5.3 REGIONAL OBSERVATIONS OF CONVECTIVELY-INDUCED TURBULENCE FROM VARIED RESOLUTION FULL-PHYSICS MODELS

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1. INTRODUCTION

Convectively-induced turbulence (CIT) occurs on scales between 10-1000m (Lester 1994) and poses a serious threat to aviation operations. Occurring on small spatial and temporal scales, CIT generation and propagation processes are a forecast challenge. High resolution models have the capability of resolving turbulent processes but are computationally expensive, limiting their operational use. Previous studies have shown on a case by case basis how model resolution influences the power spectrum (Lane and Knieval 2005) and areal coverage of turbulence (Barber 2015, Fig. 1). Barber (2015) found that the Ellrod Index over predicted severe turbulence in the tropics when calculated from high resolution simulations. This study examines summertime convection in the North Dakota region over a one-week period using a variety of model resolutions that are similar to those utilized in operational and research applications. Eddy dissipation rate (EDR) and Ellrod Index, both popular turbulence metrics, are evaluated across various model resolutions and compared to pilot reports. The variability of turbulence magnitudes with respect to model resolution and lateral distance away from convection are investigated. Results highlight biases of model-estimated turbulence for various model resolutions and turbulence indices.

2. METHODOLOGY

2.1. Full Physics Model Configuration and Setup

In this study, 30 hour forecasts of convection from July 10, 2015 to July 17, 2015 in the Northern Plains are made using the Advanced Research WRF (ARW) model version 3.7 (Skamarock et al. 2008). Severe convection was frequent during this time period and numerous storm reports were made. Simulations are initialized at 0000 UTC with ERA-Interim (European Center for Medium range Weather Forecasting Reanalysis) global reanalysis data. Four sets of horizontal and vertical grid spacings are utilized for these simulations and range from 12 km to 500 m in the horizontal (Table 1). This spectrum of grid spacings encompasses commonly used operational and research applicable model setups. Parameterizations for all of the simulations are provided in Table 2. The model top in all simulations is set to 10 hPa (approximately 30 km) and a damping layer of 10 km is used at the model top. Results from 12 to 13 July 2015 will be discussed in further detail below.

2.2. Eddy Dissipation Rate Turbulence Calculation

Eddy dissipation rate (EDR) which is calculated from the turbulent kinetic energy (TKE) of the simulation is used to estimate turbulence intensity. EDR is a popular aviation turbulence metric that is not dependent on physical aircraft variables such as type, weight, and speed (Poellot and Grainger 1991, Emanuel et al. 2013). The calculation for EDR used in this study is

$$EDR = \frac{TKE^{3/2}}{L}, \tag{1}$$

where *TKE* is the turbulent kinetic energy ($m^2\ s^{-2}$) and *L* is a length scale (Ahmad and Proctor 2012). In this study, $L = (\Delta x \Delta y \Delta z)^{1/3}$ (Schumann 1991; Sharman et al. 2012), where Δx is the grid spacing in the x-direction, Δy is the grid spacing in the y-direction, and Δz is the grid spacing in the z-direction.

2.3. Ellrod Index

The Ellrod Index is a turbulence intensity (TI) metric used for aviation turbulence avoidance (Ellrod and Knapp 1992). The United States Air Force Weather Agency (AFWA) includes the Ellrod Index as part of their turbulence forecast output at seven altitude ranges, 1.5 km extending to 12.7 km (Creighton et al. 2014). In this study the Ellrod Index is calculated by,

$$Ellrod = TI2 = VWS\ x\ [DEF + CVG], \tag{2}$$

where *VWS* is vertical wind shear, *DEF* is deformation, and *CVG* is convergence (equations below; Ellrod and Knapp 1992)

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$$VWS = \frac{(\Delta u^2+\Delta v^2)^{1/2}}{\Delta z}, \tag{3}$$

$$DEF = \left(\left(\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial v}{\partial x} + \frac{\partial x}{\partial y}\right)^2\right)^{1/2}, \tag{4}$$

$$CVG = -\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right). \tag{5}$$

Ellrod values of 4-8 represent clear-air turbulence intensities of light to moderate, values of 8-12 represent turbulence intensities of moderate, and values greater than 12 represent severe turbulence.

3. RESULTS AND DISCUSSION

3.1 Convective Intensity

Pilot reports collected from the Aviation Weather Center (Treborg 2016), indicate that there were numerous light to moderate turbulence encounters above 8 km in the ND/MN/SD area during the time period from 0700 UTC 12 July to 0000 UTC 13 July. Convection this day occurred in two periods. First, a convective bowing segment progressed through eastern ND at 0700 UTC. Later, two intense thunderstorms passed again through eastern ND at 0000 UTC on 13 July.

Model setups 2-4 did not simulate the early morning convection due to initialization of the model at 0000 UTC, but did simulate large isolated convective storms near eastern ND from 2100 UTC through 0400 UTC. Therefore, discussions hereafter will focus on results that occurred after 1800 UTC. Observed echo top heights, used as convective strength proxy, exceeded 15 km near 2200 UTC. Simulated echo top heights (Fig. 3) were less than observed but greater than 10 km for model setups 2-4. Model setup 1 never simulated echo top heights greater than 7 km, suggesting 12 km resolution simulations are not appropriate for turbulence prediction because of the under-prediction of convective strength (this setup will not be discussed hereafter). The higher vertical and horizontal resolution simulations (i.e. 3-4), had the highest maximum echo top heights.

3.2 Ellrod Index and EDR

Assessment of turbulence over the model domains of model setups 2-4 (e.g. red box in Fig. 2) shows significant over prediction of turbulence by the Ellrod Index, as was seen in previous studies (e.g., Fig. 1). The Ellrod Index for model setup 4 predicted severe turbulence in the majority of the domain and had a minimum value of 200 (≥ 12 is severe) and a maximum value of 4,000. Turbulence estimated by EDR had a maximum intensity of moderate turbulence and occurred over very small areas. These results were consistent throughout the entire simulation period for all of the simulations. The Ellrod Index cannot be utilized as a CIT forecast tool because it over estimates the intensity and areal coverage of turbulence.

To better understand the relationship between turbulent regions and convective cores (defined as echo tops > 8 km), the distributions of out of cloud EDR values were evaluated (Fig. 4). EDR was calculated at various lateral distances from the cores (10 nm, 25 nm, 50 nm) and various altitudes (8 km, 10 km, 12 km). It was found that the majority of turbulent regions were within 50 nm of convective cores at all three altitudes. Interestingly, there were very few turbulent regions within 25 nm and 10 nm miles of convection for model setups 2-4, which contradicts current lateral thunderstorm avoidance guidelines of 20-25 nm set by the Federal Aviation Administration. Resolution did not influence the distance turbulence was found away from convection. Analysis of EDR distribution values found that model setup 3 had the largest normalized areal coverage of low turbulent magnitudes at all three altitudes (Fig. 5a). This result suggests that although the maximum intensity was less than model setup 4, the areal extent of light turbulence and the probability of encountering turbulence is greater. Model setup 4 predicted small regions of turbulence of moderate intensity (the highest EDR values; Fig. 5b). Results indicate that higher horizontal and vertical resolution are necessary to predict similar turbulence intensities as those observed by pilots. Interestingly, the altitude of greatest EDR values was at 12 km altitude for model setups 2-4, even though maximum echo tops were less for model setup 2. Model setup 2 had the lowest maximum turbulence magnitudes at 12 km, suggesting that the coarse model resolution influenced the turbulence intensity due to decreased convective strength.

3.3 Directional Tendency of Turbulence

Turbulent grid cells within 50 nm of convective cores are identified to be either north, east, south, or west of the closest convective core. The motivation behind this analysis is to determine if there is a directional bias of turbulence based on model resolution. The examination of directional tendency of turbulence is provided in Fig. 6 and is analyzed at altitudes of 8 km, 10 km, and 12 km. Model setup 2 shows no consistent directional preference of turbulence location at the three altitudes. In contrast, model setups 3 and 4 have an east-west directional preference. This suggests that resolution is influencing the direction of wave propagation and wave breaking processes. By identifying directional biases of turbulence based on convective type and strength, turbulence avoidance can be more specific and efficient.

4. CONCLUSIONS

This study examined the distribution of turbulence values (EDR and Ellrod) at various heights and distances away from convection. Multiple horizontal and vertical resolutions were used to investigate the influence of resolution on turbulence prediction. 12 km horizontal resolution simulations were found to significantly under predict convective strength and turbulence. These results demonstrate that 12 km horizontal resolution simulations are not appropriate for CIT prediction. In addition, the Ellrod Index should not be used as a turbulence forecast tool when model resolution in the horizontal is less than 12 km. The use of this index at higher resolutions results in the over prediction of turbulence intensity and areal coverage. Model resolution was found to influence the magnitude and location of turbulence. Simulations with higher horizontal and vertical resolution predicted turbulence intensities similar to those reported by pilots. Model simulations with coarser resolution under predicted the intensity of turbulence. The location of turbulence was also influenced by resolution and coarser simulations had less intense turbulence at higher altitudes. Lastly, the direction of turbulence varied between model simulations suggesting that gravity wave breaking and propagation processes are influenced by resolution.

5. REFERENCES

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6. TABLES

Table 1: Simulation grid spacing and vertical levels.

Model Setup	Horizontal Grid Spacing of Inner Nest (km)	Vertical Levels	Similar Model Setups
1- "**12 km**"	12	64	NAM/RAP
2- "**3 km Oper**"	3	64	HRRR
3- "**3 km Res**"	3	100	Research
4- "**500 m**"	0.5	100	Verification

Table 2: Simulation parameterizations.

Model Physics	Model Setup			
	1	2	3	4
Microphysics	WDM-6			
PBL	Mellor-Yamada-Janjic			
Surface Layer	MM5-Similarity			
Land Surface	Noah			
Shortwave	Dudhia			
Longwave	RRTM			
Cumulus	Kain-Fritsch D01 & D02			N/A

7. FIGURES

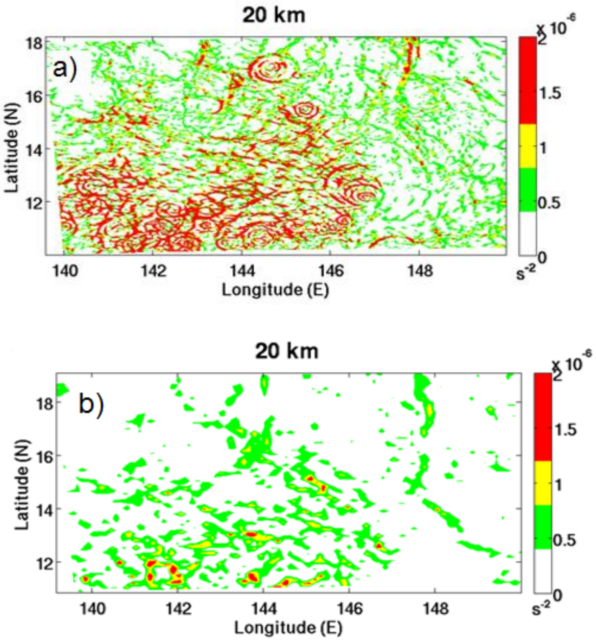

Figure 1: Comparison of Ellrod Index at 20 km for a) 1.67 km horizontal grid spacing and b) 15 km horizontal

grid spacing. Green color represents light turbulence, yellow moderate, and red severe.

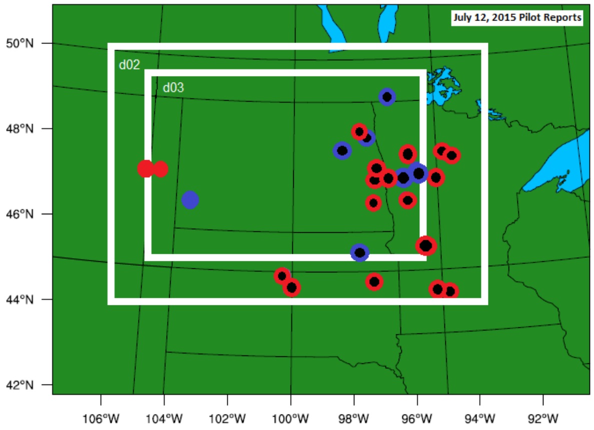

Figure 2: Pilot reports of turbulence from 12 July 2015 in North Dakota, Minnesota, and South Dakota. Red circles represent moderate turbulence and blue light. Black centers indicate the report was above 8 km in altitude. The inner white rectangle represents the inner nest of the model setups 2 and 3 (horizontal grid spacing of 3 km).

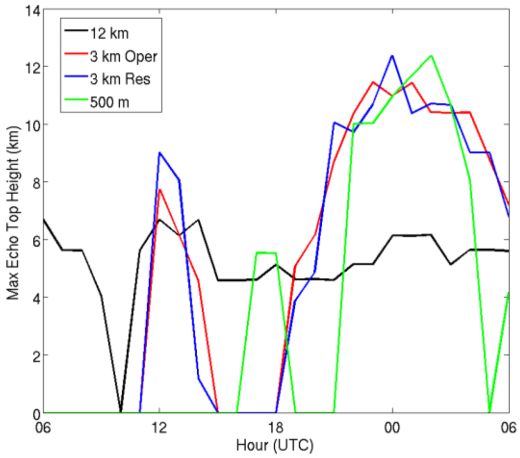

Figure 3: Simulated maximum echo tops from 06 UTC July 12 2015 to 06 UTC July 13 2015.

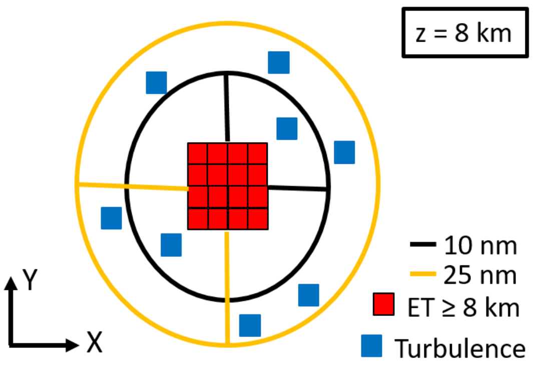

Figure 4: Schematic depicting masking methodology for determining the turbulence distribution within various distances from convective cores at various altitudes. ET represents echo top heights.

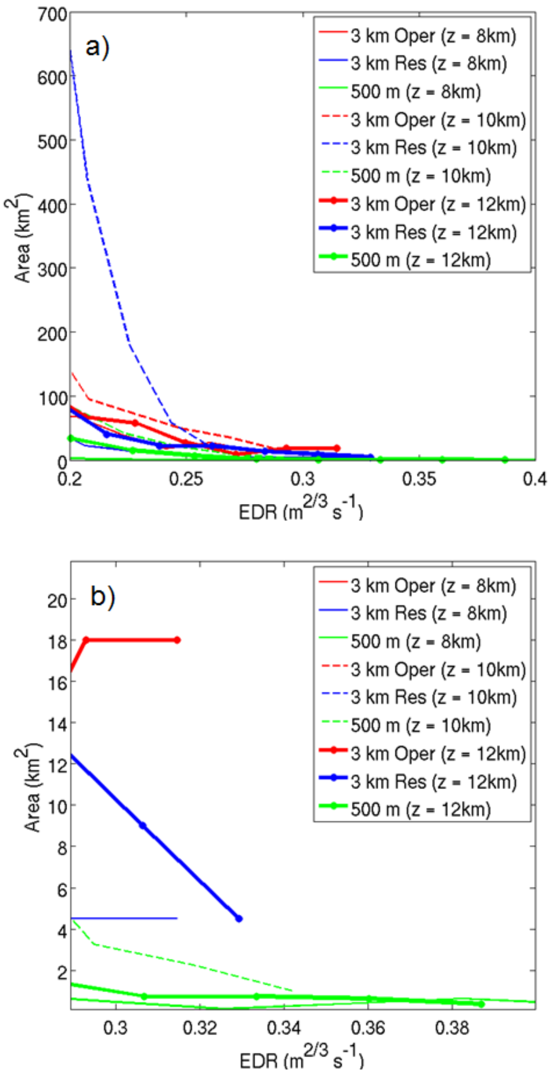

Figure 5: Eddy dissipation rates within 50 nautical miles of a convective core (echo top heights ≥ 8 km). Solid

lines represent evaluation of eddy dissipation rates at 8 km in altitude, dashed at 10 km in altitude, and circle at 12 km in altitude. a) Distribution from 0.2-0.4 $m^{2/3} s^{-1}$. b) zoomed in: 0.28-0.4 $m^{2/3} s^{-1}$.

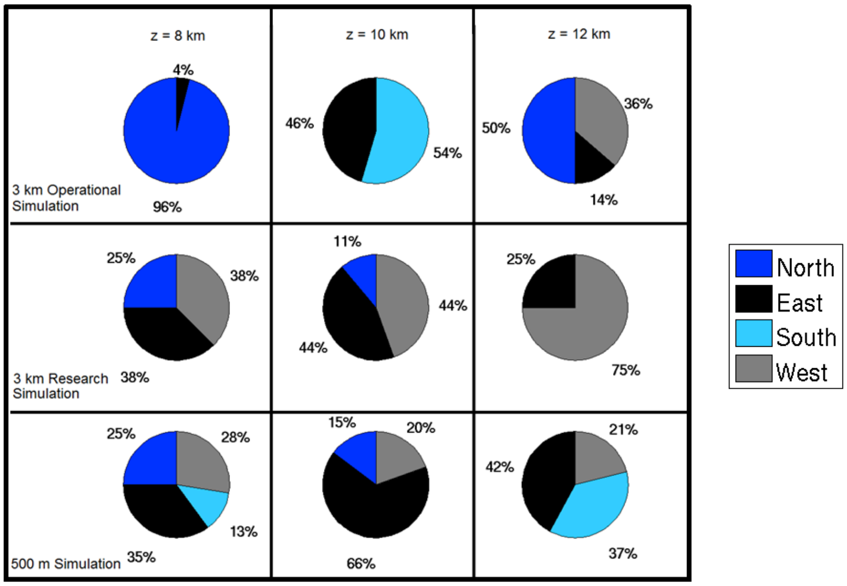

Figure 6: Percentages of turbulent pixels within 50 nautical miles north (blue), east (black), south (cyan), and west (gray) of convection for model setups 2-4 at 8 km, 10 km, and 12 km in altitude.