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Severe High Altitude Aircraft Turbulence on Thunderstorm Peripheries

Donald W. McCann*
McCann Aviation Weather Research, Inc., Overland Park KS

John A. Knox
Department of Geography, University of Georgia, Athens GA

Paul D. Williams
Department of Meteorology, University of Reading, Reading UK

1. INTRODUCTION

At the 13th Aviation, Range, and Space Meteorology Conference Trier et al. (2008) presented a case study of a moderate aircraft turbulence encounter on the north edge of a thunderstorm's anvil. Using a 3-km resolution WRF simulation, they concluded that turbulence was caused by storm-modified flow that decreased the Richardson number (*Ri*) to less than one which, they theorized, allowed Kelvin-Helmholtz instability to develop. In the subsequent discussion, this paper's lead author suggested that the storm-modified flow would probably be unbalanced which would cause spontaneous gravity waves which, in turn, could locally reduce the *Ri* to turbulence-producing levels (McCann, 2001 and Knox, et al., 2008).

Three problems arise with assuming Kelvin-Helmholtz instability develops when *Ri* < *1.* 1) It is not always turbulent with *Ri* < 1. Data from McCann (1993) show 4% of pilots reported smooth flying and another internal Aviation Weather Center study had 12% smooth reports with *Ri* that low. 2) Significant turbulence occurs with *Ri* > 1. In these same two studies, 39% and 52% of severe turbulence reports were with *Ri* > 1. 3) The Richardson number is a yes/no indicator of turbulence and has no intensity information.

Theory and observation confirm that a *Ri* < 0.25 is a necessary condition for turbulence (Miles and Howard 1964; Thorpe 1969). McCann (2001) presented an explanation of how turbulence can develop in the presence of environmental *Ri* > 0.25. A gravity wave will modify the environmental wind shear and stability. With sufficient amplitude it could lower the *Ri* to less than ¼. McCann's hypothesis is consistent with necessary condition for turbulence. The lower the environmental *Ri*, the smaller a gravity wave's amplitude needs to be to initiate turbulence. Therefore, the lower the environmental *Ri*, the higher the probability of subsequent turbulence. Additionally, turbulence intensity can be computed from the wave amplitude and the environmental stability and wind shear.

Fritsch and Maddox (1981) documented many cases of convectively-induced outflow jets similar to the case Trier et al. showed. The storms that cause these jets are very large and very long-lasting. Because of its size and longevity, a large storm's anticyclonic outflow can modify winds aloft by 20-40 m s^{-1} from the ambient environment. It follows that the outflow could easily lower the environmental *Ri* below and above the outflow jet by increasing the vertical wind shear, thereby increasing the probability of turbulence on a storm's periphery.

Might the outflow also be unbalanced and spontaneously produce gravity waves in the same manner described by Knox et al. (2008)? This paper analyzes the environmental conditions leading to moderate-severe turbulence at FL400 near St. Louis, Missouri, on 8 May 2009. We present results from the experimental 5-km resolution convective-resolving Non-hydrostatic Mesoscale Model (NMM) run at the National Centers of Environmental Prediction (NCEP). We conclude that the flow on the storm's periphery was sufficiently unbalanced to spontaneously produce turbulence-initiating gravity waves.

We also show a second case of severe turbulence at FL360 near New Orleans, Louisiana, on 2 April 2009. This case was different because the environmental flow aloft was already strong. Convection south of New Orleans slowed the flight level flow causing imbalance near New Orleans.

* *Corresponding author address:* Donald McCann, McCann Aviation Weather Research, Inc. 7306 157th Terrace, Overland Park, KS 66223; e-mail: don@mccannawr.com

2. TURBULENCE AND UNBALANCED FLOW WITH THUNDERSTORMS

Spontaneous flow imbalance is supposed to cause gravity wave production (Lighthill 1952; Ford 1994). Knox et al. (2008) computed Lighthill-Ford radiation and applied it to the McCann (2001) turbulence theory as the turbulence initiator. Although controversial (see Plougonven et al. 2009 and the Knox et al. 2009 reply), Knox et al. (2008) created successful clear-air turbulence forecasts.

They were able to simplify the Lighthill-Ford equation into quantities that could be computed on numerical model grids.

$$R = \left| f\mathbf{u}\cdot\nabla\zeta + 2Df\zeta - f\mathbf{k}\cdot\mathbf{u}\times\nabla D - 2\frac{\partial}{\partial t}J(u,v) \right| \quad (1)$$

(Ro^{-1}) (1) (1) (1)

where R is the Lighthill-Ford radiation, **u** is the vector wind with components u and v, **k** is the upward unit vector, f is the Coriolis parameter, ζ is the relative vorticity, D is the divergence, and J is the Jacobian operator. These terms scale with respect to the Rossby (Ro) number as indicated below each term. Two terms that scale with Ro and Ro^2 (see below) were deemed small assuming synoptic-scale flows have Ro << 1. Knox et al. (2008) used (1) as an indicator of gravity wave presence in their clear-air turbulence method now called the ULTURB algorithm.

Rossby numbers for thunderstorm outflow are much higher than for the free atmosphere owing to very strong divergence at storm tops. It may not be appropriate to apply (1) to the thunderstorm outflow/turbulence problem.

For Ro = 1 the two excluded terms become important:

$$2\frac{\partial}{\partial t}D^2 + 2\frac{\partial}{\partial t}\mathbf{u}\cdot\nabla D$$

(Ro^2) (Ro)

They scale with respect to Ro as indicated. For Ro > 1 these two terms dominate. Therefore, these two terms should be included in (1) in any analysis of thunderstorm outflows. Indeed, as will be shown in the first case study, these two terms are very large.

3. MODERATE-SEVERE TURBULENCE NEAR ST. LOUIS, MISSOURI

Figure 1 shows the 3-hour streamline and isotach forecast from the 1200 UTC 13-km RUC2 and the 5-km NMM forecast models valid near the time of the moderate-severe pilot report near St. Louis, Missouri (STL), 1518 UTC at FL400. The pilot report is plotted in subsequent figures. NMM forecasts convection explicitly (also shown in subsequent figures) and very accurately forecasted the large mesoscale convective complex over southern Missouri (radar imagery not shown). We assume that the RUC2 forecast represents the environmental flow without convection. The NMM forecast shows a 130 knot maximum near STL, a flow greatly altered by the large thunderstorm which is consistent with the Fritsch and Maddox (1981) findings.

We compare the NMM forecast Richardson number in Figure 2 with the low Rossby number Lighthill-Ford radiation computed from (1). While there is a large area of Ri < 1, there are only small areas of Ri < 0.25 along the leading edge of the convection a couple hundred km southwest of the pilot report. In contrast, there is a very large area of high R emanating outward from the convection to the STL area.

Figure 3 shows the magnitude of each of the two high Rossby number terms. Indeed, these terms are each generally the same order of magnitude as the sum of the low Rossby number terms and generally paint the same area although large values from the second term extend a little farther into the STL area.

We computed turbulence with the ULTURB algorithm both with and without the high Rossby number terms although we show only the low Ro result in Figure 4. Both ways forecasted nearly the same turbulence because ULTURB limits the Lighthill-Ford radiation forcing to physically realistic gravity wave amplitudes. All areas where R >~ 3×10^{-11} s^{-3} are forecast turbulent. Since the Figures 2 and 3 contours do not begin until $R = 10 \times 10^{-11}$ s^{-3}, it is easy to see why turbulence is forecast over most of eastern and southern Missouri. However, the areas of greatest eddy dissipation rates are forecasted with the largest vertical wind shear, as indicated by the low *Ri.* The moderate-severe turbulence was also reported in this area. The pilot likely wanted to avoid the intense convection to the southwest, but still got caught in turbulence on the storm's periphery.

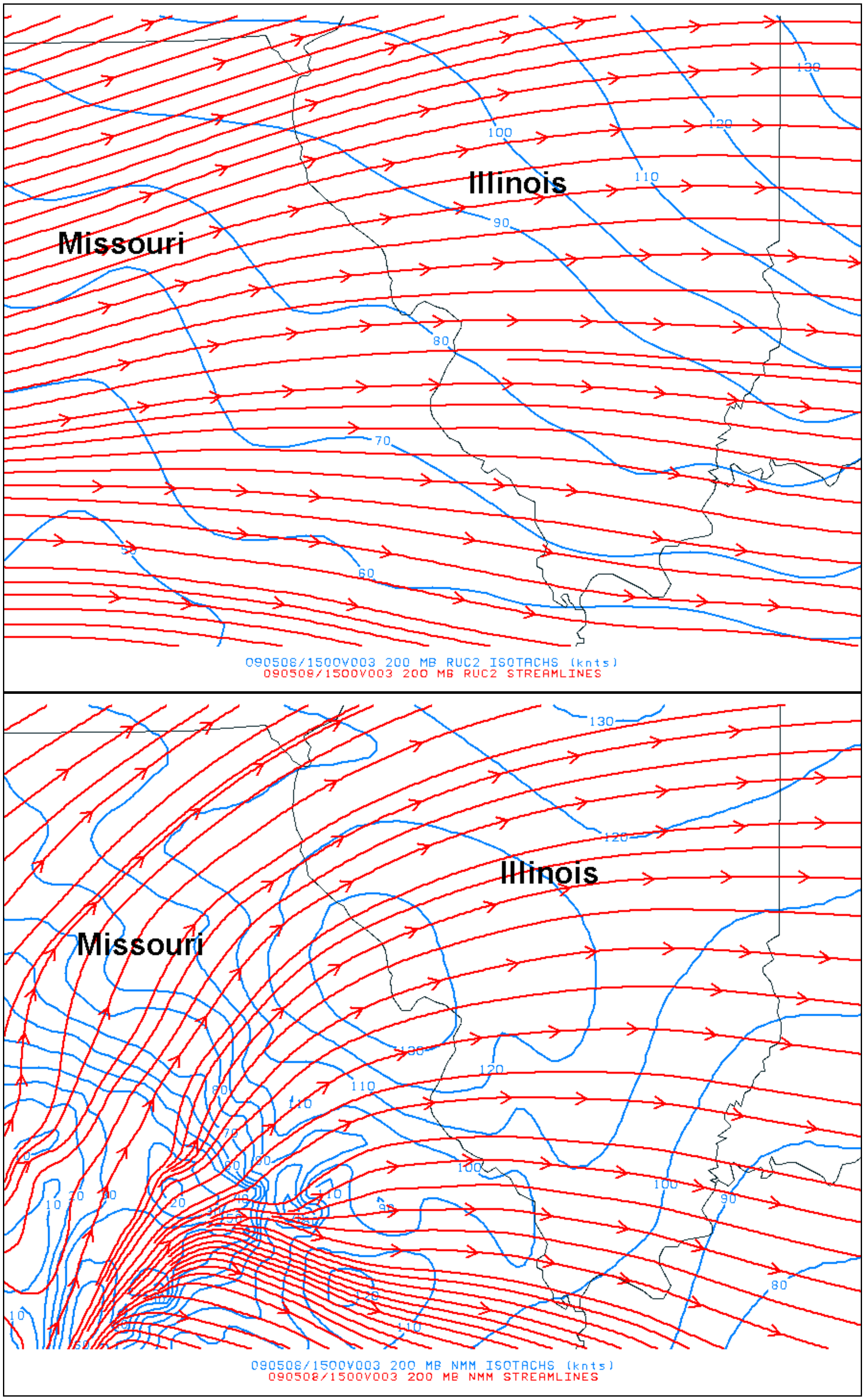

Figure 1. Three-hour forecast valid at 1500UTC 8 May 2009 of 200mb streamlines and isotachs from (top) the RUC2 model and (bottom) the NMM model.

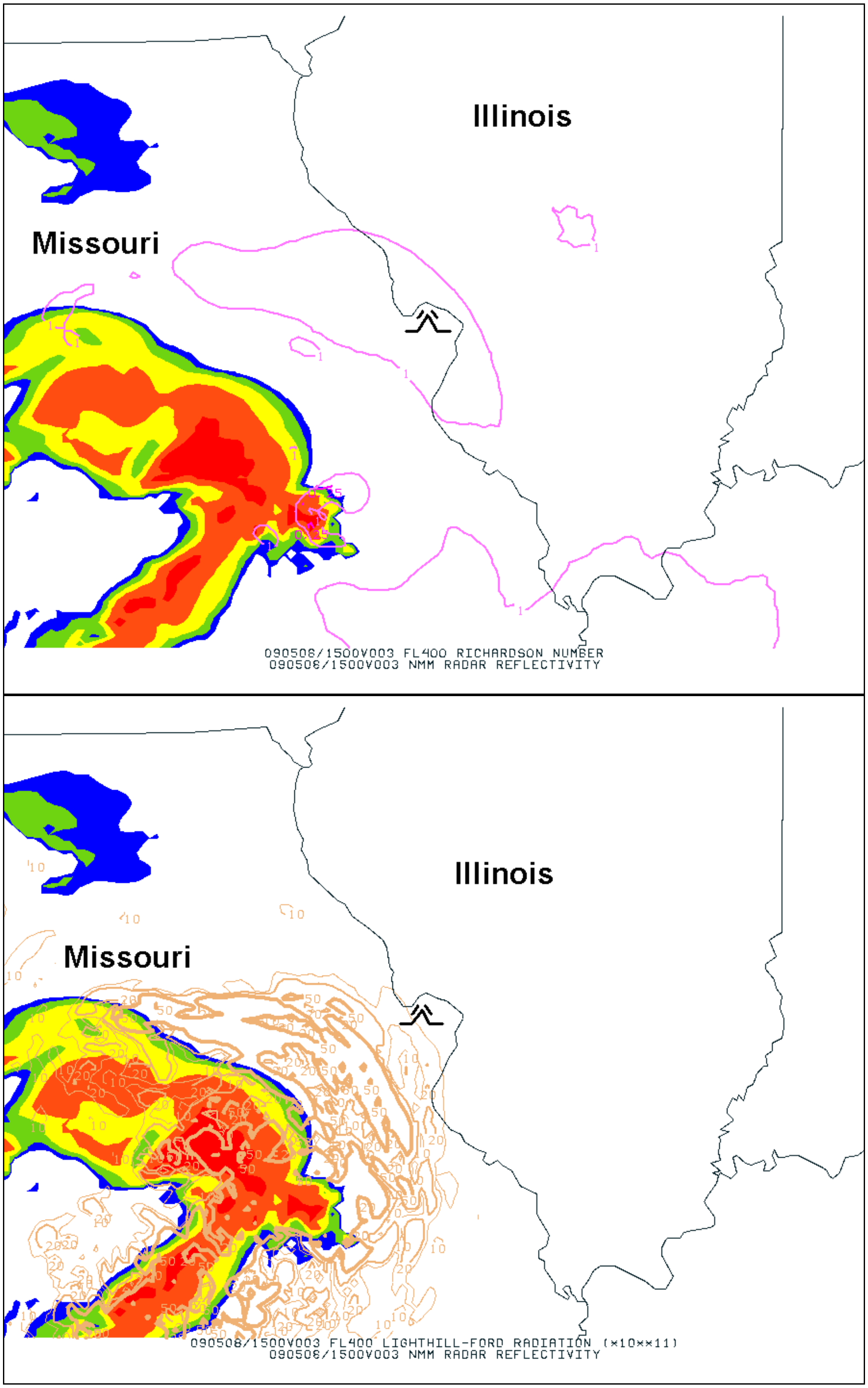

Figure 2. NMM forecast valid at 1500 UTC 8 May 2009 radar reflectivity and FL400 (top) Richardson number and (bottom) low Rossby number Lighthill-Ford radiation

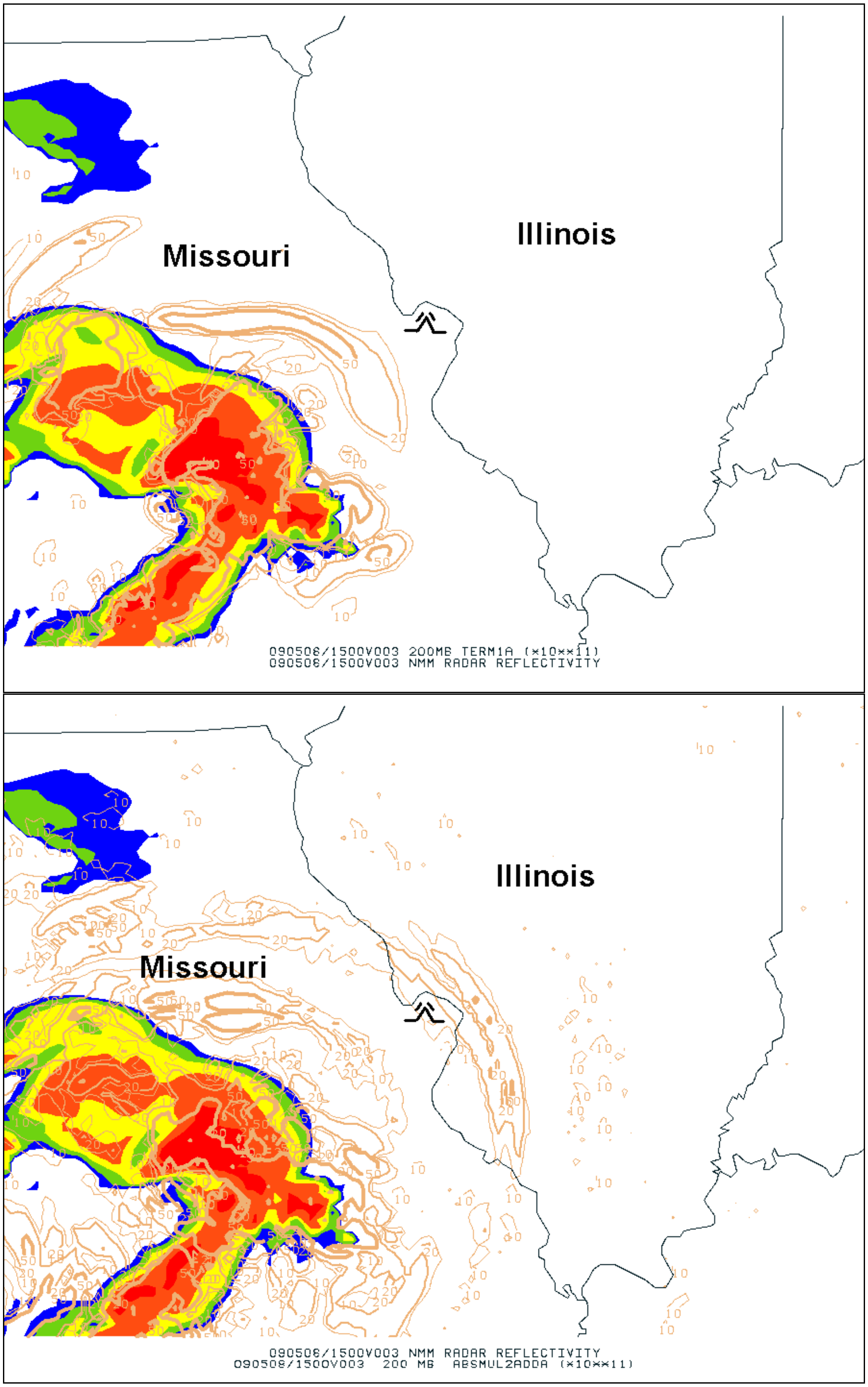

Figure 3. NMM forecast at 1500 UTC 8 May 2009 radar reflectivity and (top) first high Rossby number term and (bottom) second high Rossby number term.

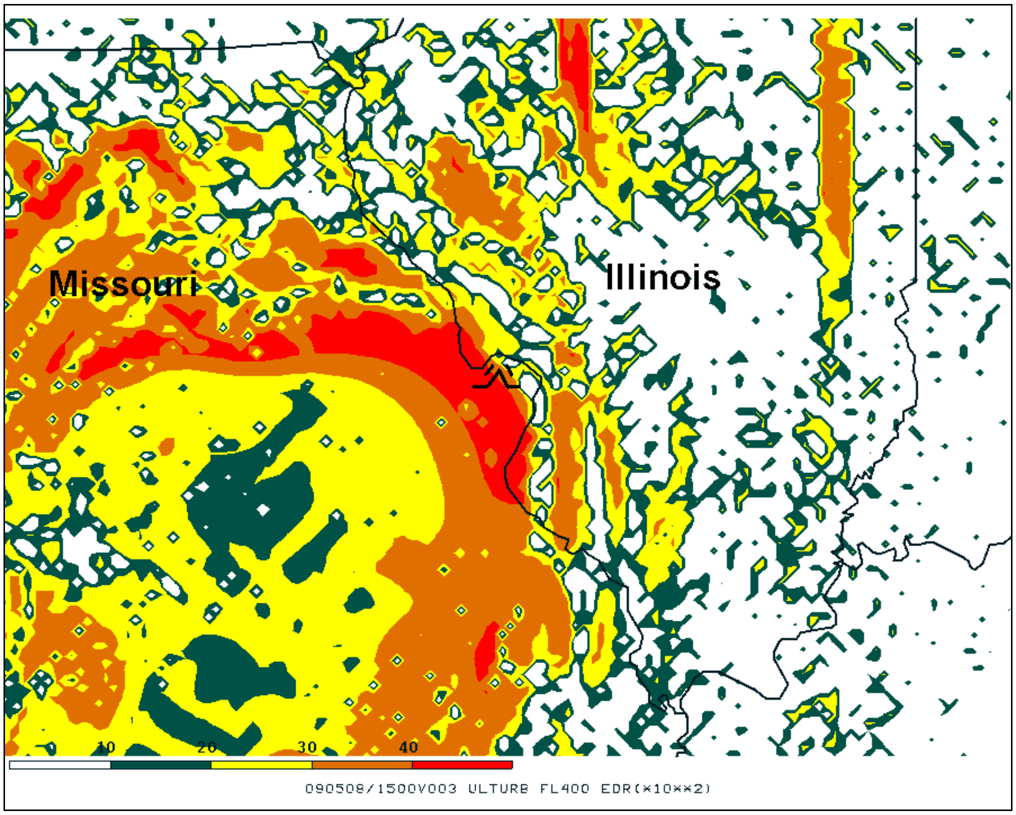

Figure 4. ULTURB forecast at 1500 UTC 8 May 2009 of eddy dissipation rates from the NMM model.

4. SEVERE TURBULENCE NEAR NEW ORLEANS, LOUISANA

Figure 5 shows one-hour forecasts of the flow at 250 mb from the RUC2 and NMM models associated with a severe turbulence report at FL360 at 1245 UTC just south of New Orleans, Louisiana (MSY). Again, the report is located in subsequent figures. This case is different from the STL case because the flow was already strong, 90-100 kt just south of MSY as seen in the RUC2 forecast. In fact, the NMM forecast speed and direction was nearly the same as the RUC2. There was no outflow jet as in the STL case. Instead, the NMM forecast convection (shown in subsequent figures) over extreme southeast Louisiana has reduced the flow to less than 70 kt.

Figure 6 shows NMM forecast Richardson number and low Rossby number Lighthill-Ford radiation for this case. The *Ri* in the PIREP's vicinity was greater than one. The Lighthill-Ford radiation extended northeastward from the flow minimum into southern Mississippi mainly where the horizontal wind shear was highest. The convection produced favorable conditions for turbulence not by creating an outflow jet, as in the STL case, but by "blocking" the flow and creating a "wake" which changed the flow to one with greater nonlinear advection on the storm's periphery.

Figure 7 shows the resultant ULTURB forecast using only the low Rossby number forcing equation. Again, we tried adding the high Rossby number terms, but it made little difference. This case illustrates that strong turbulence on a storm's periphery need not be caused by a classic Fritsch and Maddox (1981) outflow jet.

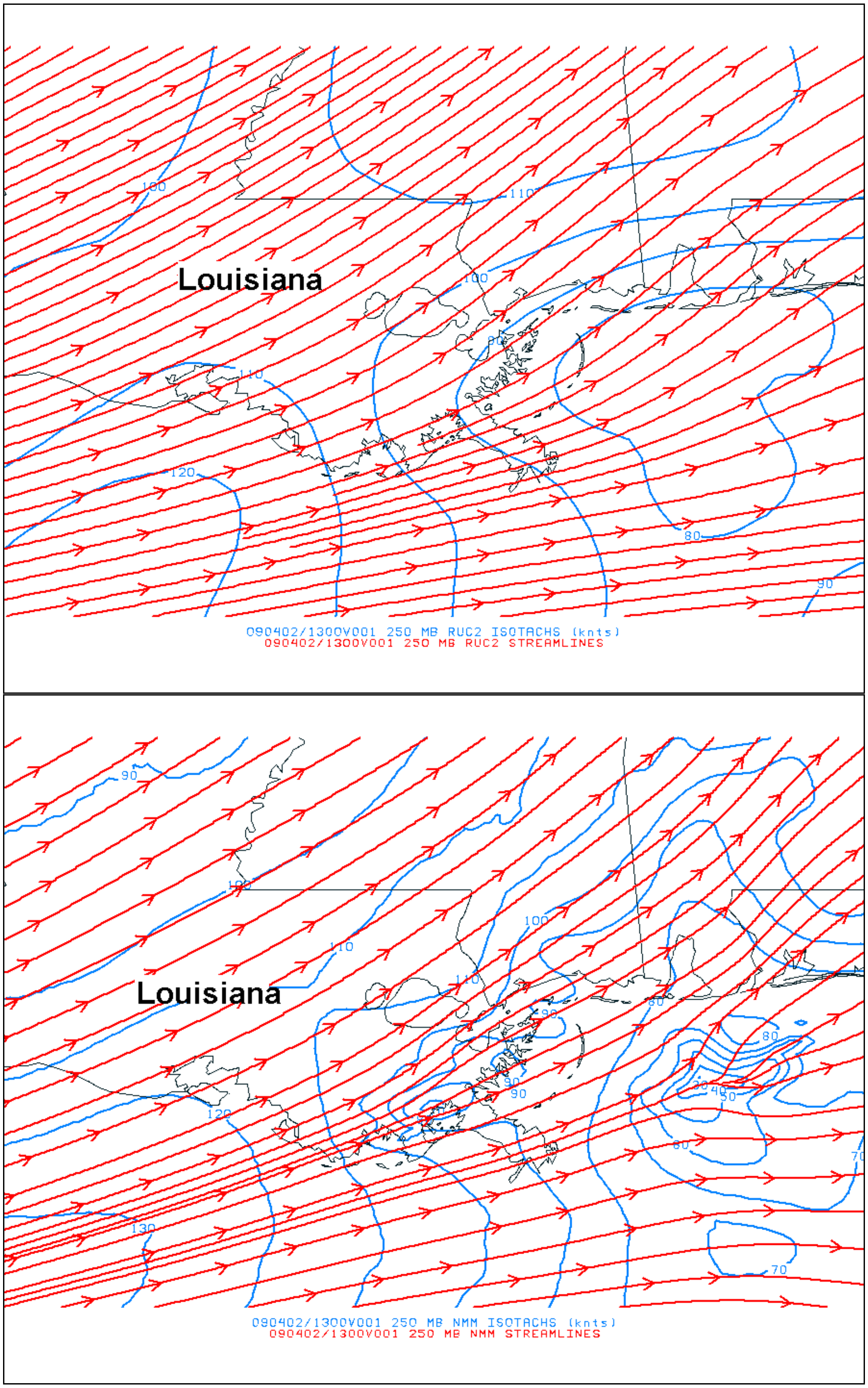

Figure 5. One-hour forecast valid at 1300UTC 2 April 2009 of 250mb streamlines and isotachs from (top) the RUC2 model and (bottom) the NMM model.

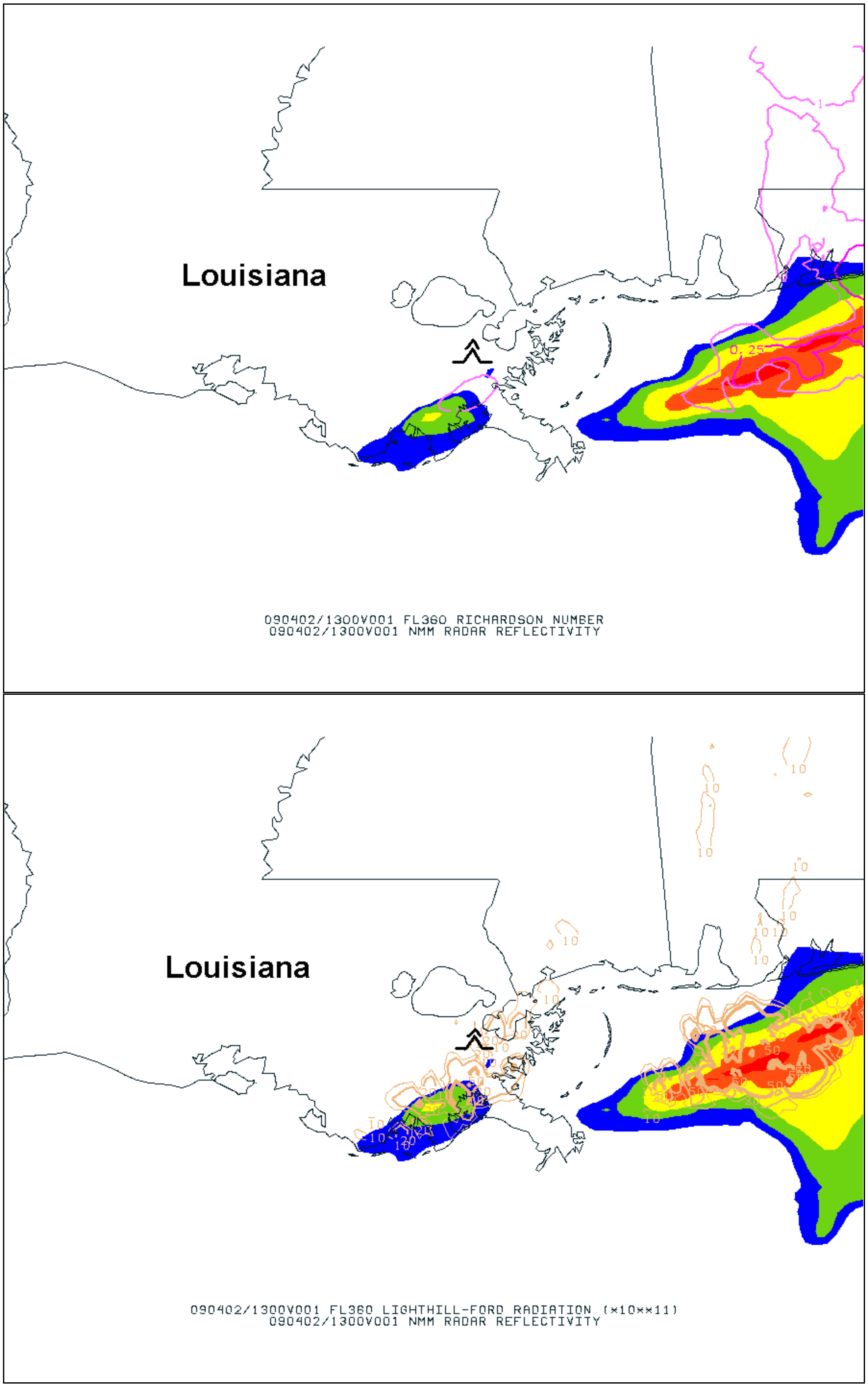

Figure 6. NMM forecast at 1300 UTC 2 April 2009 radar reflectivity and FL360 (top) Richardson number and (bottom) low Rossby number Lighthill-Ford radiation

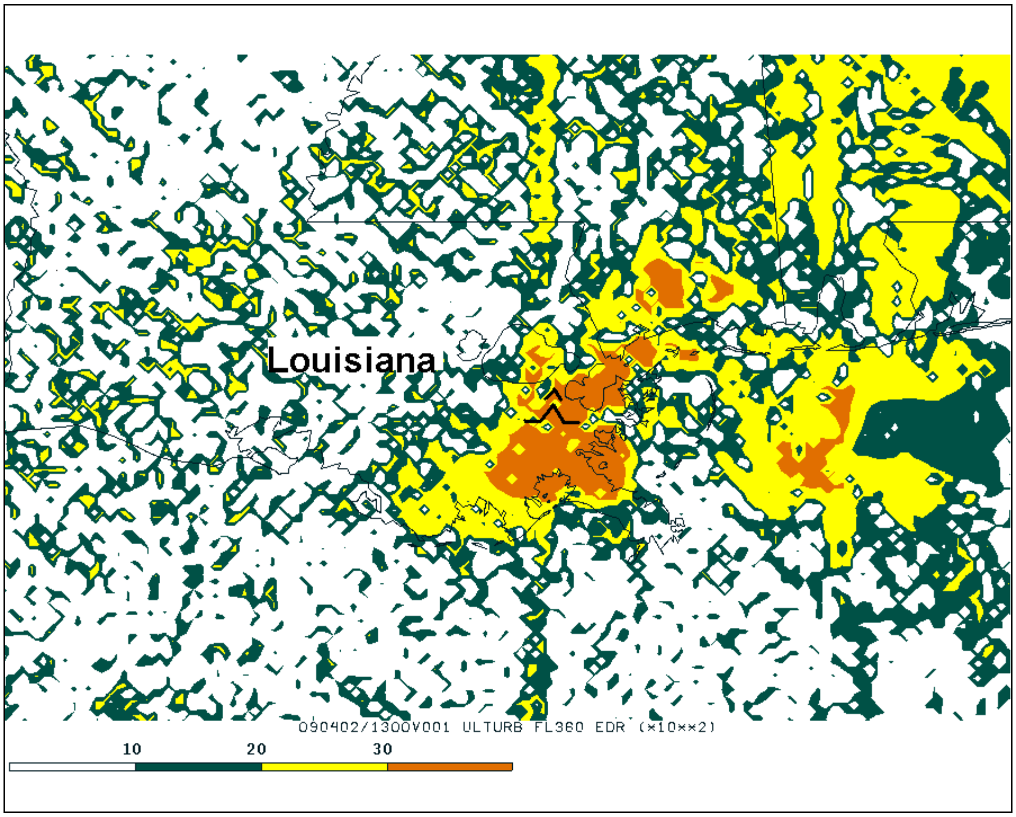

Figure 7. ULTURB forecast at 1300 UTC 2 April 2009 of eddy dissipation rates from the NMM model.

5. CONCLUSIONS

We presented two cases of a high resolution model showing unbalanced flow near pilot reports of very strong turbulence on thunderstorms' peripheries. In the STL case unbalanced flow followed the formation of a classic Fritsch and Maddox (1981) outflow jet. In the MSY case unbalanced flow resulted as the convection "blocked" the environmental winds creating a wake-like flow downwind from the storm. In both cases unbalanced flow was indicated a significant distance from the convection core which lead to severe turbulence on the storm's periphery. Although Richardson numbers in the layers where the turbulence was reported were low, they were not low enough by themselves to allow for turbulence. We conclude that unbalanced flow plays a crucial role while also recognizing the contribution of the flow-altering reduction of the Richardson number as in Trier et al. (2008).

While adding the two high Rossby number terms to ULTURB made little difference to the forecasted turbulence near the pilot reports in these cases, we cannot conclude that this will always be the case. More cases need to be examined. We do note that computing these two additional terms takes significant resources. This may be a substantial drain on efforts to realize forecasts such as these in real-time.

These two cases demonstrate the turbulence hazard that can occur near thunderstorms. Note that the air traffic control rule of a twenty nautical mile buffer around the radar reflectivity was inadequate in both these cases. However, these situations may be rare. These were the only two cases of strong high level thunderstorm periphery turbulence out of 122 convection-related moderate-severe or greater turbulence reports gathered in the spring, 2009, by McCann (2010).

Aviation interests await the operational implementation in real-time of high resolution models. We noted above that these cases may be rare, but they probably cause an above average amount of havoc since pilots may think they are clearing the convection by a wide margin.

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