SENSITIVITY OF SIMULATED SUPERCELL THUNDERSTORMS TO HORIZONTAL GRID RESOLUTION

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ABSTRACT

The effects of horizontal grid spacing on idealized supercell simulations are investigated. Motivation for the study largely stems from the NOAA Warn-on-Forecast program, which envisions a paradigm shift from "warn-on-detection", where convective hazard warning decisions are primarily based on current observations, to a new paradigm where storm-scale numerical weather models play a greater role in generating forecasts and warnings. Unlike most previous grid spacing sensitivity studies, we focus on impacts to operationally significant features of supercells. Using the WRF-ARW model, idealized supercell simulations are run for 2 hours using three different environments and horizontal grid spacings of 333 m and 1, 2, 3, and 4 km. Given that forecasts under the Warn-on-Forecast paradigm will be initialized after several radar data assimilation cycles, we initialize our coarser simulations with filtered versions of the 333m "truth" simulation valid at t = 30 min. To isolate differences in storm evolution arising from finer-scale processes being unrepresented in the coarser simulations, the latter are compared to appropriately filtered versions of the truth simulations.

Results show that operationally significant errors in supercell evolution arise as the grid spacing is increased. Furthermore, the grid spacing sensitivity is strongly influenced by the environment. The 4 km grid spacing is too coarse to even qualitatively reproduce the supercell evolution, with the storm dying before the end of the simulation in one of the three environments. The improvement as grid spacing decreases from 2 to 1 km is greater than that from 3 to 2 km. Implications of this and other findings for Warn-on-Forecast are discussed.

1. INTRODUCTION

Supercell thunderstorms, the least common thunderstorm type, produce the majority of significant severe weather (1"+ diameter hail and EF-2+ tornadoes) in the United States. Consisting of a persistent, deep mesocyclone within its updraft (i.e. vertical vorticity ≥ 0.01 s^{-1}), supercells are long-lived storms with life times on the order of hours. Known for their complex dynamics, supercells are considerably difficult to forecast numerically. Consequently, under the current operational paradigm, supercell warnings and forecasts originate from radar and on-ground observations or imminent clues from the environment. In this "warn-on-detection" paradigm, numerical models are mainly used as indicators of gross storm behavior several hours in the future.

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NOAA, however, is aspiring to a paradigm shift to "Warn-on-Forecast" in which real-time storm-scale ensemble analysis and forecasting systems are employed for severe weather warnings. Given advances in computer technology, data assimilation systems and numerical models, the Warn-on-Forecast program holds the potential to reduce false alarms and increase operational lead times for tornadoes and other severe storm hazards (Stensrud et al. 2009; 2013).

One item of concern discussed briefly in Stensrud et al. (2009) is the issue of appropriate grid spacing in the ensemble forecast system. It is well established that discretization of the governing partial differential equations creates errors and sensitivities dependent on grid spacing. It is therefore important for operational purposes to explore model errors at various horizontal resolutions (Bryan and Morrison 2012). Of greatest concern is the degree to which the neglect of fine-scale storm processes on coarser grids produces errors in operationally important aspects of storm evolution, including the timing, location, and magnitude of severe storm hazards

(Weisman et al. 1997, Alderman & Droegemeier 2002, Bryan et al. 2003, Bryan & Morrison 2012). Not coincidentally, most of the work done on the topic of horizontal grid spacing sensitivity has been on squall lines due to their frequent occurrences (Weisman et al. 1997, Bryan and Morrison 2012). On the other hand, formal studies on supercell behavior sensitivity to horizontal grid spacing are relatively few, and in some cases have placed much of the emphasis on physical parameterization scheme like microphysics or turbulence (e.g. Fiori et al. 2010). Even fewer have focused on operationally significant features like low-level mesocyclone progression and precipitation statistics.

Weisman et al. (1997), an early study on the grid sensitivity of convection allowing models, investigated squall line horizontal grid sensitivity on a range from 1 to 12 km. They discovered a 4 km grid spacing was sufficient to reproduce mesoscale storm evolution and this standard has been used for modern numerical weather models. Per contra, Bryan et al. 2003, a study of squall lines, ascertained that a 100 m horizontal grid spacing was a fundamental requirement for deep moist convective turbulence resolution. Unfortunately, computational limitations will initially limit Warn-on-Forecast systems to grid spacings of 2-4km. This may not be a detrimental limitation as many previous works have demonstrated that supercell evolution can be reasonably reproduced using grid spacings much larger than 100 m (e.g., Noda & Niino 2003, A&D 2002, Verrelle et al. 2014, Fiori et al. 2010). Since high-resolution models run on large domain require enormous computational resources a question comes forth: What is the minimum grid spacing required for capturing operationally important aspects of supercell evolution? Doubling of horizontal resolution demands an order of magnitude inflation of computational resources. Thus, the information gained going from a coarse resolution to a finer one may not justify the added computational cost (Vandenburg et al. 2014, Weisman and Klemp 1982, Bryan et al. 2003, Weisman et al. 1997, Kain et al. 2008).

A seminal paper on the topic of simulated supercell sensitivity to horizontal grid resolution is Alderman & Droegemeier 2002. In the Alderman & Droegemeier (2002), mesocyclone cycling was completely dependent upon the horizontal grid spacing as Δx less than 1.5 km was necessary for cycling in the supercell simulation. It was also discovered that storm path, rainfall totals, vertical vorticity magnitude, and resolved kinetic energy were affected by varying spatial resolution. Using the same storm environment and a similar numerical setup Noda & Niino 2003 detailed a concept of “critical grid spacing”, where a minor change in Δx can significantly change storm evolution. In their case, the decline in updraft intensity as grid spacing was decreased from 2.6 to 2.5 km resulted in the demise of the supercell. Their explanation for this will be described in Section 3.1, as it is important for our results. Verrelle et al. 2014 identified 4 km grid spacing as existing within the “grey zone” of convection, that is, being too coarse to adequately resolve convective activity but too fine for existing convective parameterization schemes. One limitation of the aforementioned supercell grid spacing sensitivity studies is that they used a single storm environment. Our study, on the other hand, uses a variety of environments in order to examine impacts on grid spacing sensitivity.

The paper is outlined as follows. Section 2 discusses the numerical model and experimental setup. Section 3 describes the results, including details on storm development, low-level mesocyclone evolution, and precipitation statistics, and how they differ between storm environments. Finally, we summarize the conclusions, implications for Warn-On-Forecast, and plans for future work in Section 4.

2. EXPERIMENTAL DESIGN AND METHODS

For all experiments, the three dimensional, fully compressible, nonhydrostatic WRF-ARW model version 3.4.1 was used with typical idealized settings (e.g., horizontally homogeneous base state, no surface layer nor radiation physics). Our motivation for using the WRF model is its extensive use in the research and operational communities. To gain insight into the effects of storm environment on horizontal grid resolution sensitivities of simulated supercells, we used three different initialization soundings: an analytical

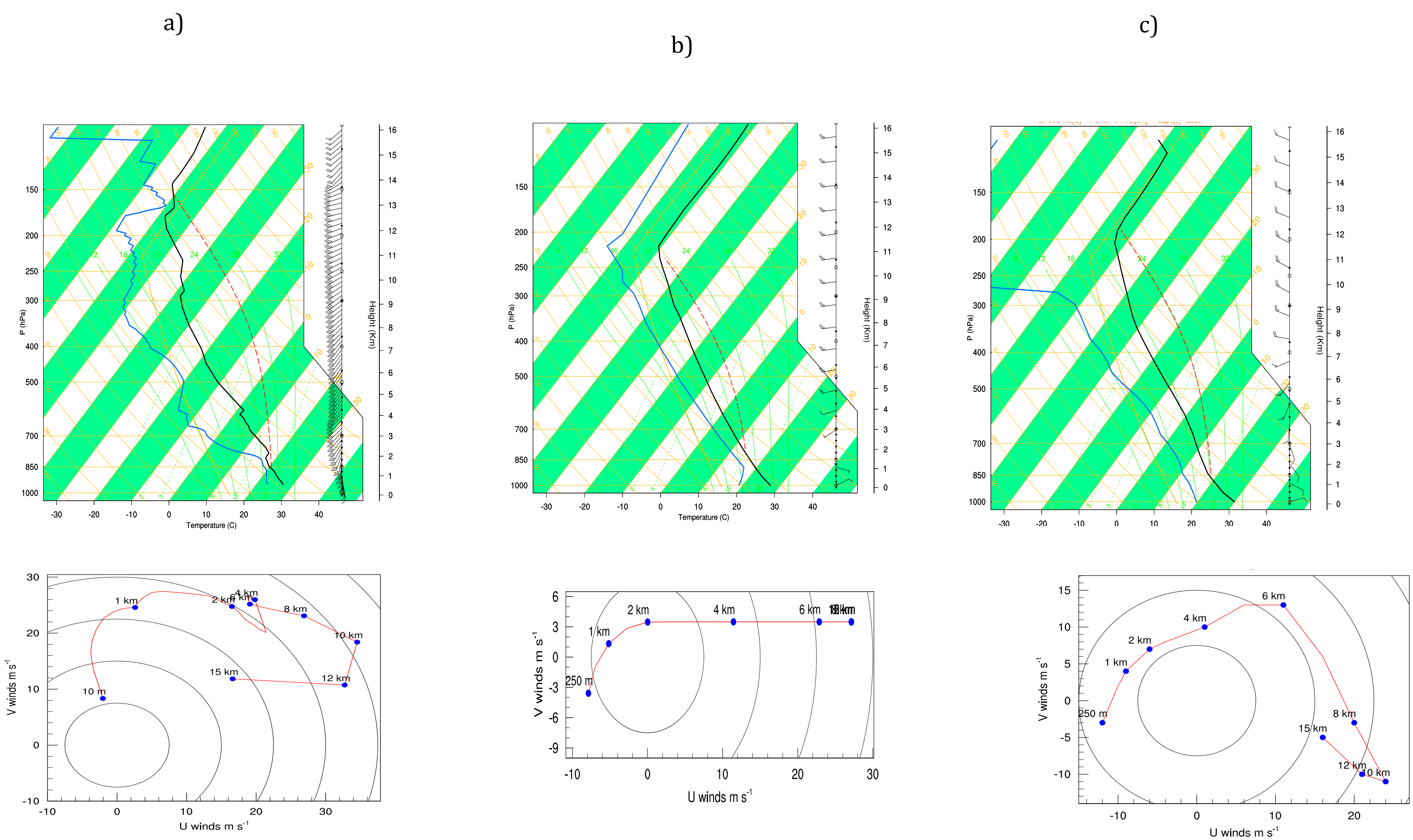


FIG.1a-b Thermodynamic profiles and hodographs for each of the environments. Starting from the left a) El Reno, b) WK82, and c) Del City sounding from Weisman and Klemp 1982 (hereafter, “WK82”), a slightly modified version of the 20 May 1977 Del City, OK sounding (Del City), and a RUC sounding valid near the 31 May 2013 supercell that produced the EF-5 El Reno, OK tornado (El Reno). For the horizontal grid spacings, 333 m represents the truth resolution and 1, 2, 3, and 4 km serve as the coarser resolutions. A stretched 20 km vertical grid was employed with the high resolution near the surface and coarser resolution towards the top of the domain (for exact spacings and other important model setup information see Table 1). The vertical grid was constant throughout all simulations. The horizontal domain size was varied from 150 to 300 km to account for varying storm motions. Similar to past studies, convective triggering in the truth simulations was the classic warm thermal perturbation often illustrated as a bubble (Alderman & Droegemeier 2002, Noda & Niino 2003, Rotunno & Klemp 1985, Fiori et al. 2010, Weisman & Klemp 1982, Verrelle et al. 2014, Cintineo & Stensrud 2013). The bubble had a 3K-temperature perturbation at the center with 10 km horizontal radius and a 1.5 km vertical radius dimensions.

The turbulence parameterization scheme used is the standard 3-dimensional 1.5 order TKE closure (Alderman & Droegemeier 2002, Cintineo & Stensrud 2013). The microphysical parameterization used was the Thompson graupel scheme since it is rather sophisticated for limited computational resources, including two-moments for the rain and cloud ice categories and has been used in operational convection-permitting models. It is understood that microphysics parameterization is far from a settled issue and we recognize a wide variety of schemes have been used in connection with supercell simulations, from Kessler warm rain (Alderman & Droegemeier 2002, Noda & Niino 2003) to mixed one-moment schemes (Cintineo & Stensrud 2013, Verrelle et al. 2014, Fiori et al. 2010). However, Bryan and Morrison (2012) found that even though certain results may be sensitive to the choice of microphysical parameterization scheme, the horizontal grid spacing had a greater effect. All truth simulations were ran out for 120 minutes with a time step of 1 second and a history output of 1 minute while coarser simulations were only ran out for 90 minutes (explained later).

Parameter	**Value**
Horizontal grid spacing	333m
Vertical grid spacing	110 m < dz < 550 m
Microphysical scheme	Thompson graupel scheme
Friction	Free-slip
Coriolis Parameter	0
Divergence Damping Coefficient	0.01
Time Integration	Runge-Kutta 3rd order
Top Boundaries	Rayleigh Damping for upper 5km
Damping Coefficient	0.03
Horizontal Momentum and Scalar Advection	5th order
Vertical Momentum and Scalar Advection	3rd order
Lateral Boundaries	Open Radiation
Turbulence Scheme	3-dimensional 1.5 order TKE closure
Filtering	Implicit tangent Filter
Total Run time	120 min
Grid Structure	Arakawa C grid
Time step	1.0 s
History Interval	1.0 minute

Table 1. Physical and computational parameters used in the truth simulations

Since the simulations are only run out for a short time, the Coriolis parameter has been set to zero similar to other storm scale numerical modeling studies.

To distinguish this study from other grid spacing sensitivity works and keeping in the theme of Warn-on-Forecast, all coarser simulation were initialized from filtered versions of the truth valid at t = 30 min and then the results were compared with the truth and truth filtered to a coarser resolution. The motivation for initializing from a nascent storm stems from the Warn-on-Forecast paradigm where a numerical model ensemble forecast would be run after several radar data volumes have been assimilated. Thus, convective initiation is not our focus, but rather how a coarser grid resolution handles convection once initiation has already occurred. In other studies on horizontal grid spacing, the analysis focused on the degree to which a coarse simulation is equivalent to a finer one, but our primary goal is to diagnose how larger scales, and especially operationally significant aspects of storm behavior, are effected by poor representation of finer-scale processes. We agree with Bryan et al. (2003) that doing so properly requires the finer-scale simulation to be filtered such that "equivalent structures" in the two simulations can be compared (Bryan et al. 2003). This was accomplished using the implicit tangent filter function (Raymond et al. 1988) to heavily damp wavelength less than or equal to twice the coarse grid spacing.

Under our simulation naming convention, the environment is follow by the grid spacing; for example DelCity_2km is the simulation initialized from the Del City environment and run with a 2 km horizontal grid spacing. Furthermore, some statistics from the three environments used in this study are presented in Table 2. A wide range of CAPE values exists: 1700 to 4600 J/kg. Moisture profiles for the three environments varying considerably, with the Del City sounding having the driest low levels and the WK82 sounding the moistest mid- to upper levels. The magnitude of the 0-6 km shear vector only varies by 5 m/s for the three environments, but differences in hodograph curvature are much more pronounced especially at low levels. Thus, while only three initialization soundings are used, they represent a broad sampling of the supercell environment parameter space.

	CAPE (J/kg)	0-6 km Shear Vector Magnitude (m/s)	0-3 km Storm Relative Helicity(m^2/s^2)
Del City	**2955**	**31**	**105.0**
El Reno	**4579**	**28**	**418.85**
WK82	**1740**	**25**	**6.98**

Table 2. Initial Environmental statistics

3. RESULTS

3.1 Overall Storm Development

Starting with a look at radar reflectivity for each environment at t = 60 and 120 min we can key on any distinction in storm development. As seen in Fig. 2a, WK82_333m at t = 60 min has already split into distinct left- and right-movers. Similarly, all of the coarser simulations have reproduced the mesocyclone splitting, but with intensity decreasing as the horizontal grid spacing increases. The ability of coarser resolutions to recreate the splitting process and qualitative storm development is similar to other studies using the same sounding (Weisman and Klemp 1982, Verrelle et al. 2014, and Fiori et al. 2010).

On the contrary, the DelCity_4km simulation at t = 60 min, as shown in Fig.3a, falls flat in a qualitative comparison with the truth simulation. The extent of higher reflectivity in the DelCity_4km suggests the absent of a hook echo structure, which is arguably evident in the DelCity_3km. Overall, the DelCity_4km storm is weaker and, as seen in Fig.3b, the right mover DelCity_4km dissipates before the end of the simulation. The improvement of DelCity_2km over DelCity_3km is greater than that of DelCity_1km over DelCity_2km. Nonetheless, other than the 4km, all the simulations have split into left- and right-movers with fairly good agreement, from an operational perspective at t=120 min. This is contrary to Noda & Niino 2003 where they found that the Del City environment was too weak to sustain storms with $\Delta x > 2.6$ km. However, their model was run with the Kessler warm rain microphysical parameterization scheme, which entails a substantial reduction in latent heat release.

Similar to DelCity_4km, ElReno_4km at t = 60 min is qualitatively different from the truth while the other simulations exhibit better correspondence (see Fig. 5a). At t = 120, there is a

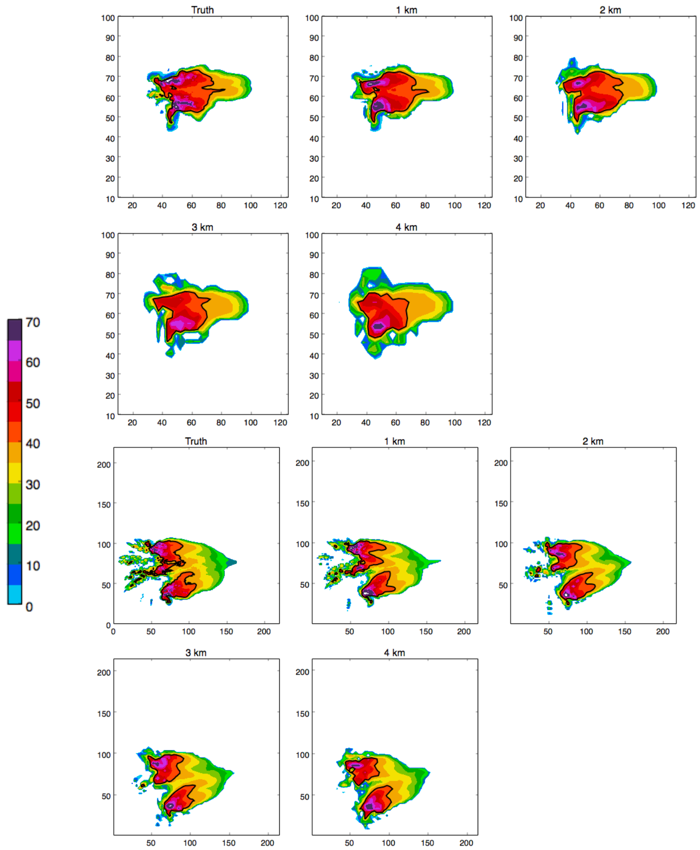


FIG. 2a-b Simulated Radar Reflectivity for WK82 environment at t= 60 min (top) and t = 120 min (bottom)

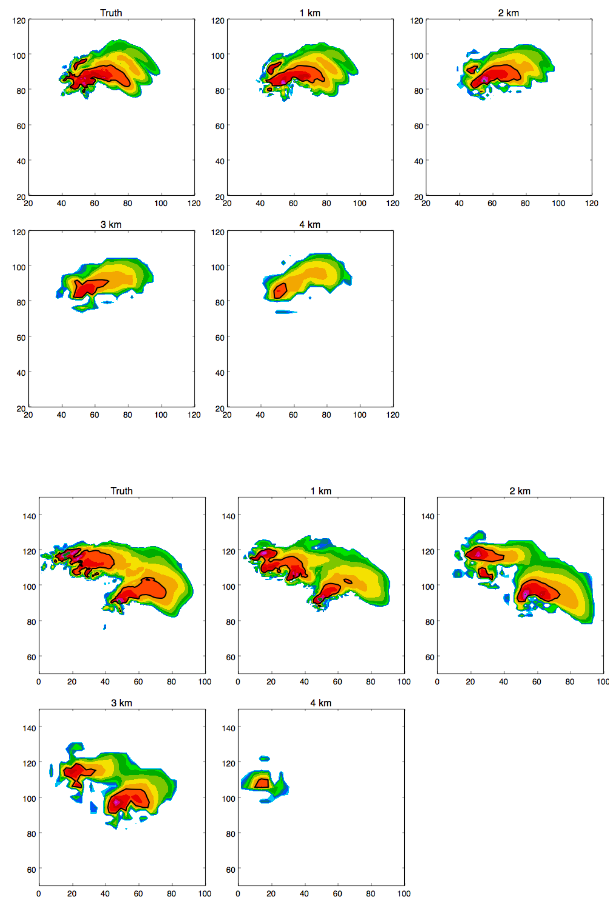


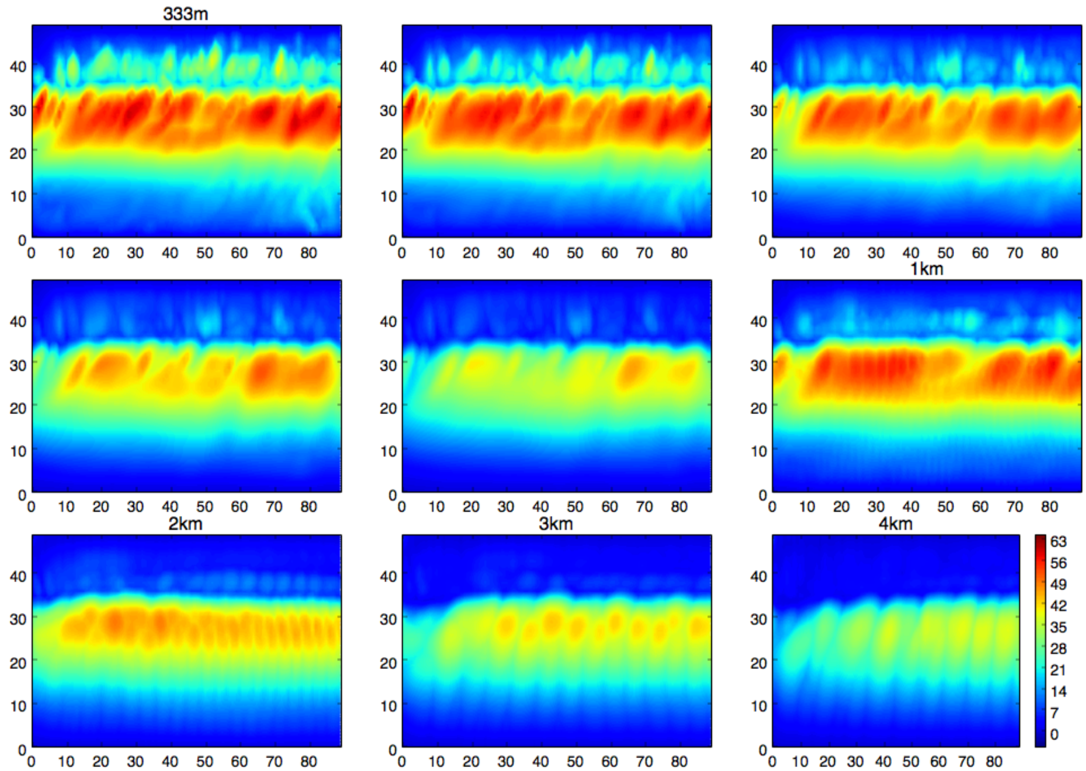
FIG. 3a-b Simulated Radar Reflectivity for Del City environment at t = 60 min (top) and t = 120 min (bottom)

strong resemblance between all the simulations, but two features stand out: the location of the ElReno_4km storm and hail core size. The ElReno_4km storm is significantly displaced significantly northwest of the other storms, which will be discussed further in Section 3.2. Moreover, the hail cores (i.e. $\geq 65\,\mathrm{dBz}$) in the ElReno_2km, ElReno_3km, and ElReno_4km are actually over-predicted, which will be discussed further in Section 3.3.

A significant topic in the discussion of numerical solutions sensitivity to grid spacing is the idea of grid convergence, which is where solutions do not vary much as smaller grid spacings are used. Many previous supercell grid spacing sensitivity studies have employed this concept (Alderman & Droegemeier 2002, Verrelle et al. 2014, Bryan et al. 2003, Fiori et al. 2010). In light of this, we also make frequent use of this concept in the discussion that follows. Quantitative analysis of the grid convergence of important variables is presented in Section 3.4.

Beginning with time height plots of vertical velocity for Del City and WK82 in Fig. 4 a-b we see a general increase as the horizontal grid spacing is decreased, which has been found in multiple studies (Verrelle et al. 2014, Fiori et al. 2010, Weisman et al. 1997, Alderman & Droegemeier 2002, Noda & Niino 2003). Remarkably, we can see that WK82_4km and WK82_333m filtered to 4km are quite similar whereas DelCity_4km after 30-40 minutes shows no evidence of the updraft present in DelCity_333m.

a)



b)

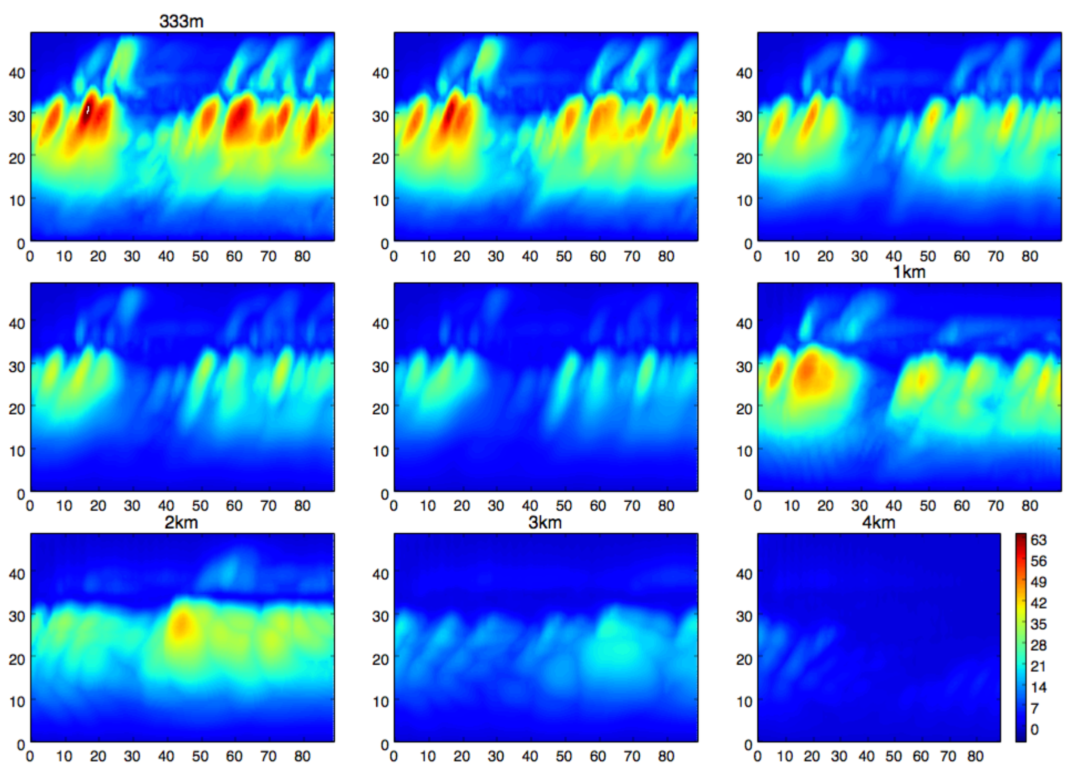


FIG.4a-b Time height plots for maximum vertical velocity for a) WK82 and b) Del City

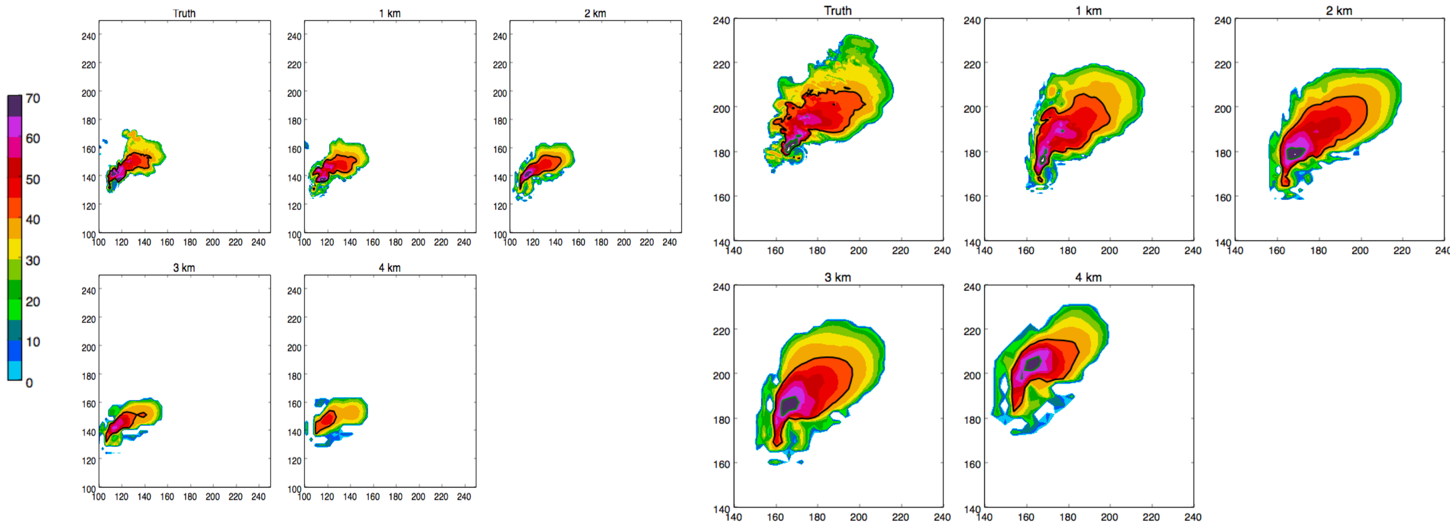


FIG. 5a - b Simulated Radar Reflectivity for El Reno environment at t = 60 min (left) and t = 120 min (right)

Before considering the cause of increasing maximum vertical velocity with increasing spatial resolution it is worth noting that the diameter of a supercell updraft is on the order of several km. Thus, the coarser simulations only marginally resolve the updrafts and force them to be too wide. Consequently, non-hydrostatic vertical pressure gradient forces are under-predicted. More generally, as grid spacing increases and the model transitions to a more hydrostatic structure, timescales artificially increase with horizontal wavelength and vertical motion scales more with horizontal wavelength (Weisman et al. 1997). These two effects result in under prediction of maximum vertical velocity and slower storm evolution. Another important impact of damping/removing finer scales is the decline of gradient magnitudes in cases where the gradient collapses to the finest resolvable scale (Alderman & Droegemeier 2002, Weisman et al. 1997, Noda & Niino 2003).

Given the postulates that coarser resolution under predicts maximum vertical velocity and gradient strength, one can understand the effects of dynamic pressure gradients on storm evolution and path. In this section it is pertinent to discuss a likely cause of the DelCity_4km dissipation, which involves an approximation of the dynamic vertical pressure perturbation force equation (Markowski and Richardson 2010).

$$-\frac{\partial p'_d}{\partial z} \propto \frac{\partial \zeta'^2}{2\partial z} - 2\frac{\partial}{\partial z}(\boldsymbol{S} \cdot \boldsymbol{\nabla_h w'}) \qquad (1)$$

$$\boldsymbol{S} = \left(\frac{\partial \bar{v}}{\partial z}, \frac{\partial \bar{u}}{\partial z}\right) \qquad (2)$$

This approach is similar to Noda & Niino 2003 and Rotunno & Klemp 1982, but it is reiterated for the readers not familiar with those works. In the nomenclature, the right most term in (1) is known as the linear dynamic forcing and it dictates the rightward propagation of supercells based on its contribution to vertical momentum from dynamic pressure perturbations. The environmental shear vector (2) in our idealized simulation is constant amongst all the Del City simulations (i.e. it is dictated by the horizontally homogeneous initial conditions), so the crucial component is the change in height of the horizontal gradient of the vertical velocity perturbation. Thus, the coarseness of 4km is weakening the dynamic forcing in the following equation and ultimately too weak to keep the storm alive.

$$\frac{dw}{dt} = -\frac{1}{\rho}\frac{\partial p'_d}{\partial z} + \left(-\frac{1}{\rho}\frac{\partial p'_b}{\partial z} + B\right) \qquad (3)$$

For the discussion of storm path, see the Low Level Mesocyclone Evolution and Path section.

3.2 Low Level Mesocyclone Evolution and Path

First recall that vertical vorticity being a gradient is grid dependent and from Alderman & Droegemeier 2002 we know that the magnitude will at least double every time the grid spacing is halved (but the general case of an *n* times increase due to a *1/n* decrease in grid spacing does not always hold true as neglecting finer scales produces larger-scale errors). In light of this, direct comparisons of simulations having different resolutions is less useful, which helps motivate our strategy of comparing coarser simulations to appropriately filtered versions of the truth.

A critical concern operationally for horizontal grid spacing is the ability of a model to exhibit cyclic mesocyclogenesis (Alderman et al. 1999, Alderman & Droegemeier 2002). It is important because tornadogenesis is not likely to occur during the mesocyclone occlusion process. Firstly, neither the El Reno_333m nor the WK82_333m exhibit cyclic mesocyclogenesis during the 120 min simulation, but DelCity_333m cycles once at t = 60 min. Comparing with Alderman & Droegemeier 2002, using the Del City environment and ice physics, they saw cycling beginning roughly at t = 108 min, which was the earliest cycling all of their experiments (this can be seen in their Fig. 2). For our experiments, we found that the DelCity_1km simulation was able to cycle once at roughly the same time as the truth simulation, but cycling was absent in DelCity_2km, DelCity_3km, and DelCity_4km. This is similar to results found in Alderman & Droegemeier (2002) (see Introduction).

For all three environments, the 1km grid resolution is the first of the coarser resolutions to exhibit strong temporal variability similar to that found in the 333m case. However, ElReno_1km is the only simulation to capture the low mesocyclone intensification. This is important to note as the ElReno_2km, ElReno_3km, and ElReno_4km, though in agreement with each other, show a completely different storm evolution than the ElReno_1km or ElReno_333m. ElReno_1km, however, produces a tornado-scale circulation, whereas ElReno_333m does not. This is a critical point as the high false alarm rate (~80 %) for tornado warnings is a major weakness of current severe storm operations.

There is also, however, a further point to be considered. As finer-scale processes are resolved they go on to affect larger scale evolution. If finer-scales processes were inessential than the evolution and magnitude of larger scale processes in a filtered finer resolution ought to match equivalent structures in a coarser resolution. With this is mind, we see that in Fig. 6c, the magnitude of the low level maximum vertical vorticity in the ElReno_4km is 50% lower than the ElReno_333m filtered to a 4km resolution. Thus, errors associated with the inability of the 4 km simulation to represent finer scales present in the 333 m simulation grow upscale to significantly contaminate scales resolvable on the 4 km grid.

One variable affected by the resolution of finer scale processes is the maximum temperature depression. Average maximum temperature depression is crucial since it is a diagnostic of cold pool intensity, which is a factor that affects low-level vertical vorticity generation. From Rotunno & Klemp 1985, baroclinic generation of horizontal vorticity due to the cold pool is tilted to form the low level mesocyclone. Thus, proper depiction of the cold pool is vital for reproducing storm and tornado evolution (Weisman et al. 1997, Rotunno and Klemp 1985, Verrelle et al. 2014).

The WK82 environment created the strongest cold pool, with the Del City not far behind, but the El Reno had the weakest by far. The cold pool intensity does increase as the horizontal grid resolution increases for all three environments However, the cold pool intensity drastically increases in ElReno_1km, which can be seen in the time height plots (not shown) and the convergence plots in Section 3.4. Thus, the strong development of the cold pool is the source of low-level mesocyclone development and intensification in ElReno_1km (see Fig. 6c).

Even though past studies have analyzed maximum vertical velocity at 5km AGL for storm path (Verrelle et al. 2014, Fiori et al. 2010), our study is focused on how grid resolution alters the path of the low level mesocyclone. Thus, for storm paths we analyzed the maximum vertical vorticity at 1.5 km AGL.

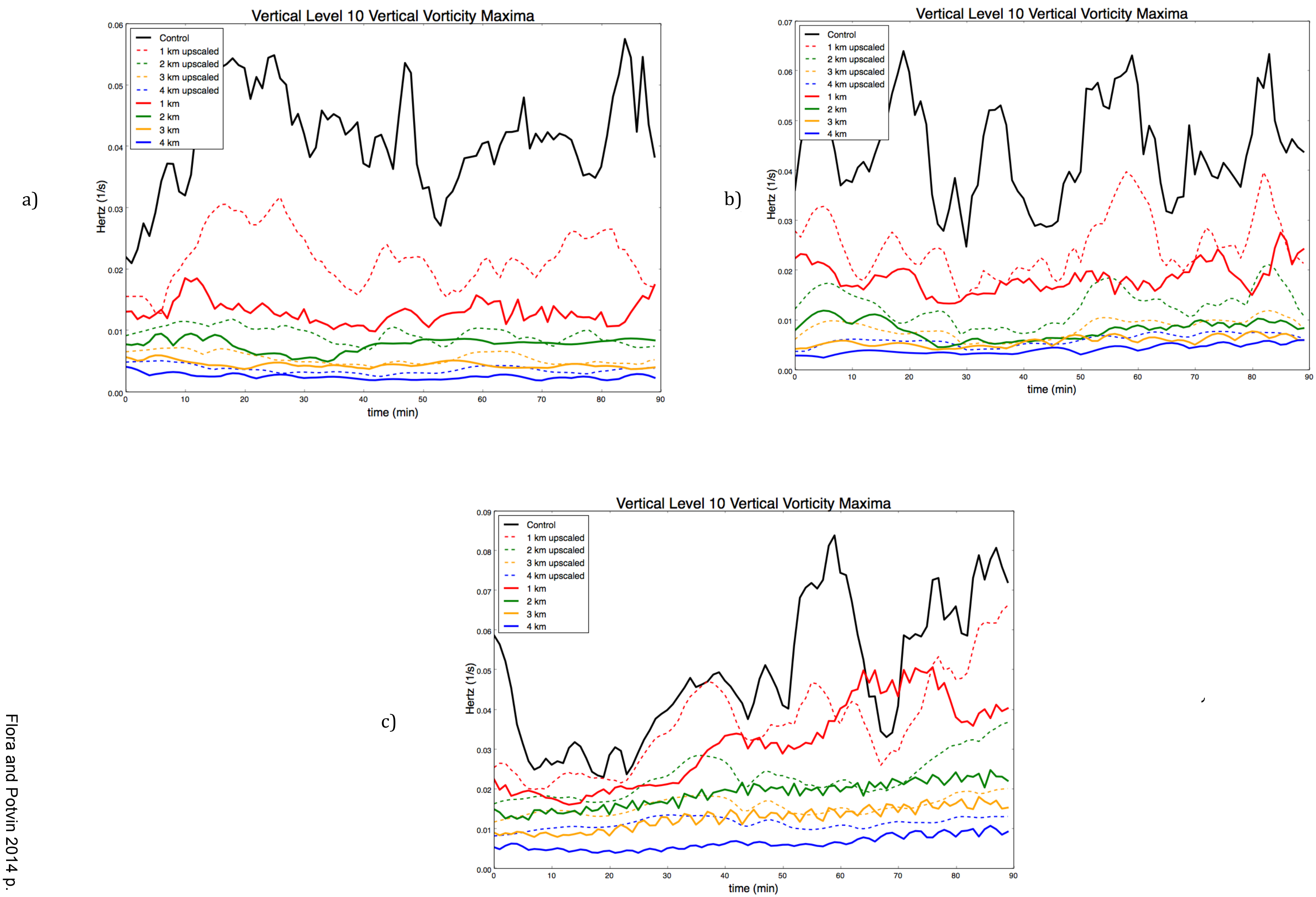
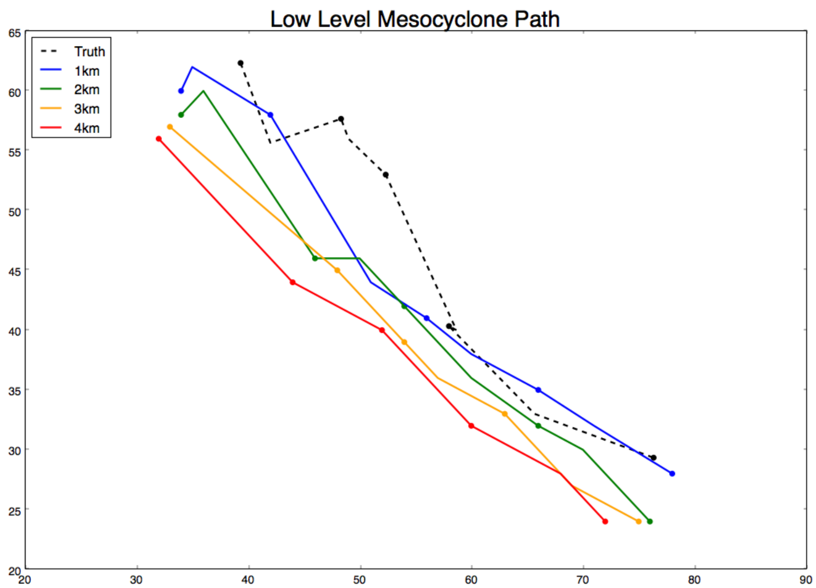


FIG. 6a-c Time series of maximum vertical vorticity at 1.5 km AGL for a) Del City b) WK82, and c) El Reno

In the process of sampling for initialization in the coarser resolution simulations it appears the maxima have shifted, which is why the storms in the WK82 storm path plot, as seen in Fig. 7a, start in separate locations. Even with that initial displacement the storm approximately end up in the same location at the end of the simulation. However, the paths of the WK82_3km and WK_4km right movers are similar to the ElReno_4km as in that they varied significantly from the truth

The Del City storm is a relatively slow moving storm with the right mover appearing rather static. In the 1-3 km cases the storms generally end up in the same location (not shown), but the 4km due to its dissipation is the outlier again. ElReno_4km is a clear outlier as it progresses further left than the other simulations (see Fig. 7b).

a)



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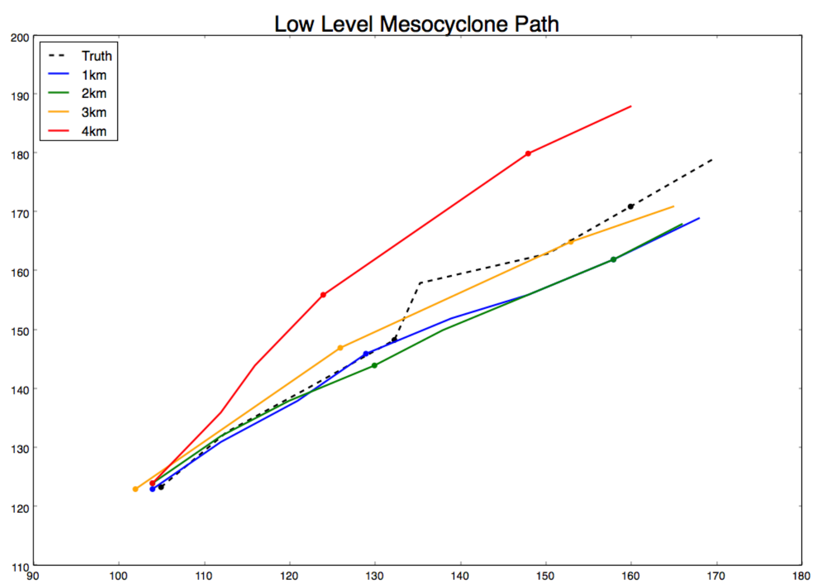


FIG. 7a-b Low Level mesocyclone path based on maximum vertical vorticity at 1.5 km AGL for a) WK82 every 10 mins. starting at t = 40 min; dots every 20 mins. a) El Reno every 10 mins. starting at t = 50 min; dots every 30 mins.

As a result of this ElReno_4km is nearly 20 km from ElReno_333m towards the end of the 120 min. simulations. From Rotunno & Klemp 1985, it is known that supercells propagate right of the mean wind flow as the results of a dynamic vertical pressure gradient that develops on the right side of the updraft. Therefore, the decrease in rightward propagation is a result of the weakening in the vertical dynamic pressure perturbation force in (1) as discussed earlier in the Section 3.1.

3.3 Precipitation Statistics

3.3.1 Rain

WK82 sounding	**333m**	**1km**	**2km**	**3km**	**4km**
30 to 60 minutes	90807	95993	96911	102236	98860
60 to 90 minutes	437259	437879	443037	441196	415999
90 to 120 minutes	1175191	1127701	1125432	11003399	1060758
Totals	1701258	1661342	1665331	1643749	1575605

Del City sounding	**333m**	**1km**	**2km**	**3km**	**4km**
30 to 60 minutes	37765	38843	40091	40903	39981
60 to 90 minutes	131637	123110	119803	101451	72188
90 to 120 minutes	263916	218087	217148	177325	76490
Totals	432915	380007	377040	319682	188659

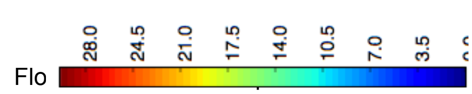
El Reno sounding	**333m**	**1km**	**2km**	**3km**	**4km**
30 to 60 minutes	29412	30444	31383	32385	31873
60 to 90 minutes	137594	135275	136725	125427	92624
90 to 120 minutes	331598	309698	350758	333315	182095
Totals	497806	475355	518852	491125	306590

Table 3. Total Rainfall volumes every 30 minutes and final accumulated total for all three environments in $(x\ 10^{12} mm^2)$ (top to bottom: Wk82, Del City, and El Reno)

For ElReno_4km and DelCity_4km, there is a significant lack of accumulated rainfall (Fig. 8a-c). This is to be expected given the DelCity_4km storm dissipates before the end of the simulation and the ElReno_4km is dramatically weaker than the other El Reno simulations.

In the Del City and WK82 simulations, total rainfall volume increases with increasing resolution, a result echoing Verrelle et al. 2014. Verrelle et al. 2014, a study using the WK82 sounding, saw an underestimation of precipitation at 4km and argued that precipitation amounts decreases with decreasing grid resolution due to less resolvable convective activity. Verrelle et al. 2014 goes as far to say that 4km grid resolution is in the "*grey zone*" of convection, where a modified convective parameterization might be necessary. Interestingly, for squall lines Bryan and Morrison 2012 found, conversely, that precipitation totals decreased with increasing horizontal grid resolution. The argument was that evaporation rates increase with increase grid resolution as the resolved turbulence creates greater entrainment. Our opposite finding in two of our three environments suggests that the poor resolution of convective activity at coarser grid spacings can overcompensate for the artificially reduced evaporation. Verrelle et al. 2014 argues that the balance between these two effects is strongly sensitive to environmental humidity noting that the thermodynamic structure in Bryan & Morrison 2012 had a particularly dry profile.

Unlike in the other two cases, no simple relationship is found between rainfall and grid spacing in the El Reno simulations. For example, the ElReno_2km had the highest accumulated rainfall total. The increased updraft intensity and arguably the size of the core means a greater upward mass flux, which will tend to create excessive rain volume.



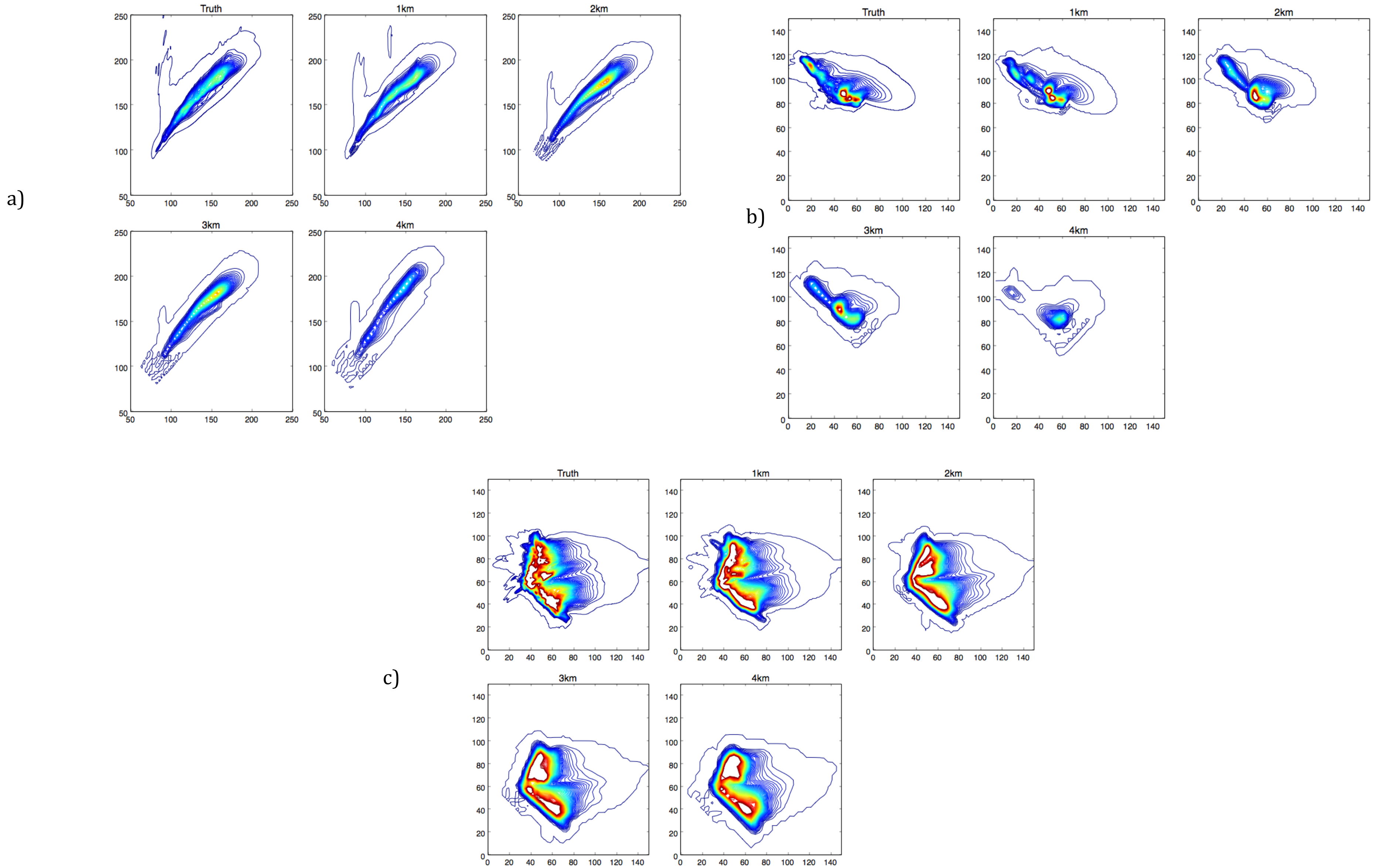


FIG. 8a-c accumulated rainfall volume for each environment. a) El Reno, b) Del City, and c) WK82 Contour intervals are 0.5 $x\ 10^{12} mm^2$)

A key concern in the analysis of precipitation statistics is not just how much, but when. If precipitation totals are the similar in two different forecasts, but the timing of the rainfall is dramatically different, this can create operational issues. For this study, rainfall was totaled every 30 minutes and the results can be found in Table 4. For all three environments, rainfall rates were greater at coarser resolution than the truth for the first part of the simulation while lesser towards the end. As with rainfall volume, all three environments saw an increase in rainfall rate with increasing grid resolution (Weisman et al. 1997, Bryan et al. 2003, Fiori et al. 2010). The rainfall rates were evidently tied to the updraft intensity and the overall strength of a given storm.

3.3.2 Hail

Even though hail is not accounted for in the Thompson microphysical parameterization scheme it is briefly worth mentioning any operationally significant results related to ice processes. Taking a look back at the simulated radar reflectivity plots, Fig.5a-b, the 65 dBz extent is used for hail core analysis. Hail cores at t = 120 min. in the 2-4km El Reno storms are actually over predicted and the location is off as well. For hail cores at 120 min for 3-4 km Del City Storms there is an under prediction of size and intensity. A crucial factor when considering the maximum growth size of hail or graupel is the maximum updraft speed. For the all three environments, we saw that maximum vertical velocity intensity begins to converge at 2km with a significant increase from 4km to 2km for the Del City and El Reno soundings. In the maximum hail mixing ratio time height plots (not shown) we see a direct correlation between hail mixing ratio intensity and maximum vertical velocity intensity. Furthermore, the hail core is roughly grid-converged around 2 to 3 km, similar to updraft intensity. All this suggests that hail core intensity should grid-converge along with maximum vertical velocity.

3.4 Grid Convergence

To analyze the extent to which unresolved fine-scale processes produce errors on larger scales and summarize the general convergence properties each environment, the time averaged ratios of maximum potential temperature perturbation depression at the surface, maximum vertical vorticity at 1.5 km AGL, maximum vertical velocity perturbation at 5 km AGL, and accumulated rainfall was examined.

WK82 Sounding	**333m**	**1km**	**2km**	**3km**	**4km**
$\Delta\bar{\theta}_{max}$**(K)**	-10.36	-8.87	-7.99	-7.07	-6.23
$\bar{\zeta}_{max}$ $(x10^{-3}\ 1/s)$	102.05	38.3	18.9	10.9	8.15
$\overline{w_{max}}$ **(m/s)**	54.5	50.86	43.9	38.2	31.9

Del City Sounding	**333m**	**1km**	**2km**	**3km**	**4km**
$\Delta\bar{\theta}_{max}$ **(K)**	-8.17	-6.85	-6.36	-6.00	-4.45
$\bar{\zeta}_{max}$ $(x10^{-3}\ 1/s)$	61.97	23.15	12.7	7.24	3.99
$\overline{w_{max}}$ **(m/s)**	43.3	32.9	30.8	16.2	**5.56**

El Reno Sounding	**333m**	**1km**	**2km**	**3km**	**4km**
$\Delta\bar{\theta}_{max}$ **(K)**	-6.45	-4.25	-2.57	-2.62	-2.36
$\bar{\zeta}_{max}$ $(x10^{-3}\ 1/s)$	95.63	37.01	20.20	13.51	7.18
$\overline{w_{max}}$ **(m/s)**	74.6	66.24	64.3	48.1	26.9

Table 4. Assorted statistics for each environment (top to bottom WK82, Del City, El Reno)

First, the WK82 environment shown in Fig. 9b is the clear outlier, as all of the solutions seem reasonably converged (with errors < 10%) even at a 4km grid spacing. Secondly, some variables obviously converge much faster in certain environments. The average maximum temperature depression at the surface is converged for the Del City environment at 3 km, but the El Reno environment is still converging at 1km (look at Fig. 9a). Finally, while it isn't clear in the convergence plots, from the previously presented time-height and horizontal cross-section plots, we can see that for all the environments greater improvement generally occurs as grid spacing decreases from 2 to 1 km than from 3 to 2 km.

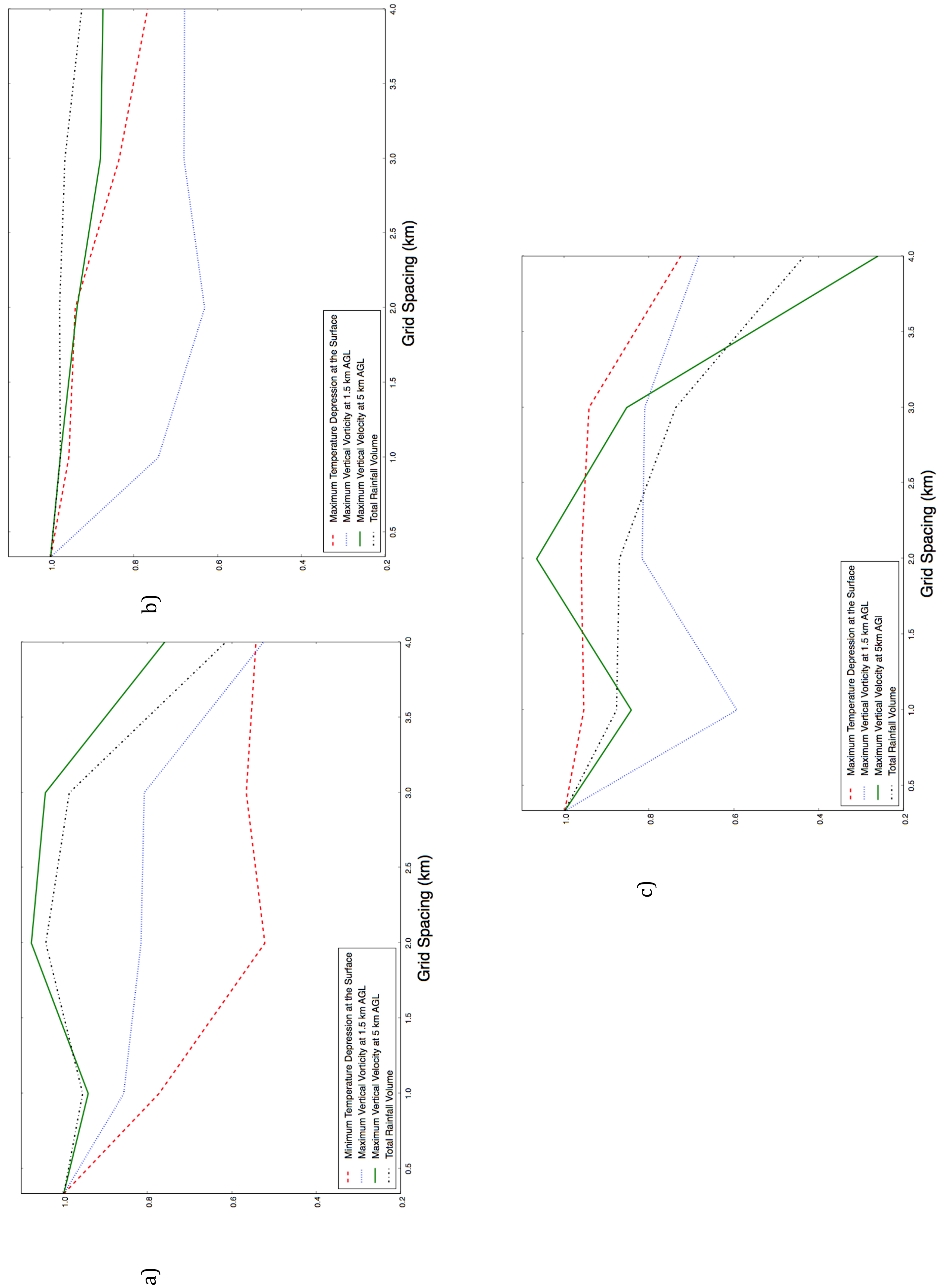


Fig. 9a-c Convergence Plots for a) El Reno, b) WK82, and c) Del City

4. CONCLUSION AND DISCUSSION:

As we have seen in this study horizontal grid spacing affects supercell evolution and environment strongly affects the degree and characteristics of the sensitivity. We found that a 4km spatial resolution was too coarse as the DelCity_4km dissipated inside of 2 hours and ElReno_4km was significantly weaker. The latter result can be attributed partly to the inversion in the El Reno sounding, which was strong enough to prevent storm initiation in a preliminary 3 km simulation with a weaker (3 K) thermal bubble. The 4km grid spacing also greatly weakened the rightward storm propagation and therefore considerably altered storm path.

It could also be said that the improvement in operational useful information was greater from 2km to 1km than from 3km to 2km. A continual problem in realm of model resolution is tradeoff between information gain and computational cost. Past studies have claimed that the additional information gained in 1-5 km range is outweighed by computational cost (Weisman & Klemp 1982, Weisman et al. 1997, Bryan et al. 2003).

It can be seen from the above analysis that horizontal grid resolution is crucial in the relationship between finer scale processes and the resolvable storm dynamics and that "The determination of adequate grid spacing is inevitably tied to the degree to which the representation of small scales alters the evolution of larger scales, and vice versa (A & D 2002)." As finer-scales processes are resolved, they go onto alter larger scale evolution. In the case of El Reno environment, scales finer than 1km are evidently needed as the 1 km simulation produces a tornado that is not present in the 333 m simulation.

It is important however to note that in terms of Warn-on-Forecast that these simulations were run in an idealized framework. Be that as it may, our hypothesis, if anything, the grid spacing sensitivity seen here will only grow as model intricacy is increased. Another point worth mentioning is that the current study was done in the framework of a deterministic paradigm and not that of an ensemble system Warn-on-Forecast seeks to use. Also, there are other approaches to improving forecasts other than increasing spatial resolution. Improving techniques in data assimilation and parameterization schemes should be explored as well

For future work, sensitivities to turbulence and microphysical parameterization schemes should be studied. The current microphysical parameterization does not explicit account for hail, which could lead to some interesting differences in hail core intensity and location. Turbulence, the unsolved problem of classical mechanics is continually in need of better understanding. Finally, this study only analyzed the effects of horizontal grid resolution on supercell evolution. Another key concern would be to analyze the sensitivity to vertical grid spacing. Alderman and Droegemeier 2002 found that cycling intensity and periodicity was directly related to vertical grid resolution. Finally, the WK82 sounding had significantly moister mid- to upper levels when compared to the other two environments and also displayed the least sensitivities. Moisture might be critical to grid spacing as it reduces the amount of entrainment even as finer scale turbulence is resolved. Thus, future work should analyze how drying the WK82 sounding affects its grid spacing sensitivity.

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6. REFERENCES

Alderman, E.J., and Droegemeier, K.K., 1999: A Numerical Simulation of Cyclic Mesocyclogenesis. *J. Atmo. Sci..* **56**, 2045 – 2069

Alderman, E.J., and Droegemeier, K.K., 2002: The Sensitivity of Numerically Simulated Cyclic Mesocyclogenesis to Variations in Model Physical and Computional Parameters. *Mon. Wea. Rev.,* **130,** 2671-2691.

Bryan, G.H., Wyngaard, J.C., and Fritsch, J.M., 2003: Resolution Requirements for the Simulations of Deep Moist Convection. *Mon. Wea. Rev.,* **131**, 2394-2416

Bryan, G.H., and Morrison, H., 2012: Sensitivity of a Simulated Squall Line to Horizontal Resolution and Parameterization of Microphysics. *Mon. Wea. Rev*., **140**, 202-225.

Cintineo, Rebecca M., and Stensrud, D.J., 2013: On the predictability of Supercell thunderstorm evolution., *J. Atmo. Sci*... **70**, 1993-2011

Fiori, E., Parodi, A., and Siccardi, F., 2010: Turbulence Closure Parameterization and Grid Spacing Effects in Simulated Supercell Storms. *J. Atmos. Sci*. , **67**, 3870-3890

Grabowski, W.W., Bechtold, P., Cheng, A., Forbes, R., Halliwell, C., Khairoutdinov, M., Lan, S., Nasuno, T., Petch, J., Tao, W.K., Won, R., Wu, X. and Xu, K.M., 2006: Daytime convective development over land: A model intercomparison based on LBA observations. *Q.J.R. Meteorol*. Soc., **132**, 317-344.

Kain, J.S., Weiss, S.J., Bright, D.R., Baldwin, M.E., Levit, J.J., Carbin, G.W., Schwartz, C.S., Weisman, M.L., Droegemeier, K.K., Weber, D.B., and Thomas, K.W., 2008: Some Practical Considerations Regarding Horizontal Resolution in the First Generation of Operational Convection-Allowing NWP. *Wea. and For.,* **23**, 931-952

Markowski, P., and Richardson, Y., 2010: Mesoscale meteorology in midlatitudes., Wiley-Blackwell 430 pp

Noda, A., and Niino, H., 2003: Critical grid size for simulating convective storms: A case study of the Del City supercell storm. *Geophys. Res. Lett.,* **30**, 2 – 4.

Petch, J.C., 2006: Sensitivity studies of developing convection in a cloud-resolving model. *Q.J.R. Meteorol. Soc.,* **132**, 345-358

Raymond, W. H., 1988: High-order low-pass implicit tangent filters for use in finite area calculations. *Mon. Wea. Rev.*, **116**, 2132–2141.

Rotunno, R., and Klemp, J.B., 1982: The influence of the Shear-Induced pressure gradient on Thunderstorm Motion. *Mon. Wea. Rev.,* **110**, 136-151.

Rotunno, R., and Klemp, J., 1985: On the Rotation and Propagation of Simulated Supercell Thunderstorms. *Journal of Atmospheric Sciences*., **42**, 271-292.

Stensrud, D.J., Xue, M., Wicker, L.J., Kelleher, K.E., Foster, M.P., Schaefer, J.T., Schneider, R.S., Benjamin, S.G., Weygandt, S.S., Ferree, J.T., Tuell, J.P., 2009: Convective-scale warn on forecast: a vision for 2020, *Bull. Amer. Meteor. Soc.,* **90**, 1487 - 1499

Stensrud, D. J., Wicker, L. J., Xue, M., Dawson II, D.T., Yussouf, N., Wheatley, D.M., Thompson, T.E., Snook, N.A., Smith, T.M., Jung, Y., Jones, T.A., Gao, J., Coniglio, M.C., Brooks, H.E., Brewster, K.A., 2013: Progress and challenges with Warn-on-Forecast. *Atmospheric Research*., **123**, 2-16.

Vandenburg, M.A., Coniglio, M.A., and Clark, A.J., 2014: Comparison of next-day convection-allowing forecasts of storm motion on 1-km and 4-km grids. *Weather and Forecasting*.doi: 10.1175/WAF-D-14_00011.1, in press.

Verrelle, A., Ricard, D. and Lac, C. (2014), Sensitivity of high-resolution idealized simulations of thunderstorms to horizontal resolution and turbulence parameterization. *Q.J.R. Meteorol. Soc*.. doi: 10.1002/qj.2363

Weisman, M.L., and Klemp, J.B., 1982: The Dependence of Numerically Simulated Convective Storms on Vertical Wind Shear and Buoyancy. *Mon. Wea. Rev*., **110**, 504-520

Weisman, M.L., Skamarock, W.C., and Klemp, J.B., 1997: The Resolution Dependence of Explicitly Modeled Convective Systems. *Mon. Wea. Rev*., **125**, p. 527-548