11B.2 Influence of Diabatic Potential Vorticity Anomalies upon Warm Conveyor Belt Flow. Part II: 3-5 January 2005

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1. INTRODUCTION

This project looked at possible effects of convection, oriented more perpendicular to the warm conveyor belt, on downstream heavy snowfall across the central and Northern Plains. Part II will focus on a winter storm which affected a large part of the central Plains from 4-6 January 2005. Heavy snowfall was forecast well in advance of the winter storm, and verified across parts of Nebraska and Iowa. Heavy snowfall was expected to fall during two time periods from two different meteorological forcing regimes. Initially, heavy snow was to develop due to strong warm air advection (WAA) and frontogenesis ahead of a closed 500 hPa cyclone. Later in the event as the mid-level wave approached, strong positive differential vorticity advection (DPVA) was expected to develop in conjunction with frontogenesis within the trough of warm air aloft (TROWAL) to continue to produce heavy snowfall.

Significant snowfall did occur during two different time periods in Nebraska and Iowa as forecast, but little in the way of snow fell during a 12 hour period from 0900 through 2100 UTC 5 January 2005 despite numerical model guidance indicating snow would continue. This study looks specifically during this time period in the winter storm where precipitation failed to materialize.

As in part 1 of this study (Schmacher et al. 2009), a piecewise PV inversion will be utilized to ascertain if a diabatically generated potential vorticity (PV) anomaly influenced the warm conveyer belt to effect the placement of heavy snowfall, or if there was a model error which resulted in a incorrect forecast. Previous studies, including Mahoney and Lackman (2007) and Brennan and Lackman (2006), have investigated the effect of upstream convection or precipitation on downstream moisture advection and rain or snowfall. The previous work generally concentrated on systems over the southeast United States. A study by Baxter (2006) is similar to the current research where piecewise inversions were used to study the effect of upstream convection on downstream heavy snowfall. Baxter 2006 indicated that the upstream convection improved the production of heavy snowfall as the diabatically generated PV anomaly enhanced the advection of moisture to the north. This study is different in that the orientation of the precipitation or convection is oriented more west to east, than south to north. Also Part I and II are from the central and northern Plains, where often winter storms are in the developing stage with the surface cyclone deepening along a strong thermal gradient oriented west to east.

2. DATA AND METHODOLOGY

a. Mesoscale model and input data

In order to create a high-resolution, dynamically consistent dataset for analysis, events were simulated using version 2.2 of the WRF-ARW, developed at the National Center for Atmospheric Research (NCAR). 48 hour simulations were performed, with two-way nesting of three domains of 36, 12, and 4 km resolution. The resolution in the vertical is comprised of 50 levels, with a model top of 100 hPa. Initial and lateral boundary conditions (updated every 3 hr) came from the North American Regional Reanalysis (NARR), which has a resolution of 32 km and 45 vertical layers. Physical parameterizations chosen include the Lin et al. microphysics scheme, the Kain-Fritsch convective parameterization (on the two outermost domains only), the YSU planetary boundary layer scheme, the Monin-Obukhov surface layer scheme, and the thermal diffusion land-surface scheme. In addition, shortwave and longwave radiation were parameterized using the Dudhia and RRTM schemes, respectively. As the available number of parameterizations increases, the choice of an optimal combination becomes increasingly difficult. The authors have used these parameterizations to simulate a number of events, and in most cases the results are sufficient for use as a proxy for the real atmosphere to conduct higher-resolution analysis of the relevant dynamics.

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The precipitation output from the Weather Research and Forecasting (WRF) model and NARR was compared to the Cooperative Observer Program (COOP) administered by the National Weather Service and archived at the National Climate Data Center. COOP data were collected at each location once every 24 h with different locations reporting at different times of the day. Because little precipitation occurred outside the event discussed in this paper, a 3-day precipitation total was found using reports from 4-6 January 2005. This data was gridded using the Barnes analysis with the General Meteorological Package (GEMPAK).

b. Piecewise PV inversion

To quantify the impact of various PV anomalies, nonlinear, piecewise PV inversion was conducted, using the methodology outlined by Davis and Emanuel (1991). Piecewise PV inversion requires the specification of an appropriate reference state to quantitatively define the anomalies, thus filtering out the planetary-scale flow. Rather than use a centered time-mean approach which would be impossible in operational meteorology, we use the climatological mean flow for the time in question, in the form of the NARR mean computed over 1979-2001 for the appropriate month. Eighteen levels were used in the inversion, ranging from 1000 to 150 hPa, with an interval of 50 hPa. Potential temperature at 975 hPa and 175 hPa was used for the lower and upper boundary conditions, respectively. Lateral boundary conditions are set to zero, as the area of interest remains far from the lateral boundaries.

3. SYNOPTIC OVERVIEW

The upper air analysis from 0000 UTC 5 January through 0000 UTC 6 January is presented in Figure 1. At 0000 UTC 5 January, a 300 hPa jet extended from the desert southwest into the high Plains associated with a closed 500 hPa low near Las Vegas, Nevada. Downstream, another 300 hPa jet extended from the upper Mississippi River valley into the Great Lakes, creating forcing for large-scale ascent in the right rear entrance region. The downstream jet was located along and to the north of a strong thermal gradient at 850 hPa. By 1200 UTC 5 January, the desert southwest jet had shifted east and extended from New Mexico into Iowa. The 500 hPa low had become an open wave located over northern New Mexico. The strong thermal gradient noted at 850 hPa remained nearly stationary across the Plains. Finally, by 0000 UTC 6 January, the 300 hPa jet had ejected into the mid Mississippi River Valley as the 500 hPa system become nearly closed across northern Kansas and southern Nebraska along the thermal gradient.

Precipitation was ongoing across eastern Nebraska and Iowa from 0000 UTC through 0600 UTC January 5 (Fig. 2), partially in response to the previously mentioned forcing in the right entrance region of the 300 hPa jet, but also from strong warm air advection (WAA) and frontogenesis (not shown). Widespread rain with scattered convection was also developing from the Texas panhandle to Illinois near the strong thermal gradient at 850 hPa during this time period. After 0600 UTC January 5, precipitation gradually diminished across Nebraska and Iowa as precipitation continued near the thermal gradient to the south.

Figure 3 is a comparison of WRF pseudo-reflectivity and the actual national radar mosaic product. The WRF initially captures well the anticipated WAA precipitation during the late afternoon and evening of 4 January. Differences quickly develop during the overnight period though. By 0900 UTC, the WRF indicates significant precipitation over Nebraska and southern Iowa while radar has much of Nebraska devoid of precipitation. These differences continued through 1800 UTC 5 January.

Although some decrease in precipitation was expected during the overnight hours as the initial wave of forcing shifted northeast, significant precipitation was expected to quickly redevelop after 0900 UTC 5 January as large-scale forcing for ascent associated with the 500 hPa short-wave approached Nebraska and Iowa. Numerical forecasts available to operational forecasters at the time reflected this, indicating precipitation would take place between 1200 and 1800 UTC 5 January (not shown). A comparison of the WRF and NARR during the 0900 to 1800 UTC 5 January period is presented in figure 4. The WRF produced precipitation across Nebraska and Iowa during this time period, while the NARR indicated that little if any precipitation was actually falling. Both capture well the band of precipitation near the strong thermal gradient from the Texas panhandle into the Ohio Valley.

The synoptic forcing for the widespread precipitation overnight and into the morning of 5 January from the WRF is seen in figure 5. At 1200 UTC, 650 hPa frontogenesis is indicated from eastern Iowa to eastern Kansas in a region of weak symmetric stability. The forcing and weak stability continued in the same general area through 1500 UTC in the area where the WRF has the greatest precipitation accumulation. In contrast, the NARR actually indicated little in the way of frontogenesis occurred and the atmosphere was stable.

4. PV DIAGNOSIS

Comparison of important meteorological fields from the WRF and NARR yield some relevant differences (Fig. 6). At 0900 UTC 5 January, the most significant differences between the WRF model and the NARR analysis are associated with stability seen in the equivalent potential vorticity (EPV) fields, as well as with frontogenesis. These differences are centered over southern Nebraska and Iowa. Here the WRF indicates higher symmetric stability across the area than the NARR along with stronger frontogenesis. Only a minor difference is noted in moisture or in temperature across the area. Given the general agreement in the temperature field, it would appear the frontogenesis dissimilarities would be in response to a difference in the wind field. These differences continue through 1200 UTC 5 January in EPV

and frontogenesis. The WRF continues to indicate more stability across southern Nebraska and Iowa than the NARR. This may be a result of the precipitation generation in the model.
Analyzing a WRF cross section from eastern Kansas to southern South Dakota through the area of persistent precipitation at 0900 UTC 5 January (Fig. 7) indicated strong diabatic heating occurring in a zone from around 850 to 450 hPa. In response to the diabatic heating in the model, there is positive PV tendency around 700 hPa. Above the diabatic heating, the PV tendency is negative, indicating a tendency to destroy upper level PV.

The positive PV tendency in the WRF around 700 hPa appears to have led to the development of a diabatically generated mid-level PV anomaly by 0900 UTC over northern Kansas and Missouri just downstream of the persistent precipitation. The NARR indicates a weaker mid-level anomaly and a position farther to the north across Nebraska and Iowa (Fig. 8).

The development of the mid-level diabatically generated PV anomaly in the model also appears to have had effects on the movement of the upper level short-wave. Figure 8 is the 300 hPa PV from the WRF and NARR. The NARR indicates a 300 hPa short-wave ejecting through Nebraska into the northern Plains, with strong PV advection implied across eastern South Dakota and southern Minnesota. The WRF places this short-wave over southwest Nebraska and northern Kansas with the implied PV advection over southern Nebraska and northern Kansas.

Piecewise PV inversions were performed on the NARR and the WRF on cyclonic PV from 975 to 500 hPa to recover the induced heights and winds (Fig. 9). Although similar across a large part of the domain, the differences in the orientation of the trough axis and wind speeds and direction near the central Plains are significant. The NARR indicates a trough oriented west to east with the axis from central Nebraska into northern Illinois, while the WRF indicated this trough from west central Nebraska into northeast Kansas and northern Missouri. The WRF induced winds are also stronger across Kansas and Missouri and indicate a stronger deformation zone in this area.

The differences in the PV induced winds lead to significant dissimilarities in deformation over northeast Kansas and northern Missouri at 700 hPa (Fig. 10). The stronger deformation is near the same area of differences in frontogenesis (Fig. 6). The stronger deformation leading to enhanced frontogenesis in the WRF appears to contribute to continued precipitation production in the model over this area of frontogenesis.

A piecewise PV inversion was also completed for all cyclonic PV in the 450 to 175 hPa layer to ascertain the influence of upper level PV in the 700 hPa heights and winds (not shown). Both the WRF and NARR agree well over the entire domain with few differences noted, indicating any dissimilarity in upper level cyclonic PV had little effect on the heights and winds near 700 hPa.

5. SUMMARY AND CONCLUSION

The 4-6 January 2005 central Plains winter storm is examined to ascertain the effects, if any, of significant precipitation to the south of the forecast area of heavy snowfall on the warm conveyer belt. Significant precipitation, including scattered convection, developed in a southwest to northeast orientation from the southern Plains to the Ohio Valley early in the event. After convective development, during a 12 hour period from 0900 to 2100 UTC 5 January, precipitation that was forecast to develop over areas of Nebraska and Iowa failed to materialize.

NARR data was used and compared to a WRF model initialized from the NARR data for the time period of the event. Both models were in reasonably good agreement in the development of the extensive precipitation band from the southern Plains to the Ohio Valley, but significant differences were noted between the WRF run and the NARR during this 12 hour period on 5 January. While little appreciable precipitation fell during this period, the WRF continued to indicate significant precipitation. Careful diagnosis of the model indicated differences in the forcing fields over Kansas and Missouri on the morning of 5 January.

The WRF appears to incorrectly develop a mid-level PV anomaly associated with the precipitation band over the southern Plains which the NARR indicates did not develop. This diabatically generated PV anomaly in the WRF model led to significant differences in the evolution of the winter storm during the 12 hour period. Piecewise PV inversions performed on both the WRF and NARR indicated that the mid-level PV anomaly in the WRF led to a strong area of deformation over northeast Kansas into northern Missouri, which led to more frontogenesis in this area. Further comparison of the models indicated little difference in the temperature or moisture in Nebraska and Iowa, but did yield discrepancies in the EPV fields. From the piecewise inversion, it appears that the development of the mid-level diabatically generated PV anomaly allowed for the enhanced wind field, stronger deformation, and continued precipitation production in the model, while in reality, little in the way of precipitation fell (Fig. 11). This may have also occurred in operational models at the time, leading to an overforecast of precipitation during the winter storm.

Convection within models and the associated induced PV anomaly is common in summertime forecasting across the central and eastern United States. Forecasters routinely disregard a particular model solution due to the presence of convective feedback depending on whether convection actually developed or not. Although typically weaker, diabatic heating above a persistent wintertime stratiform precipitation band can lead to the development of a mid-level PV anomaly. Operational forecasters should use real-time observational tools (i.e. radar, satellite, wind profiler data) to monitor the development, movement and effect of PV anomalies during wintertime precipitation events as well while comparing these real-time analysis tools to models to anticipate model errors in handling these features. Although there were no indication from this study of convection “robbing” or “stealing” of southern Plains moisture, the development of a mid-level PV anomaly in the model, which failed to materialize in reality, did lead to a redistribution of the moisture and forcing in the model that was incorrect.

Acknowledgments. This work is supported by COMET grant S07-62782.

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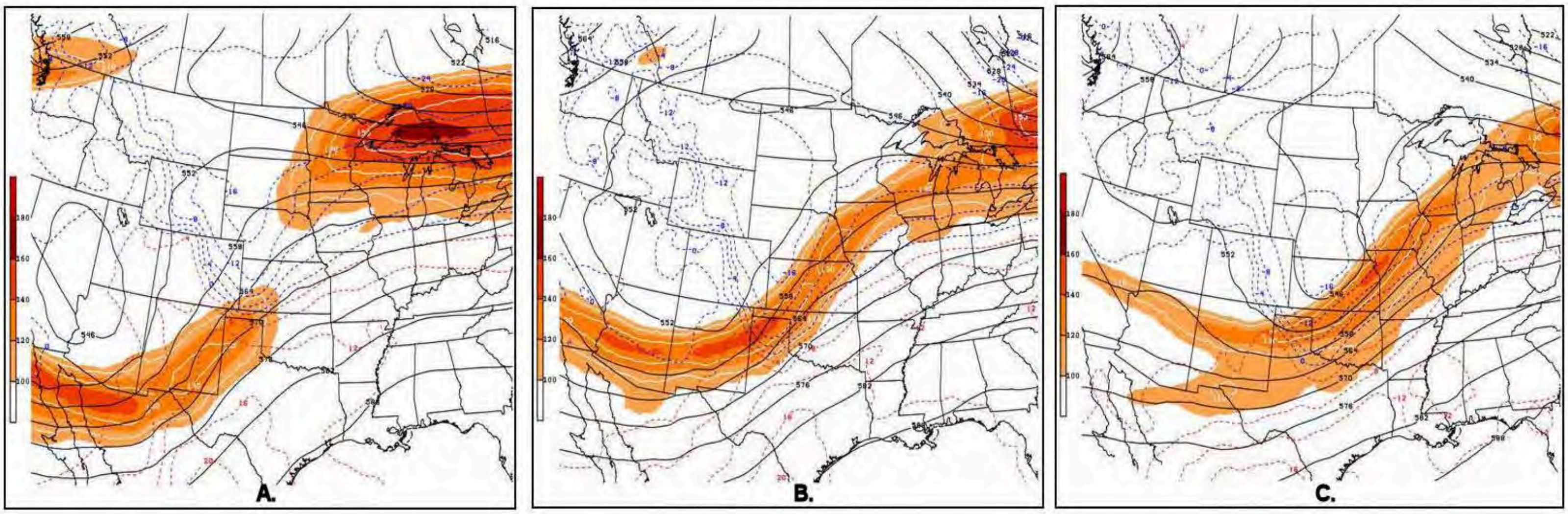


Figure 1. Upper air analysis from 0000 UTC 5 January (A), 1200 UTC 5 January (B), and 0000 UTC 6 January (C). Shading and thin solid while contours are 300 hPa isotaches greater than 100 kt. Thick black contours are 500 hPa, heights. Dashed lines are 850 hPa temperature, blue 0 °C and below, red above 0 °C.

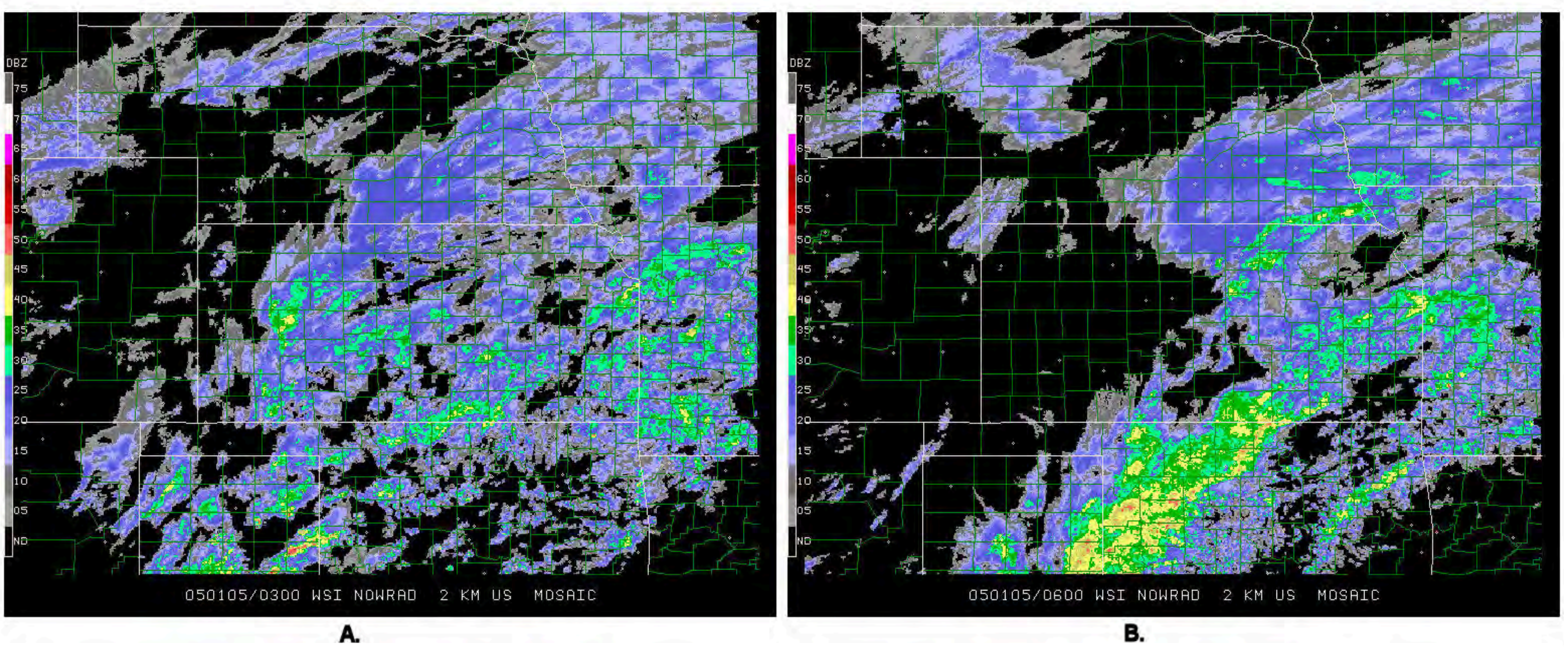


Figure 2. NOWRAD radar data over the central Plains from 0300 UTC 5 January (A) and 0600 UTC 5 January (B).

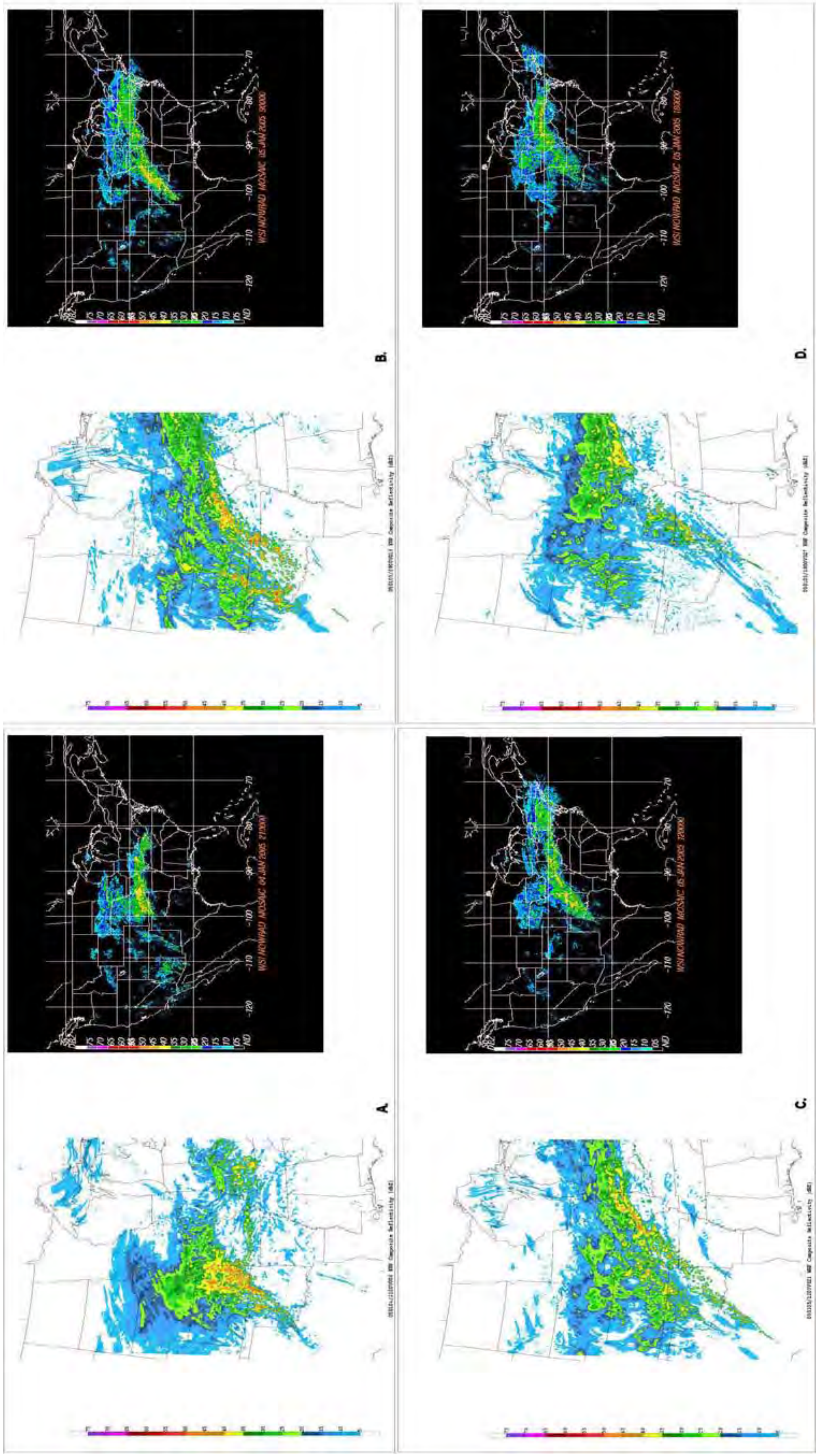


Figure 3. Comparison of psedo reflective from the WRF and NOWRAD radar data for 2100 UTC 4 January (A), 0900 UTC 5 January (B), 1200 UTC 5 January (C), and 1800 UTC 5 January (C).

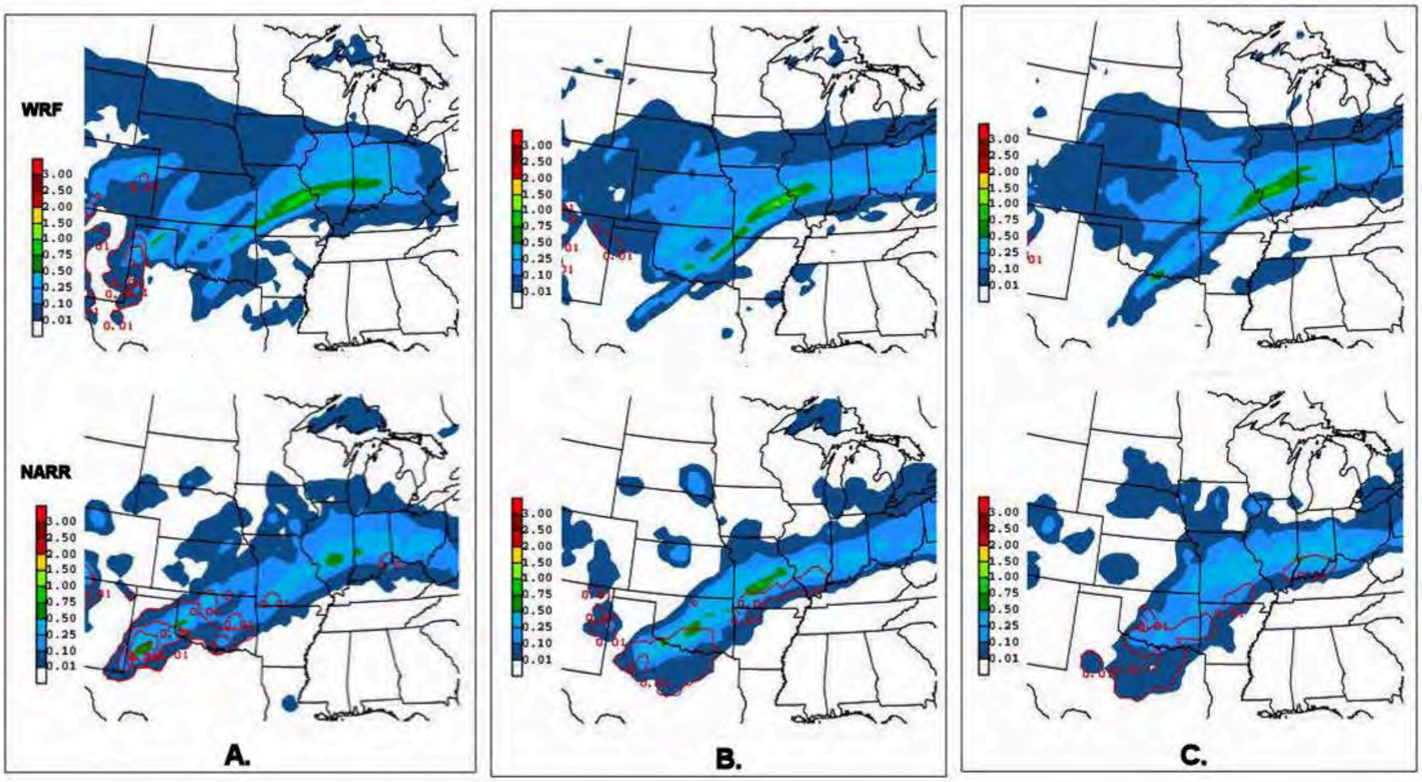


Figure 4. Comparison of 3 hour accumulation precipitation from the WRF (top) and the NARR (bottom) from 0900 UTC (A), 1500 UTC (B), and 1800 UTC (C) from 5 January 2005. Total precipitation is shaded, and contours are convective precipitation.

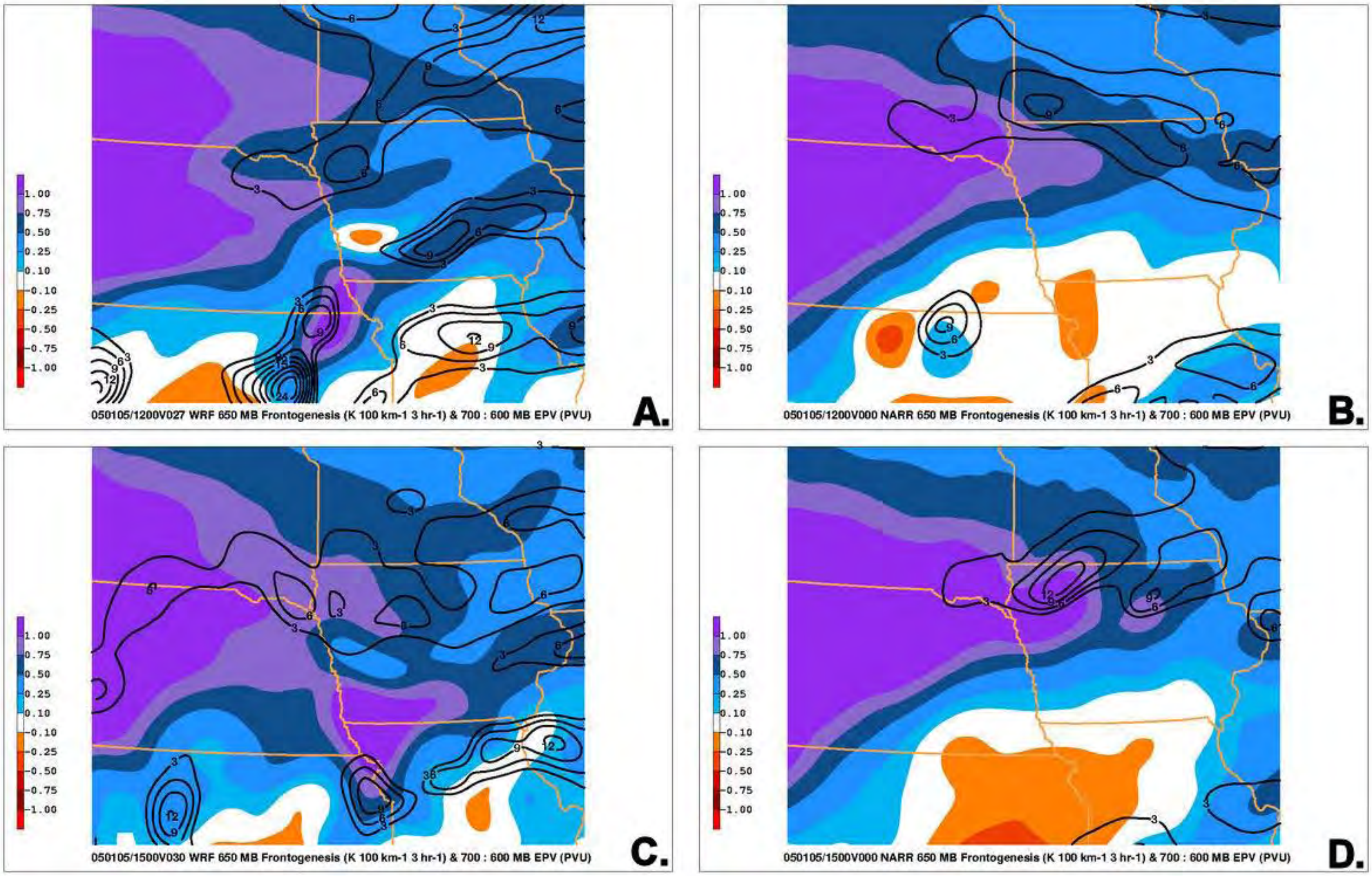


Figure 5. Comparison of 650 hPa frontogenesis K 100 km^{-1} 3 km^{-1} contoured think black lines, and 700 to 600 hPa EPV (PVU) shaded. At 1200 UTC 5 January from the WRF (A), NARR (B), and 1500 UTC 5 January WRF (C), NARR (D).

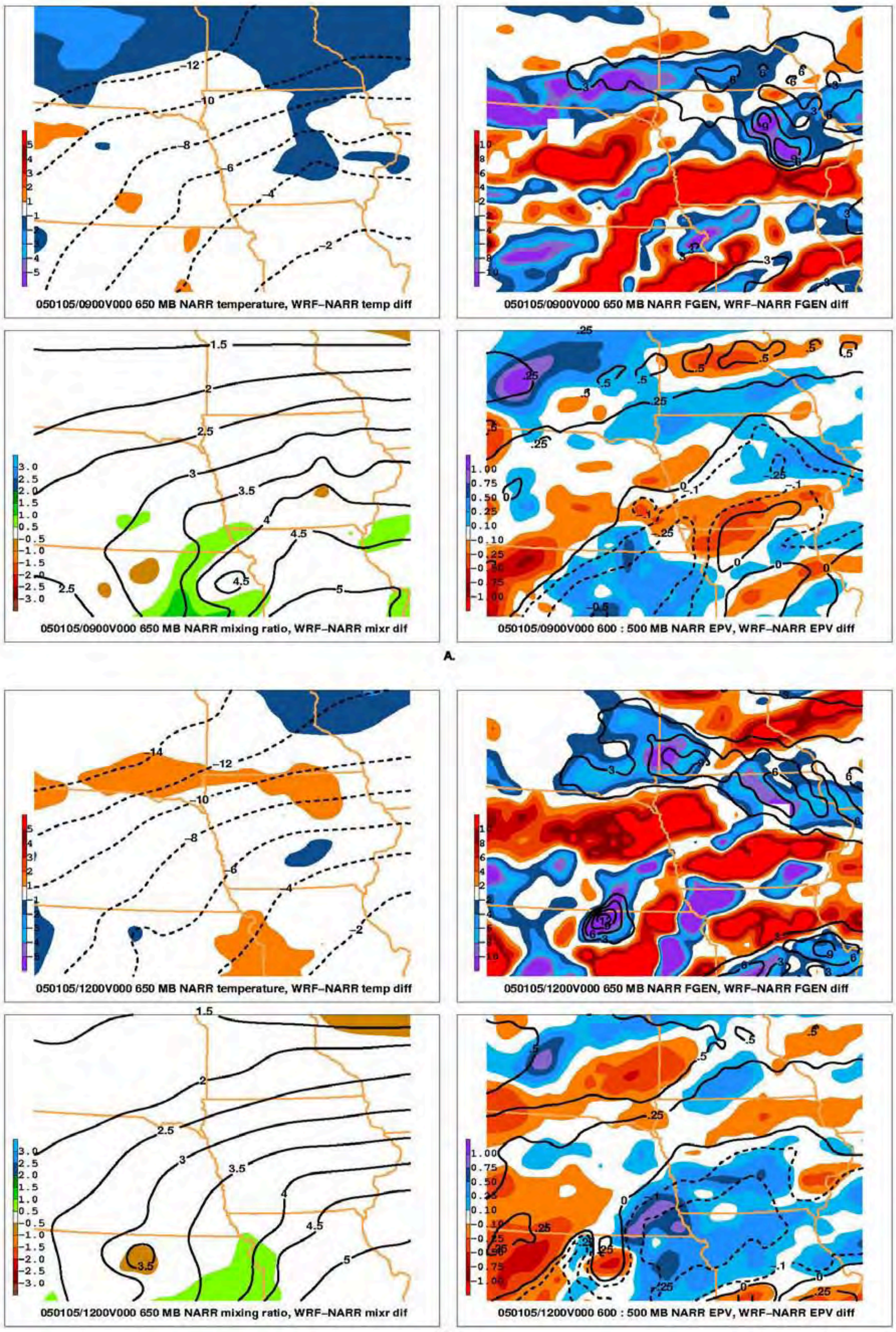


Figure 6. Difference fields, WRF minus NARR in the shading, and NARR values contoured at 0900 UTC 5 January (A) and 1200 UTC 5 January (B). Temperature difference is in top left, frontogenesis top right, mixing ratio bottom left, and EPV bottom right.

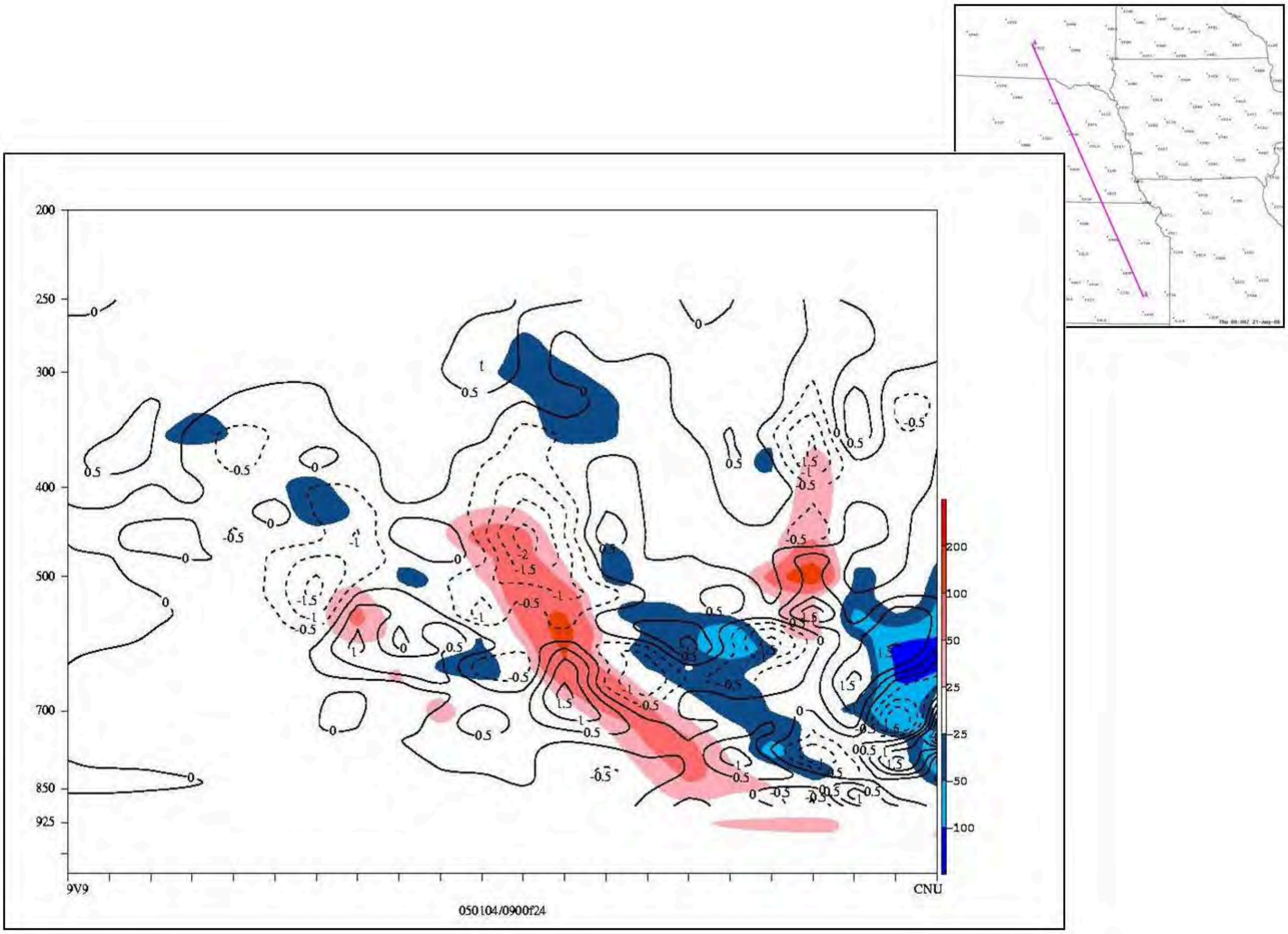


Figure 7. A WRF cross section from Chanute, KS to Chamberlain, SD at 1200 UTC 5 January. The shading is diabatic heating, warm colors positive and cool colors negative. Contours are PV tendency, negative dashed and positive solid contours.

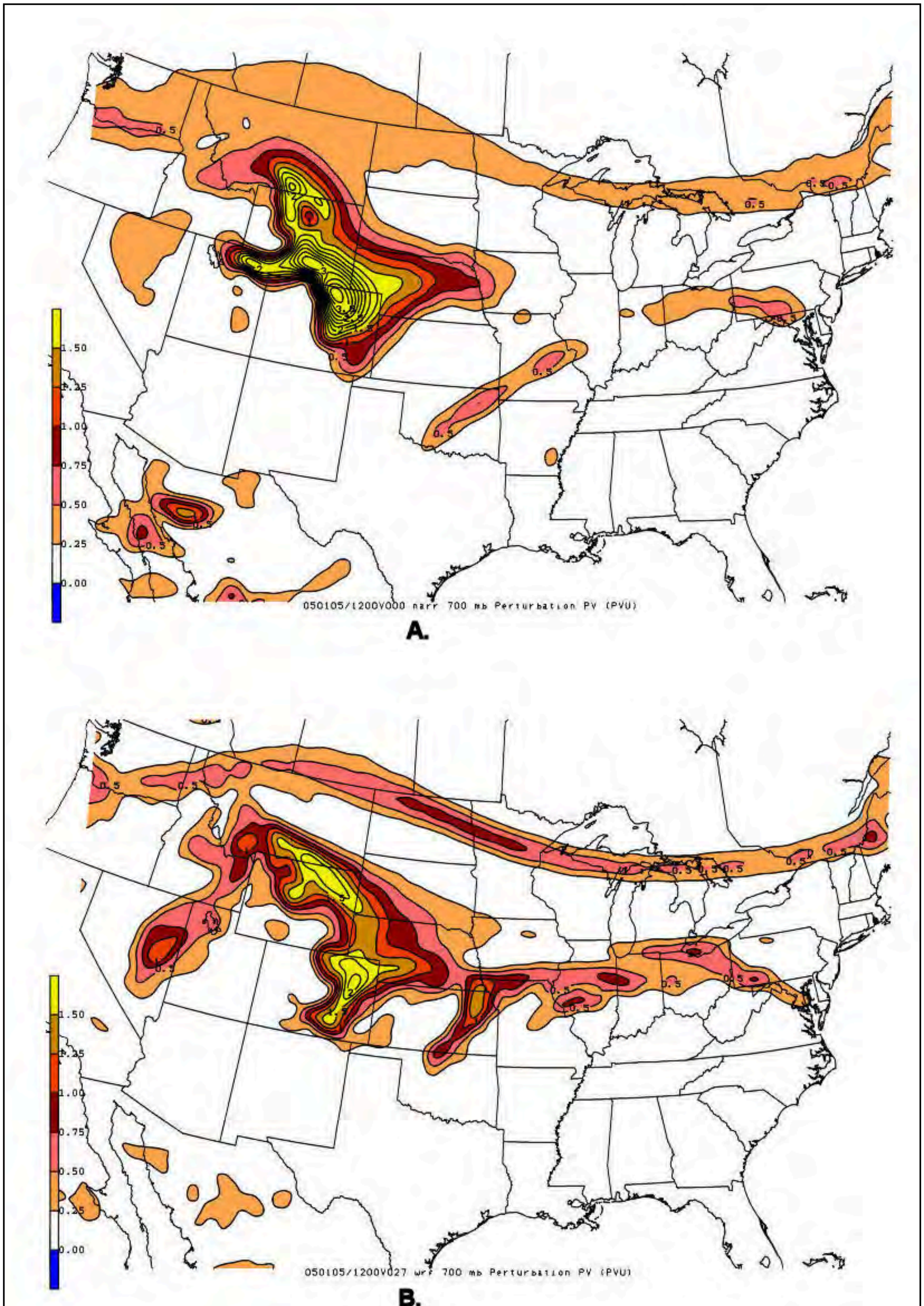


Figure 8. NARR (A) and WRF (B) potential vorticity (PVU) at 700 hPa for 1200 UTC 5 January.

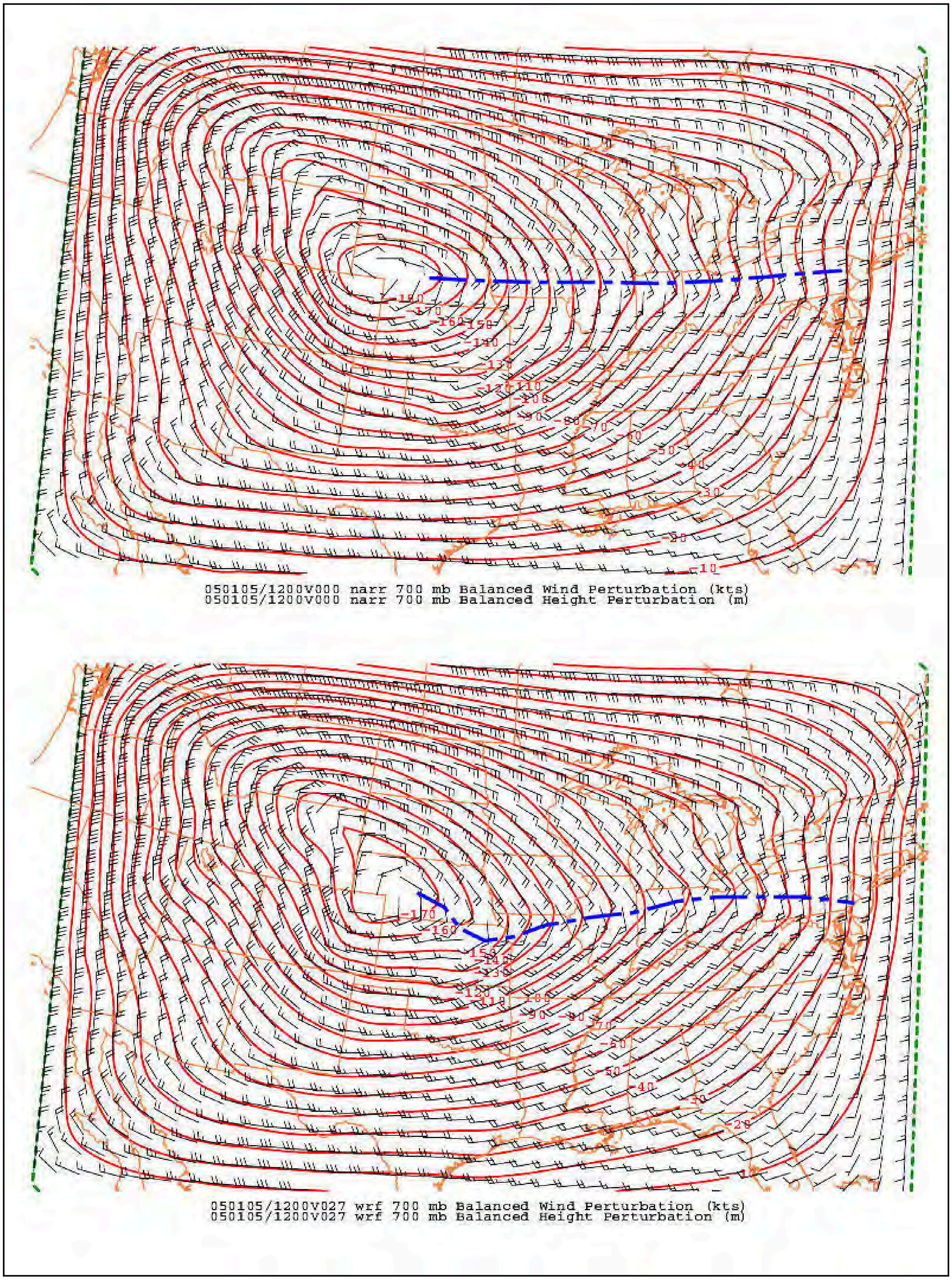
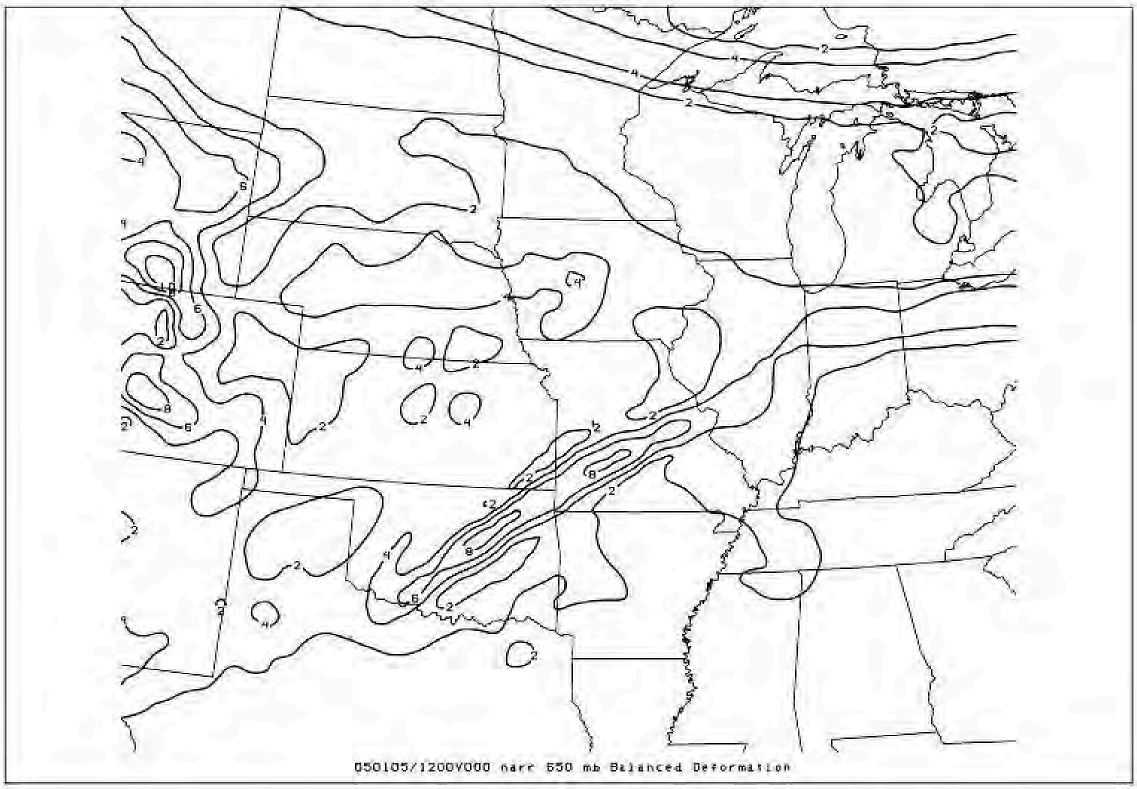
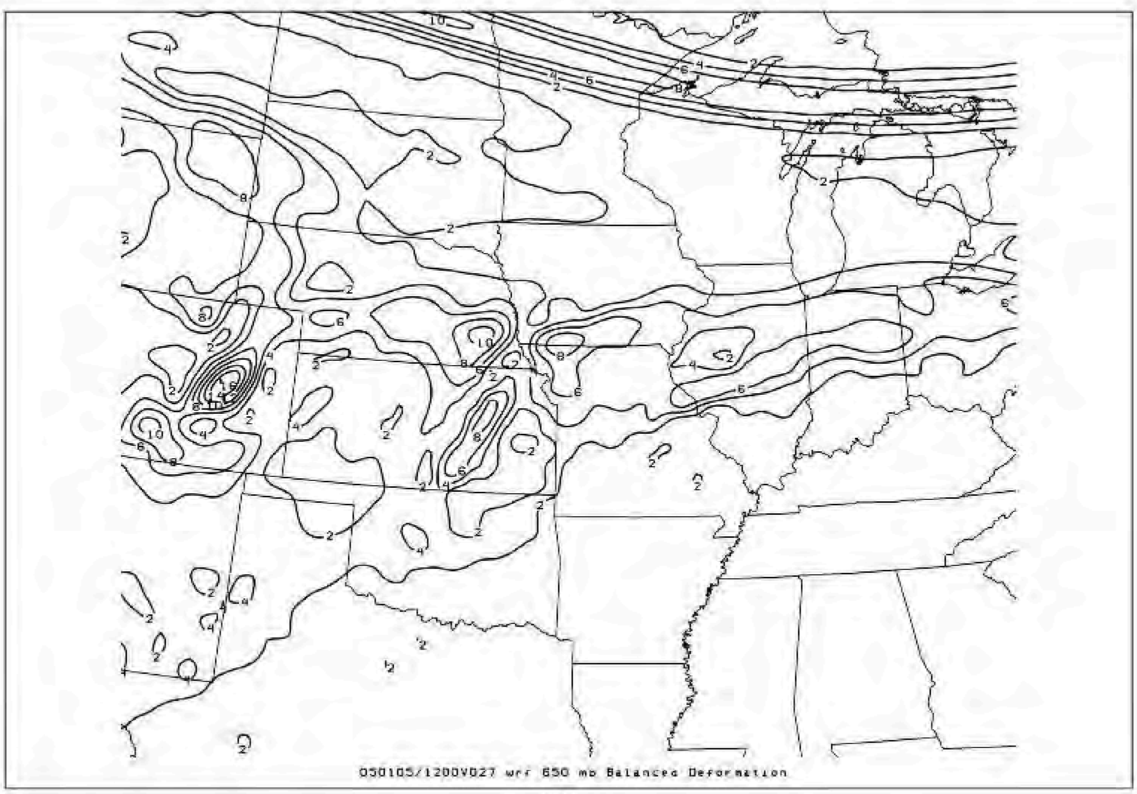


Figure 9. Balanced winds and heights at 700 hPa from 1200 UTC 5 January for NARR (A) and WRF (B). Balanced heights and winds are from PV inversion of all cyclonic PV from 975 to 500 hPa.



A.



B.

Figure 10. NARR (A) and WRF (B) deformation from balanced wind field from PV inversion of cyclonic PV from 975 to 500 hPa at 1200 UTC 5 January.

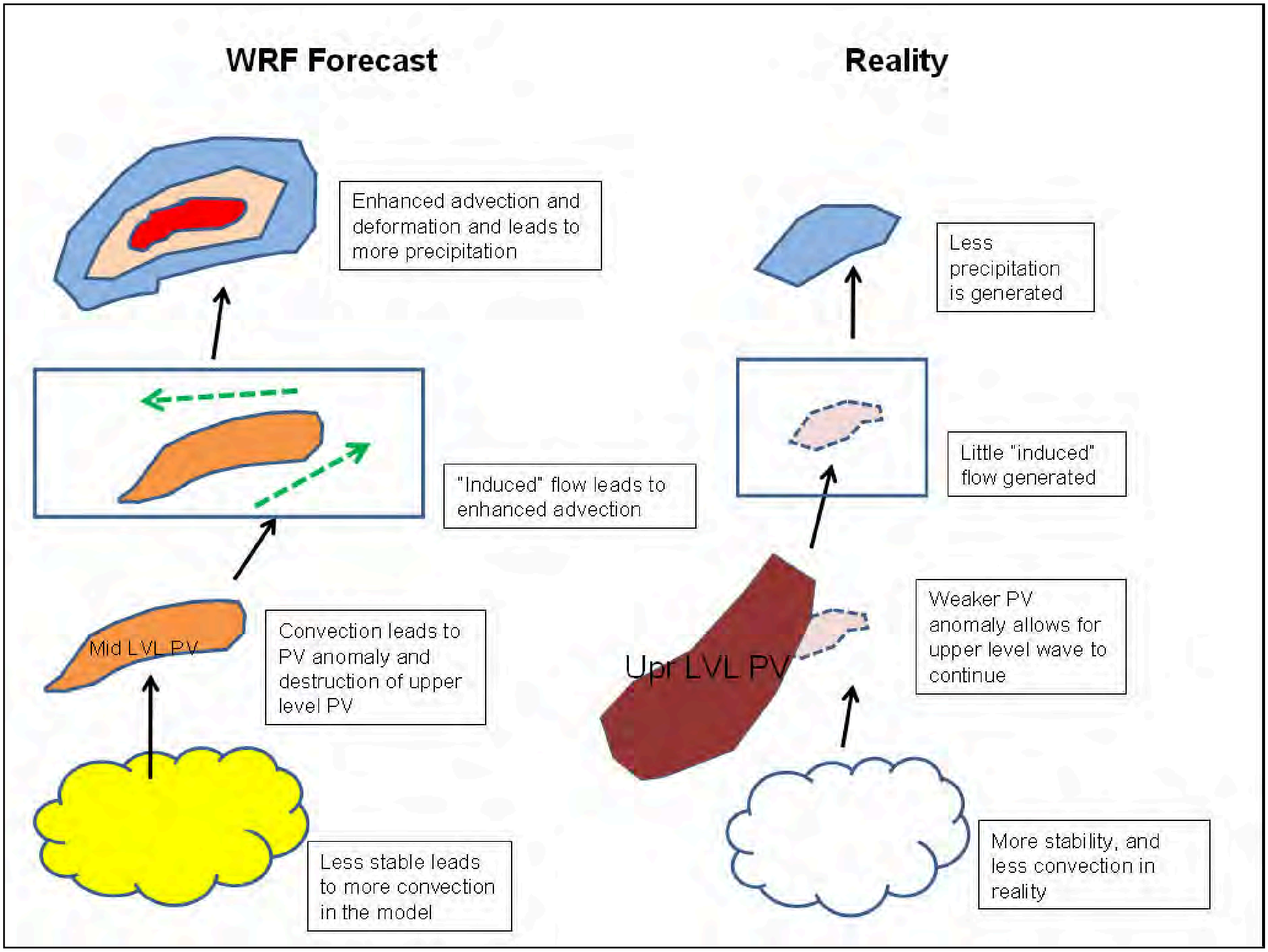


Figure 11. A summary of events which led to the forecasting area from the 4-6 January 2005 central Plains winter storm with WRF on the left and NARR on the right.