a prime candidate for retrospective simulation. The primary tornado itself was extremely intense, described by Ted Fujita at the time as the most intense he had ever studied. In addition, the primary cyclonic tornado was accompanied during an unusually long 25 minute period by an anticyclonically-rotating F3 tornado that traveled along a parallel path just a few miles away (Brown and Knupp 1980). Both tornadoes took unusual cycloidal paths with a very sharp change in direction about three quarters of the way into their life cycles, from movements primarily northward to movements east or east-southeast. The time of occurrence, just after 1500 LDT, was rather early for tornado events in Iowa. Finally, and of most interest in the present study, triggering mechanisms for the storm were not obvious (Brown and Knupp 1980), and synoptic forcing appeared to be weak, although thermodynamic instability was extremely high with unusually strong winds aloft for such an unstable environment.

In the present study, high resolution Weather Research and Forecasting (WRF) model simulations are performed for the Jordan event using NNRP (NCAR-NCEP Reanalysis Project) data for initialization and lateral boundary conditions to determine how well such a subtly-forced event can be simulated. In addition, sensitivity tests are run to gain insight into the triggering mechanism for the central Iowa storms

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2. Data and Methodology

The WRF model version 3.2 was run using three domains: an inner domain having 4 km grid spacing centered over Iowa, with outer nests having 16 and 64 km grid spacing. The 16 km nest used a domain covering roughly three quarters of the continental United States, with the 64 km nest covering the entire continental United States and surrounding regions. Simulations were initialized at 12 UTC 13 June 1976 using NNRP (Kalnay et al. 1996) output available on a 2.5 x 2.5 degree grid, and were then integrated for 18 hours. The model used the Thompson microphysical scheme (Thompson et al. 2008) with a bug fix later implemented in version 3.3 of WRF, with the YSU PBL scheme (Hong et al. 2006), RRTM longwave and Dudhia shortwave radiation, Kain-Fritsch convective parameterization on the outer two domains, and no convective parameterization on the 4 km grid. Sensitivity tests were performed using the Ferrier, WSM-6, and Morrison double-moment microphysical schemes. In addition, many tests were performed that altered initial soil moisture, and several initialized tropospheric variables through layers of varying depth.

3. Overview of Event

The Jordan Iowa case is discussed in detail in Brown and Knupp (1980) and only a cursory discussion is provided here. An active weather pattern was present in the Midwest June 12-14 1976, and severe thunderstorms hit many areas of Iowa during the afternoon and evening of June 12 as a cold front moved southward into the state. Hail as large as baseballs was common over much of Iowa, with up to 5-8 inch rainfall in the west-central part of the state. Several tornadoes also occurred, focused in the region just southwest, west, and north of Des Moines. These storms may have been important in that they would have increased soil moisture in parts of the state, possibly affecting the evolution of weather events the following day.

At 12 UTC 13 June, the cold front was lifting back northwards across the state of Iowa as a warm front, with much more humid air following (Fig. 1). Upper-level winds were strong, as seen in Fig. 2 (from Brown and Knupp, 1980). An estimated sounding valid at 19 UTC in the central part of the state (Brown and Knupp, 1980) revealed extreme instability, with a lifted index of -13 (Fig. 2). Dew points above 72 F were advancing northward by 18 UTC into the region where the tornado would soon develop (Fig. 3).

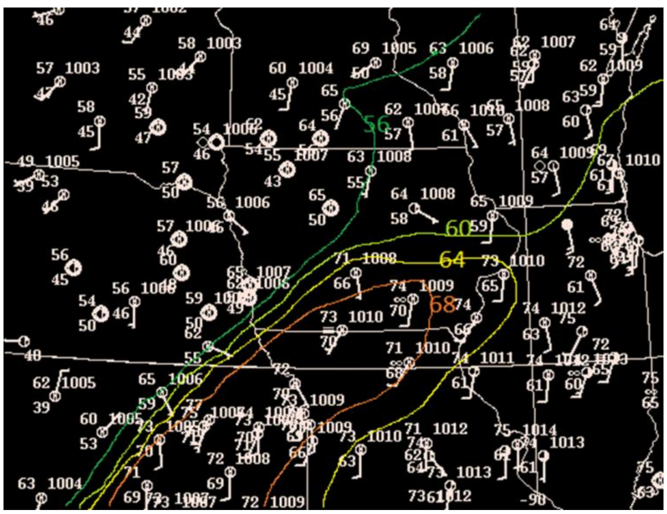

Figure 1: Surface observations valid at 12 UTC, with dew points above 56 F contoured every 4 F.

According to Brown and Knupp (1980), cumulus congestus had developed roughly 60 km west of Des Moines shortly before 19 UTC (14 LDT). Large hail that fell to the northwest of Des Moines around 20 UTC was the first severe weather reported. The first tornado followed shortly thereafter by 1956 UTC. The storm itself moved ENE to NE. The most intense of several tornadoes associated with this thunderstorm complex touched down at 2023 UTC and remained on the ground until 2111 UTC, receiving an F5 rating. It had a maximum damage path of 1.5 km and had a length of 34 km. Around this time, several severe storms had developed in a band from west of Omaha to near Waterloo. The storms merged into a severe squall line by 22 UTC which moved southeast from southwest and central Iowa and persisted for over 7 additional hours. Surface observations indicated strong cold pools associated with the storms, with dew points falling into the 50s F within the rain-cooled regions (Fig. 4).

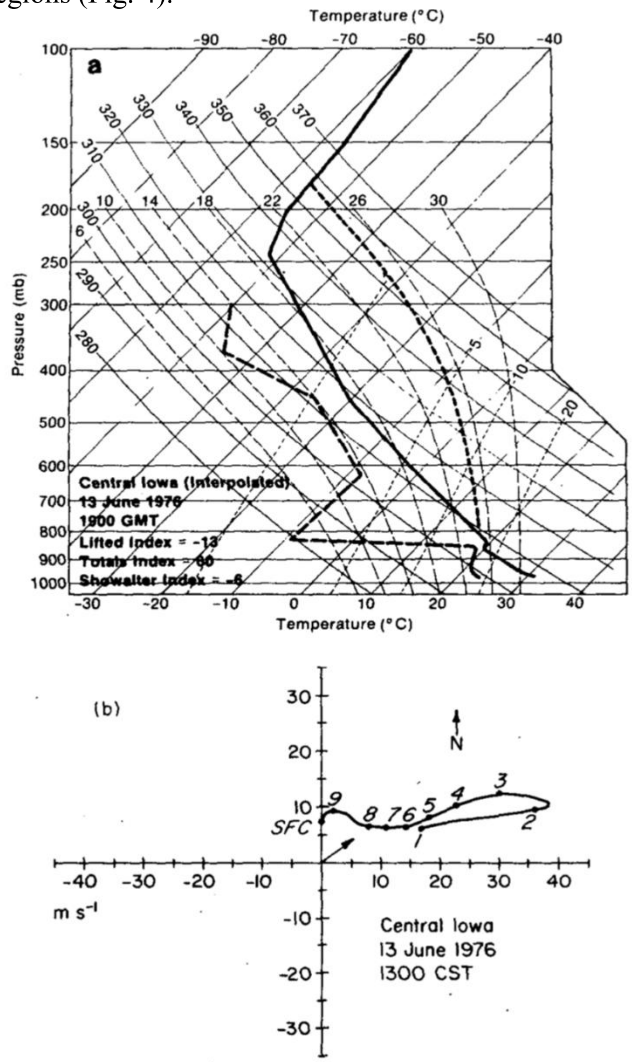

FIG. 2. Interpolated environmental conditions over central Iowa at 1900 GMT 13 June 1976, near the time of formation of the parent thunderstorm. (a) Skew T–log$P$ plot of temperature and dewpoint. The wet adiabat ($\theta_w = 24.8°C$) corresponding to mean conditions in the subcloud layer is shown. (b) Wind hodograph: The abscissa and ordinate are the u and v wind components, respectively, and the numbers in italics indicate pressure in hundreds of millibars; SFC indicates the surface wind. The small arrow emanating from the origin indicates the motion of the centroid of the high-reflectivity portion of the radar echo during the tornadic activity.

4. Control WRF Simulation

The control WRF run correctly showed a rapid northward push of moisture between 12 and 18 UTC, with dew points at 18 UTC (Fig. 5) exceeding 72 F in parts of southeastern Iowa, rather similar in value to observations (Fig. 3), but the surge was lagging in

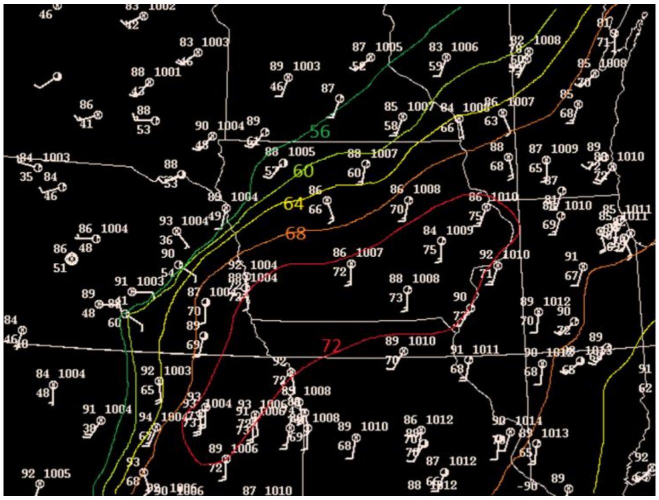

Figure 3: Surface analysis valid at 18 UTC with dew points above 56 F contoured every 4 F.

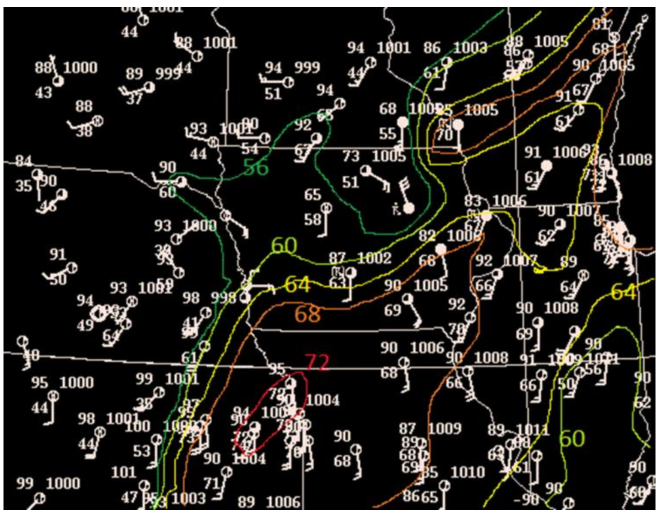

Figure 4: As in Fig. 3 but for 23 UTC.

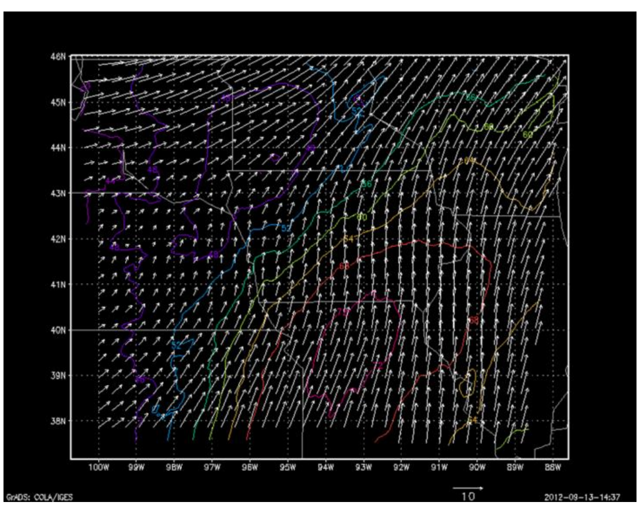

Figure 5: 18 UTC surface winds (vectors) and dew points (4F contour interval) in control WRF run.

intensity on its north and particularly northwest side. Whereas observations showed 72 F dew points all across SW Iowa into far SE Nebraska, the model run only showed 64 F dew points as far west as the southwest tip of Iowa, and was also about 3-4 F too dry in central Iowa where the tornado event would occur roughly 2 hours later. Surface winds were primarily from around 190 degrees in the model across much of Iowa. In much of the southern or southeastern half of Iowa, these winds matched observations well. However, the model missed some enhanced backing of winds that could be seen (Fig 3) in parts of east-central Nebraska and near Fort Dodge in northwestern Iowa along the retreating warm front (as implied by the dew point gradient). The enhanced backing would explain some of the higher moisture values observed in some parts of the region compared to the simulation, but the lack of significant differences between the model and the observations in the winds in southwestern Iowa and nearby regions makes it harder to determine why the simulation was so much drier in this region. The 60 F contour at 12 UTC in the model (not shown) was well-aligned with the observations (Fig. 1). However, the gradient was weaker in the model initialization with a 64 F dew point occurring at the northeast tip of KS, compared to observed values around 70 F. It is likely the weaker gradient is due to the coarseness of the NNRP output used to initialize the model.

A sounding from near Jordan at 19 UTC in the model simulation (Fig. 6) showed general agreement with that shown in Brown and Knupp (1980) (Fig. 2).

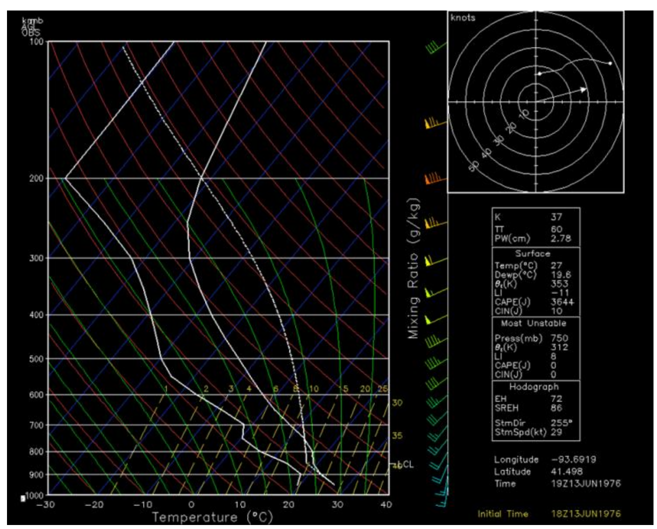

Figure 6: Control run sounding taken near Jordan at 19 UTC

Both soundings showed a small capping temperature inversion remaining in the 800-900 mb layer, although it appears to be a bit stronger in the simulation. Conditions are very warm and humid below the cap, although a bit drier in the model run compared to observations. Perhaps the biggest difference between the model run and the observations is in the strength of the dry layer associated with the cap. Relative humidity values were as low as 15% around 800 mb in the Brown and Knupp sounding (Fig. 2) but closer to 50% at 800 mb in the control run (Fig. 6). It appears the model did not have as much dry air nor was able to depict it as close to the ground as was observed. At least some of these differences are likely due to resolution issues in the NNRP output. Nonetheless, the hodographs do not show significant differences, with surface winds indicated as southerly at this time in this region in both the model and the observations.

In the control run, precipitation initiates in northern Missouri just south of the Iowa border between 19 and 20 UTC and several individual cells then track northeastward across the southeastern corner of Iowa through 00 UTC. A plot of total rainfall through 23 UTC (Fig. 7) shows that no storms develop in central Iowa.

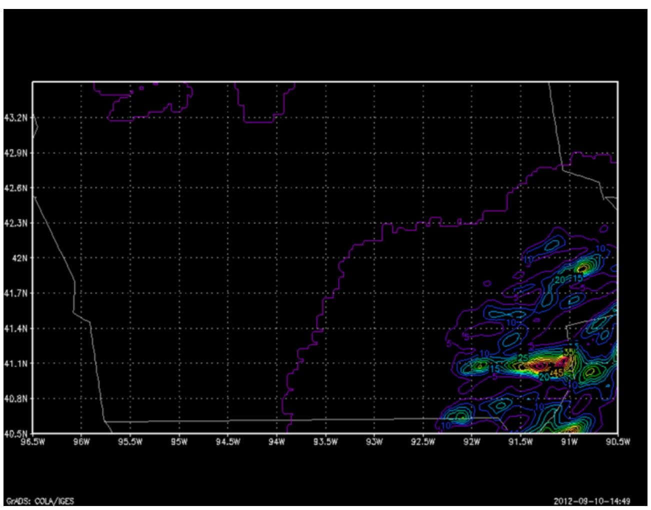

Figure 7: Accumulated rainfall from 18-23 UTC in control WRF run (5 mm contour interval).

5. Sensitivity Tests

Because the control run differed drastically in its depiction of precipitation for this event, despite the fact many other fields did not appear to have serious errors, a series of sensitivity tests was performed with the WRF model. These tests were generally designed based on possible errors in the initialization data.

Soil moisture was examined for this case and it was found that the NNRP depicted very uniform volumetric soil moisture values of around 0.25 in the top soil layer across the southwest half or so of Iowa, with slow increases northward to values over 0.3 in Minnesota (not shown). Other soil layers were not appreciably different. Because these values did not seem to match with the evidence that very heavy rains occurred the previous evening in much of SW and central Iowa, volumetric soil moisture was increased to over 0.4 in a portion of this region, with a buffer zone of 0.3 around it. Gradients were purposely kept sharp since thunderstorms often result in sharp gradients. In the simulation that used these adjusted soil moisture values, no precipitation developed in central Iowa and the run seemed relatively insensitive to the adjustment.

A different set of sensitivity tests was then performed making adjustments to thermodynamic conditions. As mentioned earlier, by 18 UTC, the control run was substantially too low with dew points on the west and northwest edge of the moisture surge, particularly in southwest Iowa. In one test, water vapor mixing ratios were increased by 20% in roughly the 850-925 mb layer at initialization time in a rectangular region 260 km wide over the central Plains from central NE to central IA and southward. It was felt that with southerly low-level flow veering to southwesterly aloft, this adjustment should increase the available moisture into Iowa during the afternoon hours. The adjustment did result in some minor increases in surface dew point that can be seen at 18 UTC in Fig. 8. Overall, the changes are most

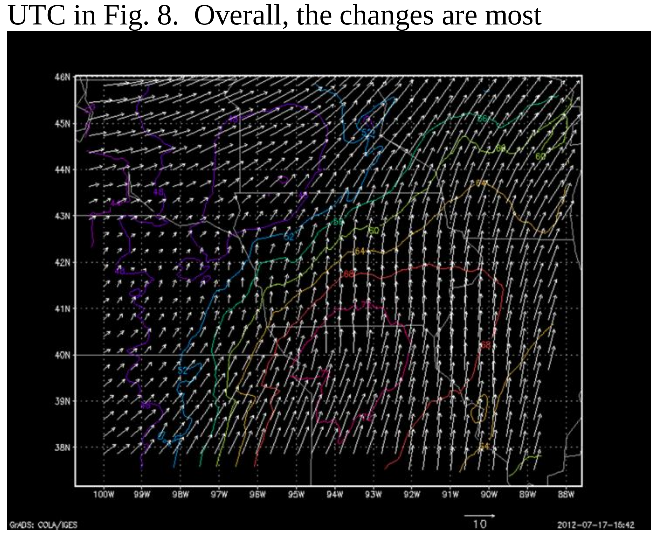

Figure 8: As in Fig. 5 except for run with 20% increase in lower tropospheric water vapor.

pronounced in parts of southwest Iowa where dew points increased by up to 3 F. Despite the relatively modest impacts at the surface, the increased moisture led to the formation of precipitation in parts of central IA that previously had remained dry (Fig. 9). Cells began forming in central Iowa about 75 km SW of Des Moines between 20 and 21 UTC and then tracked northeastward, with the axis of precipitation in the model being located only 25 km or so east from the Jordan area, with the closest approach of any cell around 22 UTC, a delay of about 90 minutes from the observed event.

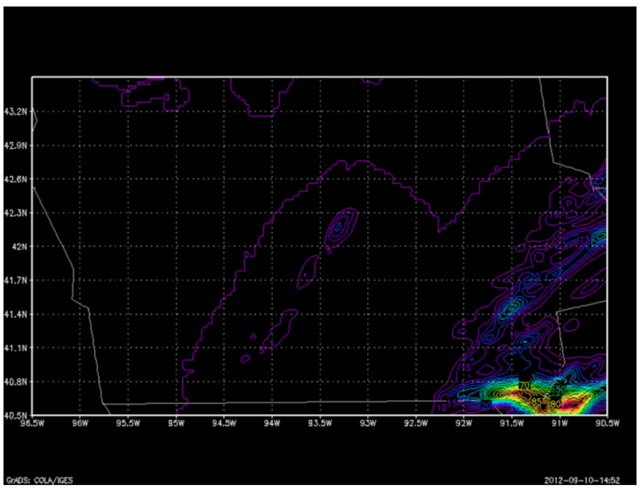

Figure 9: As in Fig. 7 except for the run with 20% increase in lower tropospheric water vapor.

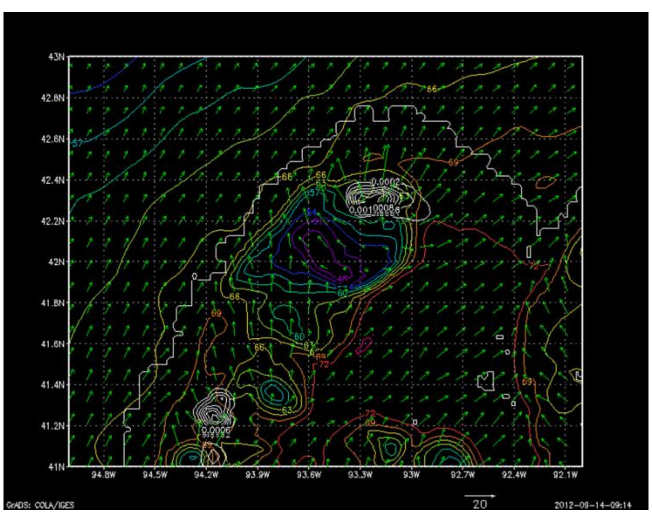

Figure 10: Surface dew points (colored with contours every 3 F), rainwater mixing ratio (white every .0002 g/g) and winds at 23 UTC.

One interesting aspect of the storms that formed in central Iowa in the model run was the intensity of the cold pools. Fig. 10 shows surface dew points, rain water mixing ratios, and winds at 23 UTC, revealing that the strongest cell, producing the heaviest rain amounts in Fig. 9, was associated with dew points that dropped below 48 F. Observations (Fig. 4) supported unusually low dew points in the cold pools, with some suggestion in northcentral Iowa of dew points in the lower 50s. In the model run, even very light showers (producing less than 5 mm of total rainfall) dropped dew points below 60 F, from ambient values above 72 F. The wind field and rainwater mixing ratios at this time imply outflow-dominated storms, with strong divergence, no hint of circulation in the lower troposphere, and little evidence of supercellular organization. Thus, although this moisture adjustment did result in storms in roughly the correct region, the model run did not appear to capture the type of storm that led to the tornadoes. It is possible the 4 km grid spacing was too coarse to show this. However, other simulations run for different tornadic cases using this 4 km configuration (not shown) did depict circulations and pendants in the rainwater field, implying 4 km should be sufficient to at least imply some supercellular structure.

Further tests were performed with other adjustments to water vapor amounts. Interestingly, in a test where the increase was only 10% in vapor, no real changes happened from the control run. Also, when vapor was increased another 10% beyond the original 20% increase, all central Iowa precipitation vanished. In that run, it appeared the even more moist conditions fueled a stronger MCS in southeastern Iowa that ended up suppressing convection in central Iowa. In addition, when the initial moistened area was made about 50% narrower, storms vanished in central IA. Also, when the layer of moistening was made shallower and closer to the ground (below 925 mb), and also deeper (extended up to 700 mb), the band of precipitation in central Iowa disappeared. Because soundings in central Iowa in the control run (Fig. 6) indicated that the model was not dry enough near and above the capping inversion, some additional tests were performed where not only was the vapor increased below about 850 mb but drying was enhanced in the 100 mb deep layer above that level. In all tests where further drying was introduced, precipitation did not develop in central Iowa. These various tests show that the formation of any storms in central Iowa was extremely sensitive to low-level moisture.

The final set of sensitivity tests concentrated on the intensity of the shortwave trough moving across the central Plains. The control run had failed to produce a region of southeasterly surface winds near the front, and may have had the flow veering a little too much in southwestern Iowa. An insufficiently strong shortwave in the NNRP data might explain both the lack of backing in surface winds as the disturbance approached Iowa during the afternoon, and also the insufficient moisture return to the northwest. It seems plausible that the relatively coarse 2.5 x 2.5 degree grid spacing of the NNRP data might result in smoothing of the wave and a failure to capture its full intensity. The lack of a sufficiently strong shortwave trough and the resulting impact on shear conceivably might also explain the failure of the run that increased vapor by 20% to depict supercell characteristics in the storms that did form in central Iowa.

To investigate the impact of the shortwave trough, the temperature, height, and u and v components of the wind were adjusted in a roughly 800 x 600 km region at initialization time in the western High Plains (adjustments made in the middle nest). The adjustments were loosely based on the hypsometric equation and an assumption of geostrophic wind balance. Heights were reduced up to 20 m in the center of the adjustment region from 500 mb upward, winds increased by up to 10 ms^{-1}, and temperatures decreased in the 500-850 mb layer, with maximum cooling of 1.8 C at 740 mb.

When the shortwave was intensified from the control run, changes in the simulation were as expected, with a small increase in the amount of backing at low levels (not shown). The u component decreased by less than 1 ms^{-1} at the surface with larger changes aloft. However, the changes did not lead to any precipitation in central Iowa. Once again, the 20% vapor increase adjustment was needed before the simulation produced any rain in central Iowa. In this particular run where both adjustments were made, the storms initiated in a slightly different location from that found in the original 20% vapor increase run, but precipitation was still produced much closer to central Iowa than without the vapor adjustment. Of perhaps most interest, the precipitation field in this test implied some supercell characteristics. Accumulated rainfall and the 21 and 22 UTC positions of cells based on surface rainwater mixing ratios for both the run having increased vapor but the control shortwave strength (Fig. 11) and the increase in vapor and the intensified shortwave trough (Fig. 12) show these differences, with evidence of a storm split and both rightward and leftward deviant motion in east-central Iowa in the run where shear was enhanced (Fig. 12). The storm split occurred about 70 km east-southeast from Jordan. Winds near the storm (not shown), however, did not depict a circulation, and the rainwater fields did not clearly evidence any type of pendant.

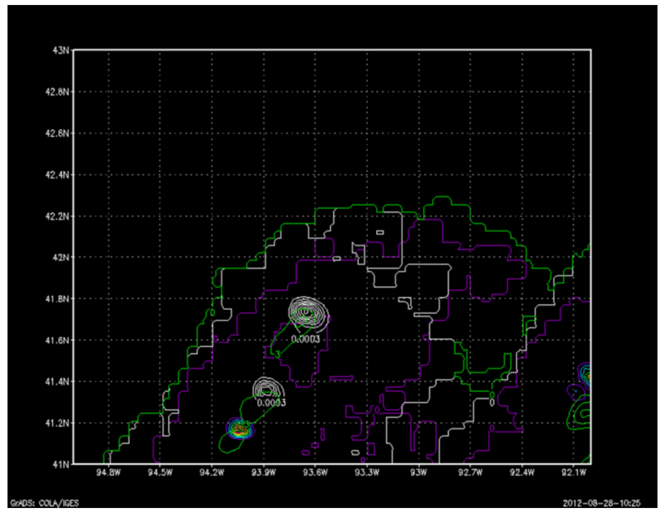

Figure 11: Accumulated rainfall during 18-22 UTC (green with 3 mm contours), surface rainwater mixing ratio at 21 UTC (multicolored contours) and at 22 UTC (white contours) for the run with a 20% increase in lower tropospheric vapor.

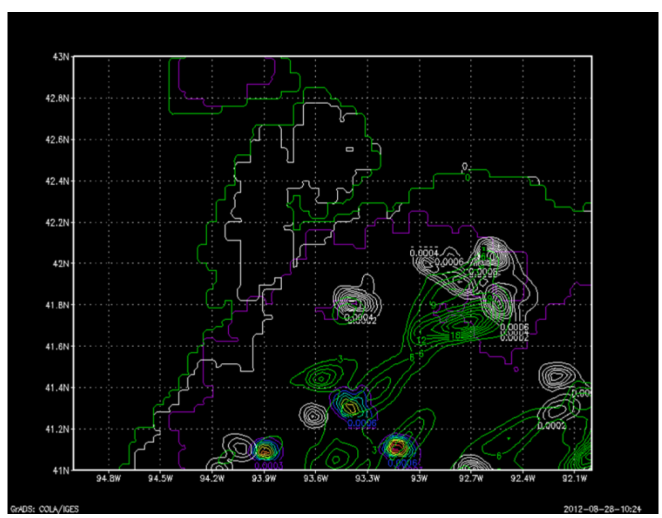

Figure 12: As in Fig. 11 but for model run with both a 20% increase in vapor and an intensified upper-level shortwave trough.

6. Summary and Conclusions

The subtly-forced F5 Jordan Iowa tornado event from 13 June 1976 has been simulated using NNRP output for initialization and lateral boundary conditions in WRF runs using a 4 km grid inner nest. The control run for this event failed to produce any rainfall in central Iowa, despite correctly depicting the broader-scale features present on this day, including a rapid northward surge of moisture behind a warm front, extreme instability, and strong flow aloft. A few key features were identified in the initialization and early hours of the simulation which did differ more noticeably from observations. These differences included a soil moisture field that did not reflect very heavy rainfall occurring the previous evening, a lag in how fast high moisture values returned northward into southwestern Iowa, and a failure to show a small area of enhanced backing resulting in southeasterly surface winds in parts of east-central Nebraska and northwestern Iowa.

The differences noted above were used to create several sensitivity tests. Alterations in soil moisture were not found to affect the simulation. Variations in lower tropospheric water vapor exerted extreme sensitivity on precipitation in central Iowa. A run that used an increase of 20% in water vapor in the 925-850 mb layer resulted in storm formation very close in both space and time to the actual Jordan event. Other alterations that included both more or less moistening, and also intensified drying just above this layer to better resemble an estimated sounding from Brown and Knupp (1980) for this event, caused the precipitation to disappear from central Iowa. These tests imply extreme sensitivity to moisture for this subtly-forced event.

Other tests used an intensified shortwave trough. Although some positive impacts occurred in near-surface winds to better resemble observations with increased backing, precipitation still failed to develop in central Iowa. The 20% increase in vapor was needed once again to initiate central Iowa convection. The increased shear in this test resulted in at least one storm split with deviant leftward and rightward motions, implying more supercell characteristics than in the run without the intensified shortwave. However, low-level circulations did not reflect any mesocyclones, and mixing ratios of hydrometeors likewise did not hint at supercell structure. Although it is possible the 4 km grid spacing was insufficient to allow these features to form, other runs performed for other tornado events did show some of these other supercell characteristics, implying their absence in the Jordan case is likely not just a consequence of coarse resolution.

This study suggests that numerical model forecasts for some potentially violent tornado events will be difficult, even with convection-allowing grid spacing. The extreme sensitivity found here to moisture implies that even small errors in initialized moisture, or an inability to resolve small-scale features with the current observational network, will hamper efforts to accurately predict some severe storms. In many ways, the Jordan Iowa event is similar to the May 3 1999 Oklahoma outbreak where although the general environmental conditions were ideal for tornadic storms with extreme instability and strong wind shear, a pronounced lifting mechanism at the surface to trigger storms in a forecastable specific location was lacking.

The study also raises some questions about the storm-scale processes that allowed strong tornadoes to occur in this region on this day. Both observations and the model runs imply extremely intense cold pools with dew points falling well down into the 50s F, and even into the 40s F in the model runs. It has been increasingly accepted that cold air within rear flank downdrafts is detrimental to the formation of strong, long-lived tornadoes. The unusual cycloidal tracks of the Jordan Iowa tornado pair on this day have been attributed to the influence of a cold pool. Questions remain about how such long-lived tornadoes were able to form when cold pools were so strong. It is possible that extreme heterogeneity existed over very small scales in central Iowa on this day, such that conditions near the mesoscyclone were favorable for strong tornadogenesis, with cold air kept just far enough away so as to not interfere with tornado formation, even though the tornadoes themselves would later be deflected in their paths by the intensity of the cold pools.

7. Acknowledgments

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8. References

Brown, J. M., and K. R. Knupp, 1980: The Iowa cyclonic-anticyclonic tornado pair and its parent thunderstorm. *Mon. Wea. Rev*., **108**, 1626-1646.

Jungbluth, K., 2008: Re-creation of historic Iowa EF-5 tornado environments using high-resolution workstation WRF output initialized with NCEP Reanalysis grids. *24th Conf. on Sev. Local Storms*, Savannah, GA, Amer. Meteor. Soc., 16A.2.

Kain, J. S., S. J. Weiss, D. R. Bright, M. E. Baldwin, J. J. Levit, G. W. Carbin, C. S. Schwartz, M. L. Weisman, K. K. Droegemeier, D. B. Weber, and K. W. Thomas, 2008: Some practical considerations regarding horizontal resolution in the first generation of operational convection-allowing NWP. *Wea. Forecasting*, **23**, 931-950.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-year Reanalysis Project. *Bull. Amer. Meteor. Soc*., **77**, 437-471.

Locatelli, J. D., M. T. Stoelinga, and P. V. Hobbs, 2002: A new look at the super outbreak of tornadoes on 3-4 April 1974. *Mon. Wea. Rev*., **130**, 1633-1651.

Weisman, M. L., C. Evans, and L. Bosart, 2010: The 8 May 2009 “Super Derecho”: Analysis of a 3km WRF ARW real-time forecast. 25th Conf. on Severe Local Storms, Amer. Meteor. Soc, Denver, CO, 3B.4.