

# The Evolution of Mesoscale Ingredients that Created an Intense Mesoscale Snowband on 15 March 2004 in Des Moines, Iowa

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## ABSTRACT

Mesoscale snowbands cause areas of locally heavy snowfall. Over 20 years of research into the formation of mesoscale snowbands has brought a unique understanding into the interaction of ingredients that create snowbands. Recent research has focused on understanding the evolution of the magnitude of mesoscale ingredients. The ingredients necessary for heavy banded snow are moisture, instability, and lift, which often are found to the northwest of the surface cyclone. These ingredients are identified by mesoscale phenomena such as the trough of warm air aloft, frontogenesis, and conditional symmetric instability (found where equivalent potential vorticity is negative). Herein these mesoscale phenomena and diagnostics are investigated and compared to the radar reflectivity of a snowband. This particular case study revealed a pattern in the evolution of frontogenesis and equivalent potential vorticity as the snowband intensified. Further investigation of more cases is needed to confirm this pattern in the evolution of mesoscale phenomena in environments conducive to heavy banded snowfall.

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## 1. Introduction

Forecasting the location and amount of localized heavy snow due to snowbands remains a challenge; however, conceptual models and high-resolution numerical models have improved our ability to predict this mesoscale phenomenon. Moisture, instability, and lift, which are necessary for mesoscale snowband formation, can be created northwest of the low pressure center by mesoscale ingredients/processes such as the trough of warm air aloft (TROWAL), frontogenesis, and conditional symmetric instability (CSI). CSI is typically assessed in the environment via examining values of equivalent potential vorticity (EPV). Negative values of

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EPV indicate that CSI and/or convective instability (CI) are in the environment; hereafter, when referring to CSI, negative EPV will be implied by the notation  $CSI_{EPV^-}$ . These mesoscale phenomena have been investigated since the 1980s, and as a result are more clearly understood in the operational environment (Bennetts and Hoskins 1979; Emanuel 1979, 1983a, 1983b; Sanders and Bosart 1985; Sanders 1986; Moore and Blakley 1988; Nicosia and Grumm 1999; Schultz and Schumacher 1999; Novak et al. 2004; Moore et al. 2005). Continuing to investigate how  $CSI_{EPV^-}$  and frontogenesis interact by identifying patterns in their evolution can further increase our “situational awareness” and forecasting skill during such events.

One of the challenges that remains is conceptualizing the evolution of frontogenesis and  $CSI_{EPV^-}$  and how they change in magnitude as mesoscale bands form, mature, and dissipate. Meteorologists have developed an understanding of the relative roles of the TROWAL, frontogenesis, and  $CSI_{EPV^-}$ . However, there has only been minimal work on how frontogenesis and EPV change in magnitude as snowbands evolve. One particular problem is that the level or layer of frontogenesis and EPV can vary for different events, and they can even vary throughout an event. Banacos (2003) demonstrated that frontogenesis is usually strongest near 700 hPa. It is well known that there is no particular magnitude of frontogenesis to look for; however, the magnitude of EPV has physical meaning. If EPV is negative, the environment is conducive to CSI and/or CI and there is a preference for multiple bands. However, when EPV is positive and less than 0.25, the environment is conducive to weak symmetric stability (WSS), and single band development is preferred (Schumacher 2003).

Questions about how changes in instability, moisture, and lift relate to the snowband life cycle can be addressed through the use of high-resolution observations and model simulations as demonstrated by Novak et al. (2008). Is there a pattern to how frontogenesis and  $CSI_{EPV^-}$  evolve,

or is each storm unique in the evolution of these ingredients? This article focuses on documenting the physical model in Nicosia and Grumm (1999), which describes the positive feedback mechanism between frontogenesis and EPV ([Fig. 1](#)). The evolution of the magnitude of frontogenesis and EPV as bands develop, mature, and dissipate will be examined through analysis of 20-km Rapid Update Cycle (RUC) model data.

It is hypothesized that there are two possible patterns related to the positive feedback mechanism in the evolution before a band intensifies: (1) a sharp increase in frontogenesis just before EPV is reduced or (2) a sharp increase in frontogenesis after EPV is reduced. These patterns are consistent with the feedback between frontogenesis and EPV ([Fig. 1](#)). The alternative hypothesis is that the positive feedback is not taking place and there is no association between the reduction in EPV and the increase in frontogenesis. This type of investigation will provide more insight into how frontogenesis and EPV interact and evolve to form mesoscale snowbands. Through the investigation of numerous cases, an identified pattern in the evolution of mesoscale snowbands eventually may be applied operationally for anticipating when a mesoscale snowband will intensify.

## **2. Background**

Previous studies have been integral in documenting the interaction of the ingredients important for mesoscale snowband events (Sanders and Bosart 1985; Moore and Blakley 1988; Nicosia and Grumm 1999). For example, Nicosia and Grumm (1999, see their Fig. 17) and Moore et al. (2005, see their Fig. 15) show how the interactions of the conveyor belts in the

vicinity of an extratropical cyclone create an environment favorable for heavy banded snow where the zone of reduced EPV overlays the warm side of the frontogenesis region.

The interactions of the conveyor belts provide moisture, instability, and lift. Moisture and instability are provided by the TROWAL, lift is associated with midlevel frontogenesis, and the dry conveyor belt is associated with enhancing instability. The cyclonically curving branch of the warm conveyor belt—the TROWAL—was studied extensively by Martin (1998a,b). It wraps cyclonically into the extratropical cyclone and provides moisture and instability in the environment northwest of the low pressure center. Additionally, the bifurcation of both the warm and cold conveyor belts north of the warm front creates deformation (Martin 1998a,b; Schultz 2001). The deformation acts on the potential temperature gradient through stretching and shearing, resulting in midlevel frontogenesis northwest of the surface low pressure center. The role of the dry conveyor belt is to destabilize the atmosphere through the advection of midlevel dry air over low-level moist air.

Frontogenesis is the Lagrangian time rate of change of the magnitude of the horizontal potential temperature gradient. Petterssen (1956) expressed it as:

$$F = \frac{1}{2} |\nabla \theta| [Def_r \cos(2\beta) - Div] \quad (1)$$

where  $\nabla \theta$  is the potential temperature gradient,  $Def_r$  is the resultant deformation,  $\beta$  is the angle between the isentropes and the axis of dilatation, and  $Div$  is divergence. Emanuel (1985) showed the frontogenesis circulation is enhanced/modified in the presence of WSS, with the upward branch of the ageostrophic vertical circulation contracting and becoming stronger.

According to Nicosia and Grumm (1999), an increase in frontogenesis increases the vertical wind shear, and in turn differential moisture advection is enhanced as the dry conveyor belt overlays low-level moisture northwest of the surface low pressure center. The differential moisture advection steepens the  $\theta_e$  isentropes and EPV is reduced; a reduction in EPV then increases frontogenesis again (Fig. 1). This nonlinear process continues as frontogenesis and reduced EPV interact. Areas impacted by frontogenesis and  $CSI_{EPV}$  have the potential to receive heavier snowfall due to the contraction of mesoscale ascent into enhanced, narrow bands. Therefore, heavy banded snow is a result of the synergistic interaction of the conveyor belts and mesoscale ingredients. Identifying the interaction between frontogenesis and EPV is integral, but an understanding of CSI, WSS, and CI is necessary to ascribe physical meaning to values of EPV.

CSI is an instability in which air parcels are stable with respect to horizontal and vertical motions, but unstable with respect to slantwise motion. It occurs in environments with strong anticyclonic shear, strong vertical shear, and low static stability (Moore and Lambert 1993). Slantwise convection arises from the release of latent heat during slantwise ascent of a parcel in a saturated environment (Bennetts and Sharp 1982).

A means to assess the atmosphere for areas of CSI, CI, or WSS can be done by examining EPV. CSI is present in a baroclinic, saturated environment when EPV is negative and the atmosphere is statically stable ( $\partial\theta_{es}/\partial p < 0$ ). EPV was described by McCann (1995) as a diagnostic tool capable of evaluating a mixture of CI and CSI. Moore and Lambert (1993) expanded the EPV equation following Martin et al. (1992) to yield a two-dimensional version:

$$EPV = g \left[ \left( \frac{\partial M_g}{\partial p} \frac{\partial \theta_{es}}{\partial x} \right) - \left( \frac{\partial M_g}{\partial x} \frac{\partial \theta_{es}}{\partial p} \right) \right] \quad (2)$$

(A)                      (B)

where  $M_g$  is the absolute geostrophic momentum. Term (A) represents the contribution to EPV from the vertical wind shear and the horizontal temperature gradient. Therefore, when the vertical wind shear and the horizontal temperature gradient are large, EPV becomes negative, indicating the presence of CI or CSI. Term (B) represents absolute vorticity and a measure of convective stability. CSI requires an inertially stable and statically stable environment. Under these conditions  $\partial M_g / \partial x$  will be positive and  $\partial \theta_{es} / \partial p$  will be negative. Therefore, Term (B) will be a smaller negative number than Term (A) and EPV will be negative. The interaction and evolution of frontogenesis and  $CSI_{EPV}^-$  will be investigated in the case study below.

### 3. Data

The General Meteorological Package (GEMPAK, desJardins et al. 2002) was used to analyze upper-air data, model data, satellite imagery, and radar imagery. Surface maps were obtained from the Hydrometeorological Prediction Center (HPC) and the upper-air data were obtained via Unidata's Internet Data Distribution. The upper-air data were collected for over 100 stations across the United States spaced approximately 400 km apart. The 20-km 3-hourly RUC initialization model data were obtained from the Atmospheric Radiation Measurement (ARM) Program sponsored by the United States Department of Energy, Office of Science, Office of Biological and Environmental Research, Environmental Sciences Division. Level III

WSR-88D radar data were obtained from the National Climatic Data Center and satellite data were obtained from the Space Science and Engineering Data Center at the University Wisconsin-Madison.

#### **4. Event overview**

This case was characterized by an east-west oriented snowband over Des Moines, Iowa. A radar animation ([Fig. 2](#)) depicts the main band's formation, maturation, and dissipation. The band began to form about 0930 UTC 15 March 2004, as multiple bands aligned northwest-to-southeast merged. The band was initially oriented northwest to southeast and extended from southeastern South Dakota into northeastern Nebraska and western Iowa. The main band continued to propagate east and began to rotate counterclockwise around 1200 UTC. It developed an east-west orientation and remained quasi-stationary over Des Moines. By 1900 UTC, the main band began to weaken on radar imagery. However, multiple bands persisted over Des Moines from 2015–2245 UTC. Another band formed and moved southeast, but dissipated by 1015 UTC 16 March 2004. The heaviest snow fell over west-central Iowa with 46.7 cm (18.4 inches) in Sioux City and 39.6 cm (15.6 inches) in Des Moines ([Fig. 3](#)).

Synoptically, a surface low pressure system moved southeast from western Nebraska into Kansas and Missouri, and experienced weak cyclogenesis over its life cycle ([Fig. 4](#)). Observations show the upper-level features were characterized by a broad trough over the Midwest ([Fig. 5](#)), and RUC data show upper-level divergence at the right entrance region of a jet streak over Iowa ([Fig. 6](#)). RUC data were filtered to 80-km for Q-vector analysis, and the results indicated there was synoptic scale ascent associated with the shortwave trough as it traversed

Iowa and Illinois ([Fig. 7](#))—albeit the Q-vector fields still were rather noisy. By 1200 UTC 15 March the system had a closed circulation at 850 hPa over Nebraska, coincident with band intensification (Figs. [2](#) and [5](#)). This system would be classified as the frontal/weak cyclogenesis pattern from Banacos (2003) since it was characterized by a positively tilted 700-hPa trough and downstream confluent flow.

## 5. Snowband formation phase

As the band was forming around 0930 UTC, the presence of a TROWAL feature indicated warm, moist air was in the vicinity of the low pressure system ([Fig. 8](#)); the TROWAL became well defined from 0900–1200 UTC as the 700-hPa trough deepened. Cross sections were taken from Duluth, Minnesota (DLH), to Oklahoma City, Oklahoma (OKC), and from DLH to Springfield, Missouri (SGF), to analyze  $CSI_{EPV}$  and frontogenesis. During the initial formation until about 1100 UTC, frontogenesis was in the presence of WSS as noted by the  $M_g$  surfaces parallel to the  $\theta_e$  isentropes within the saturated region near DSM ([Fig. 9](#)). CSI was evident by 1100 UTC ([Fig. 10](#)) as indicated by (i) the defined region of  $EPV < 0$  above the region of frontogenesis, (ii) the lack of  $\theta_e$  folding in a saturated environment, and (iii) absolute geostrophic vorticity  $< 0$  (to rule out CI and inertial instability). CSI was present as a consequence of the  $M_g$  surfaces being flatter than the  $\theta_e$  surfaces. Technically this is PSI (potential symmetric instability), but  $\theta_e$  can be used in place of  $\theta_{es}$  when the atmosphere is saturated. This “flattening” was also a sign of increased wind shear in the environment due to increased frontogenesis. The cross section reveals that frontogenesis and EPV can be adequately examined at the 750-hPa level and the 750–600-hPa layer, respectively. Accordingly,

overlaying frontogenesis and EPV on the radar imagery shows the band formation was coincident with the region of reduced EPV above the region of frontogenesis ([Fig. 11](#)).

## 6. Snowband mature phase

The band's maturity occurred during a 7-h period from 1200–1900 UTC. During the mature phase, the TROWAL was present, but not characteristically “wrapped” into the system due to weak cyclogenesis ([Fig. 12](#)). In the cross sections ([Fig. 13](#)) there was a region of reduced EPV above the frontogenesis, but by 1800 UTC there was a larger region of reduced EPV—coincident with the dry slot—approaching from the south. As the ageostrophic circulation vectors significantly increased in magnitude, the band intensified and the vectors became more parallel to the  $\theta_e$  isentropes—evidence of a mesoscale circulation (cf. the upper-right and lower-left panels in [Fig. 13](#)). The region of EPV < 0 portended the release of CSI and CI at later time periods. At 1400 UTC there were folded  $\theta_e$  isentropes near OKC, and they were closer to the band by 1700 UTC ([Fig. 14](#)). The folded  $\theta_e$  isentropes within a saturated environment were an indication of CI developing as a result of advection of midlevel dry air over low-level moist/warm air. CI can be diagnosed (rather than potential instability) in [Fig. 14](#) if relative humidity is plotted with  $\theta_e$  (see Moore et al. 2005). During the mature phase the band became quasi-stationary over Des Moines and was located within a region of slowly increasing wind shear. The increased vertical wind shear was important for the flattening of the  $M_g$  surfaces, necessary for the presence of CSI from 1100–1700 UTC before CI developed in the environment ([Fig. 14](#)). The band intensified as the dry slot approached from the southwest around 1700 UTC, contributing to the reduction in EPV. On the southwestern side of the band, CI and upright

convection began to dominate over CSI (see folded  $\theta_e$  isentropes in the cross section from DLH to OKC). However, CI was not yet evident on the eastern side of the band at 1900 UTC (cf. Figs. [13](#) and [14](#)).

In an effort to understand how the environment changed as the band approached, the average evolutions of frontogenesis and EPV were plotted. [Appendix A](#) outlines the procedures that were used to obtain the average frontogenesis and EPV at ten points across the band. This same type of investigation for more cases can help identify if there is a systematic pattern that could be used as a forecast tool to anticipate the time of heaviest snowfall and to better understand the evolution of ingredients in the environment. The average evolution of frontogenesis and EPV was only plotted until 2300 UTC, because the initial band dissipated by 2200 UTC 15 March 2004 and another band formed and dissipated by 1015 UTC 16 March 2004 ([Fig. 15](#)). In the graph, frontogenesis was maximized while EPV was minimized, demonstrating the positive feedback as described by Nicosia and Grumm (1999). Specifically, EPV was close to zero from 0700–1300 UTC, indicating the presence of WSS, CSI, or CI. In this particular case, EPV was reduced 3-h prior to formation and frontogenesis was maximized coincident with band intensification at 1200 UTC. The average evolution was plotted again and used to forecast the second band that developed after 2200 UTC ([Fig. 16](#)). Frontogenesis decreased with time; but when EPV was close to zero, frontogenesis maximized again. This positive feedback occurred when the second band was mature from 0300–0500 UTC. If this pattern is observed and confirmed in more cases, a program could be developed to calculate these average values and used in a real-time, operational setting.

## 7. Snowband dissipation phase

There is a clear dissipation of the band at 1900 UTC on radar imagery; however, the frontogenesis did not significantly decrease in magnitude until 2200 UTC ([Fig. 17](#)). The main band dissipated after 2200 UTC, but multiple bands merged and strengthened to form another band. The new band intensified, moved southeast, and dissipated after 1015 UTC 16 March 2004. During this time, the TROWAL moved southeast ([Fig. 18](#)) as the system traversed the Midwest. After 2200 UTC, reduced EPV was no longer in the region, and frontogenesis continued to decrease ([Fig. 19](#)). The dry filament appeared to help intensify the band before it dissipated by destabilizing the environment, but once a significant amount of dry air was over Des Moines, the band actually began to break up after 2200 UTC. Examination of the cross section from DLH to SGF shows there was CSI in the environment from 0300–0500 UTC while the second band was mature ([Fig. 20](#)).

## 8. Conclusions

Examination of the mesoscale ingredients revealed their evolution and interaction during a Midwest snowband event. This case demonstrated characteristics represented in the conceptual models from Nicosia and Grumm (1999) and Moore et al. (2005), where reduced EPV indicated instability was superimposed over midlevel frontogenesis—producing heavy banded snow. A more detailed investigation into the evolution of these ingredients within the band revealed that frontogenesis peaked just as the band was intensifying and EPV was close to zero. The average evolution was applied to the second band that formed after 2200 UTC 15 March 2004, and again

indicated another positive feedback between frontogenesis and EPV. Evaluation of one case is not sufficient to provide a robust forecast model; therefore, more cases need to be tested to establish the validity of the average evolution being used as a forecast tool to predict the positive feedback, intensification, and maturity of a band.

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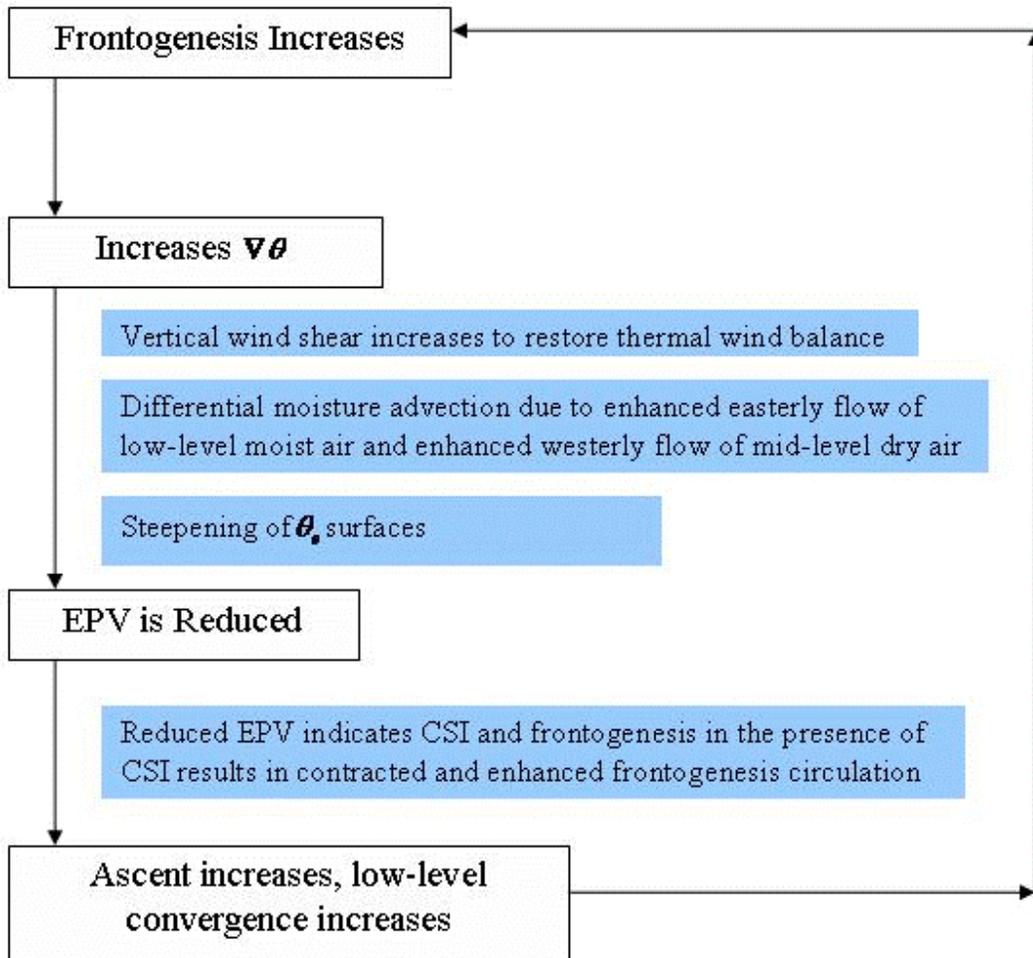
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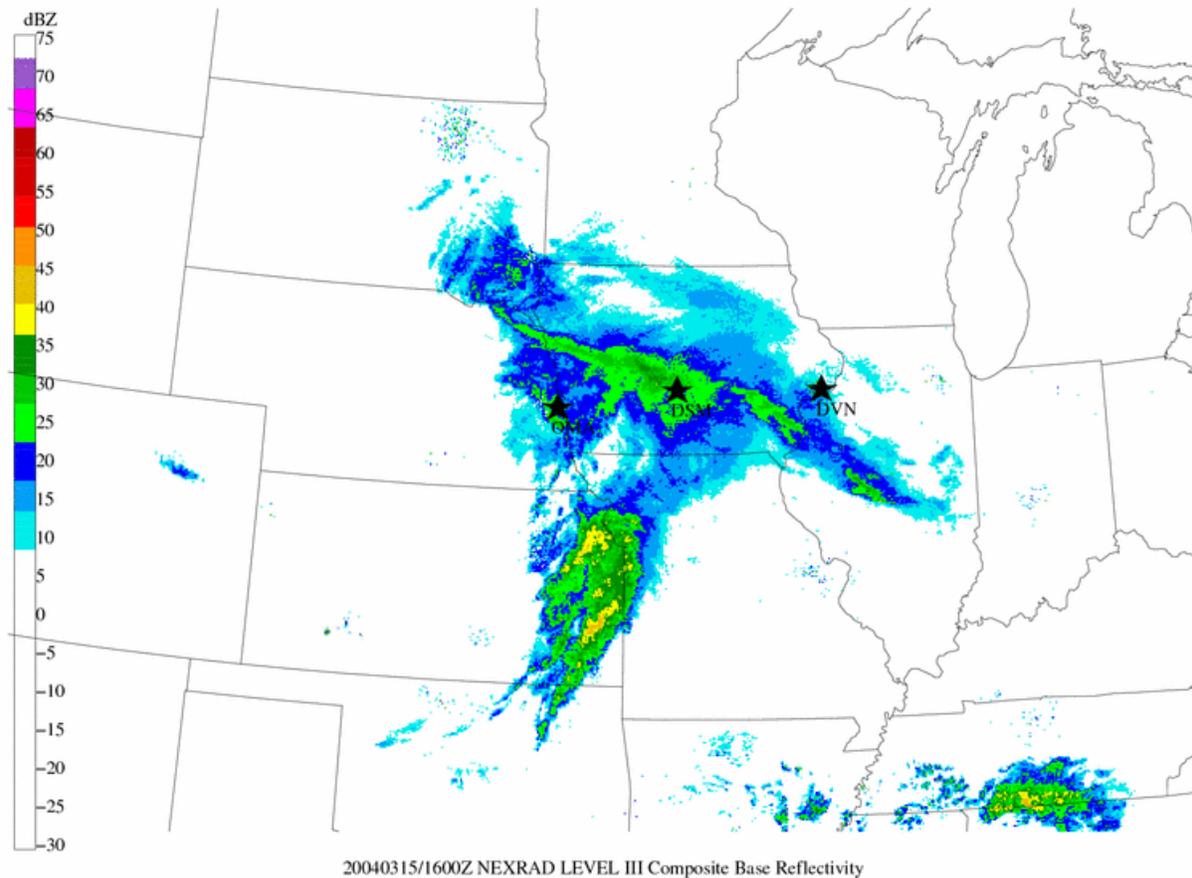
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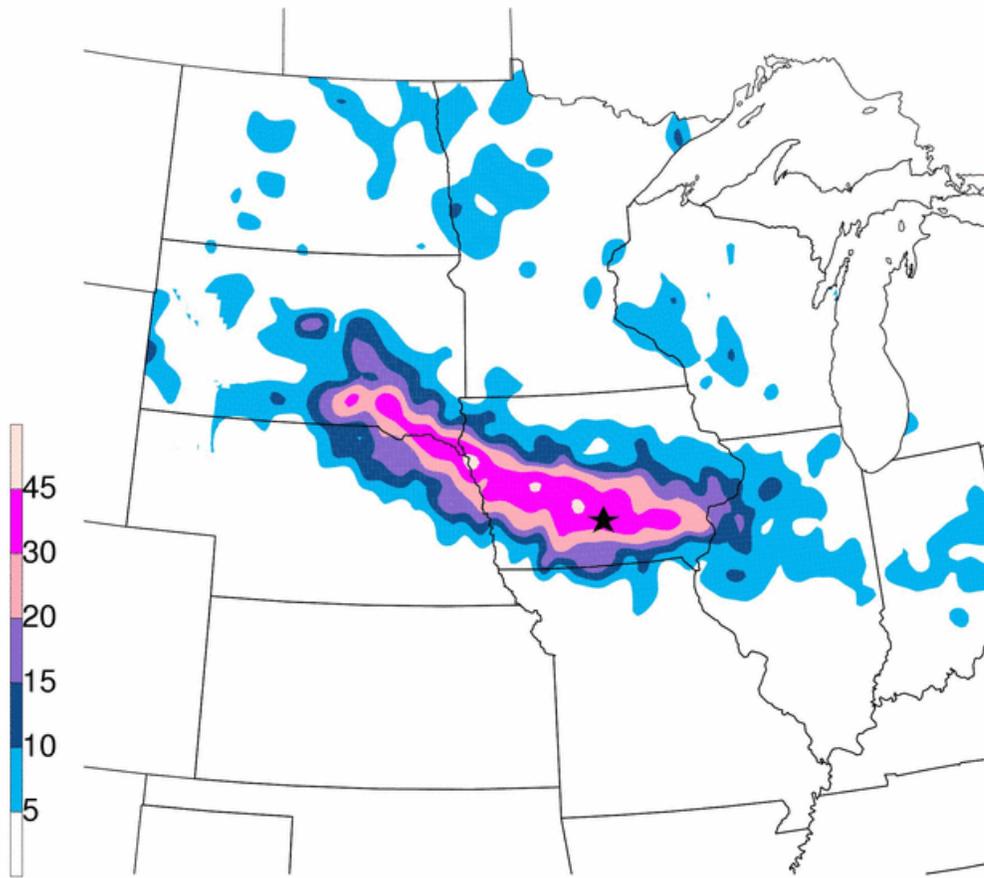
## TABLES AND FIGURES



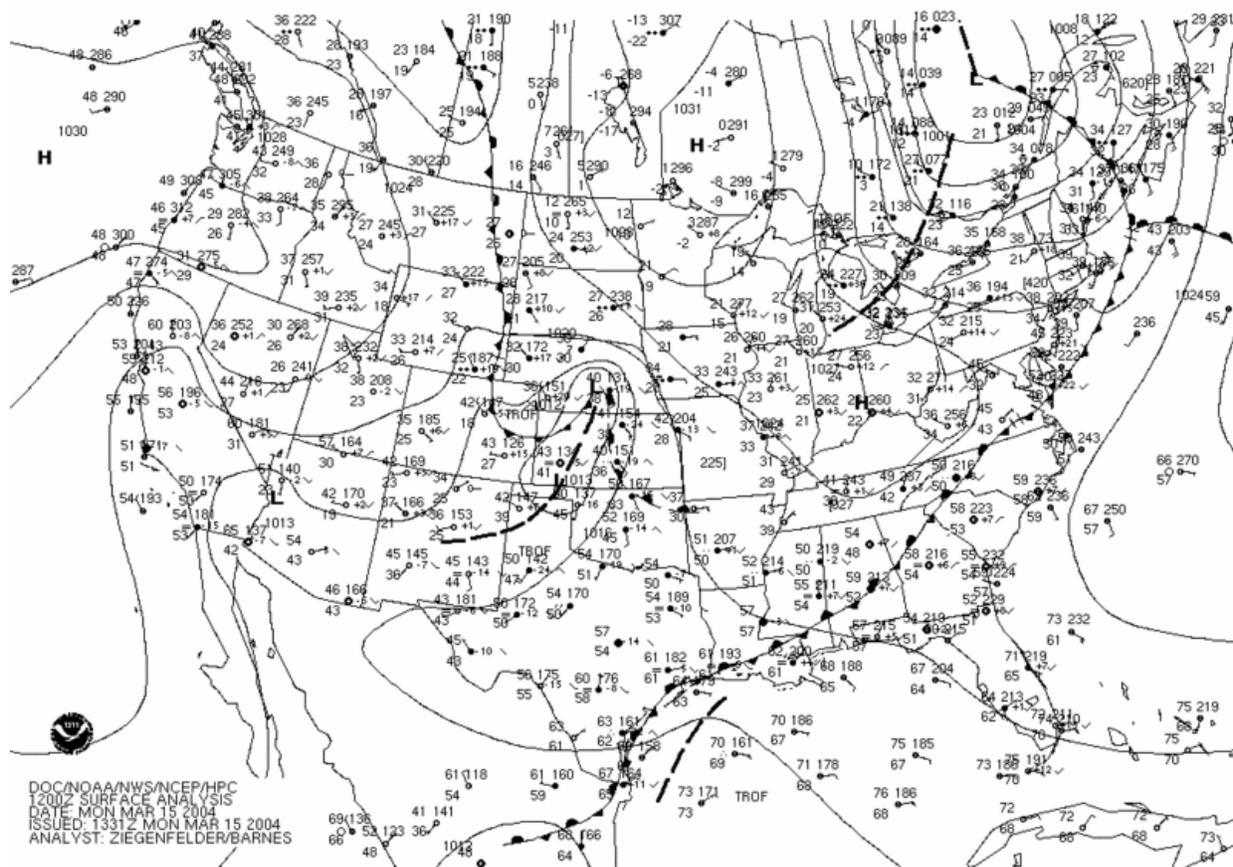
**Figure 1.** Schematic of positive feedback mechanism between frontogenesis and reduced EPV (adapted from Nicosia and Grumm 1999).



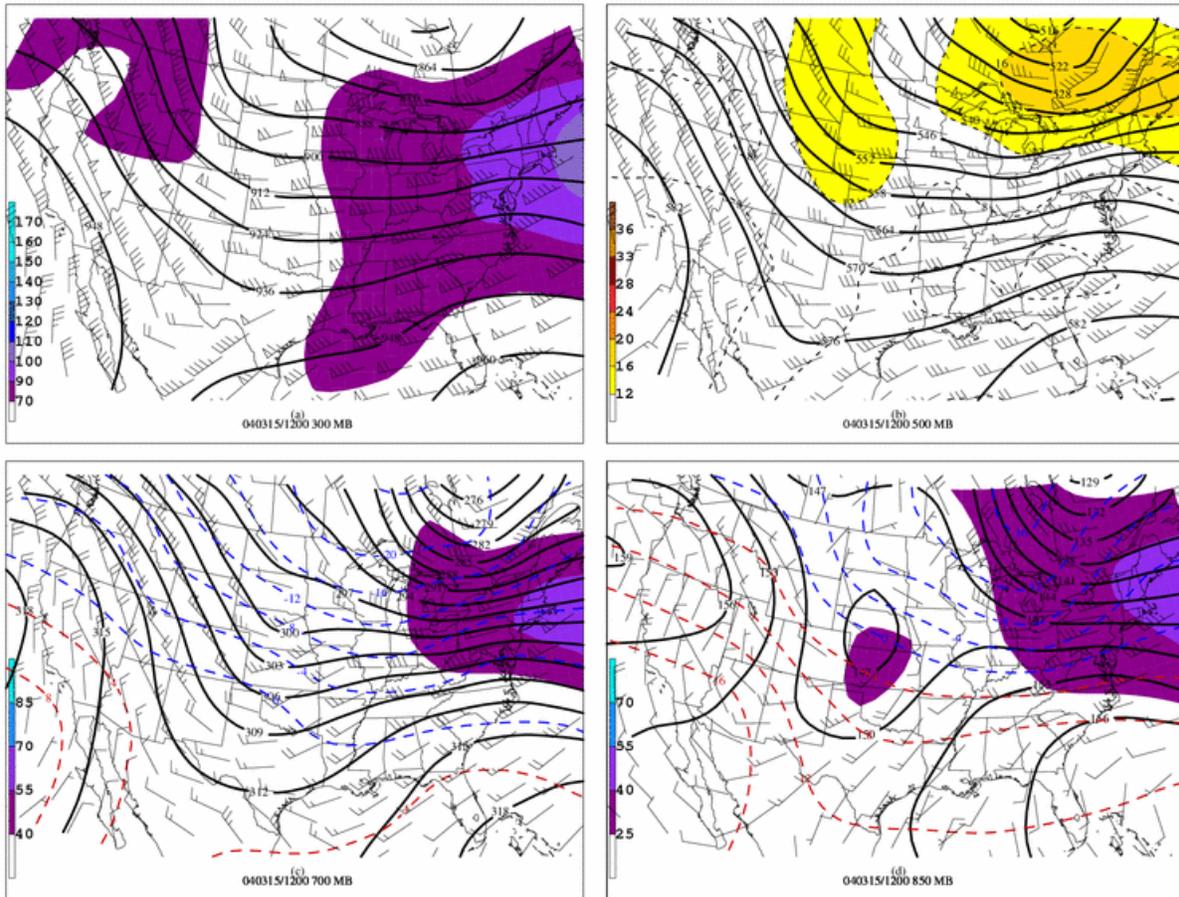
**Figure 2.** NEXRAD level III composite reflectivity animation from 0600 UTC 15 March 2004 to 1200 UTC 16 March 2004. Black stars indicate the locations of Omaha, NE (OMA), Des Moines, IA (DSM), and Davenport, IA (DVN). Note that the animation is limited to the html version of this paper, and only the most pertinent image of the animation (1600 UTC 15 March 2004) is given in the PDF version.



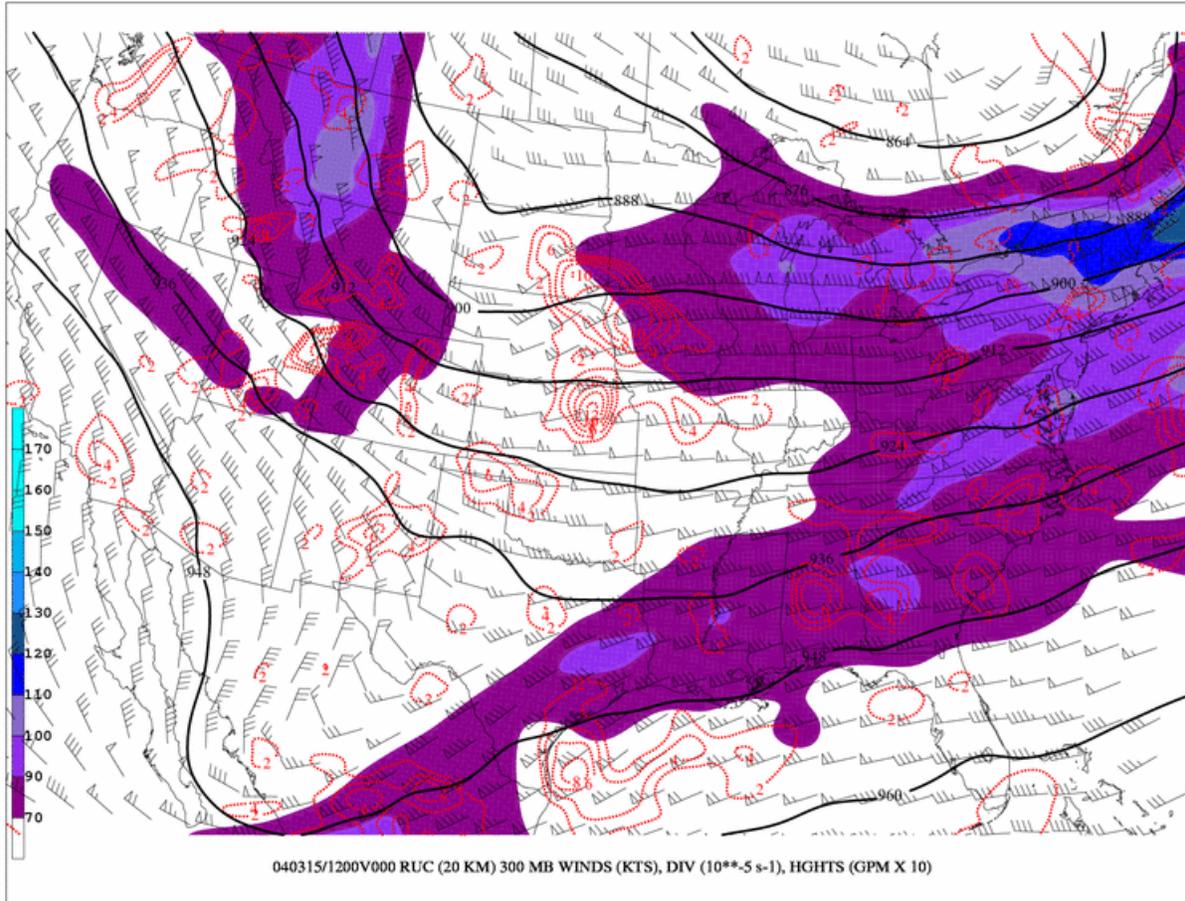
**Figure 3.** 48-h snowfall map of cooperative observer (COOP) data ending at 1200 UTC 16 March 2004. The black star indicates the location of Des Moines, IA. Units are in cm.



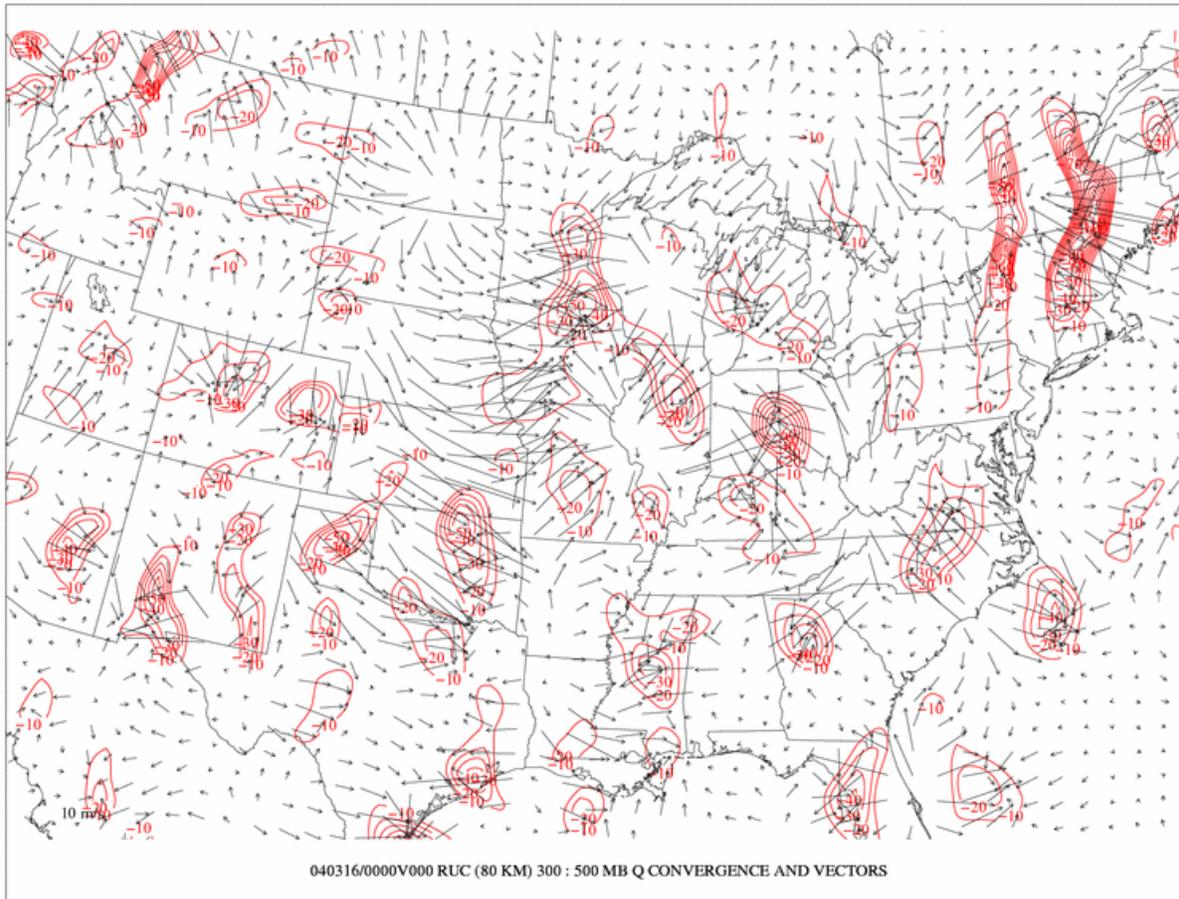
**Figure 4.** Animation of the surface analyses from HPC from 1800 UTC 14 March 2004 to 1200 UTC 16 March 2004. Note that the animation is limited to the html version of this paper, and only the most pertinent image (1200 UTC 15 March 2004) of the animation is given in the PDF version.



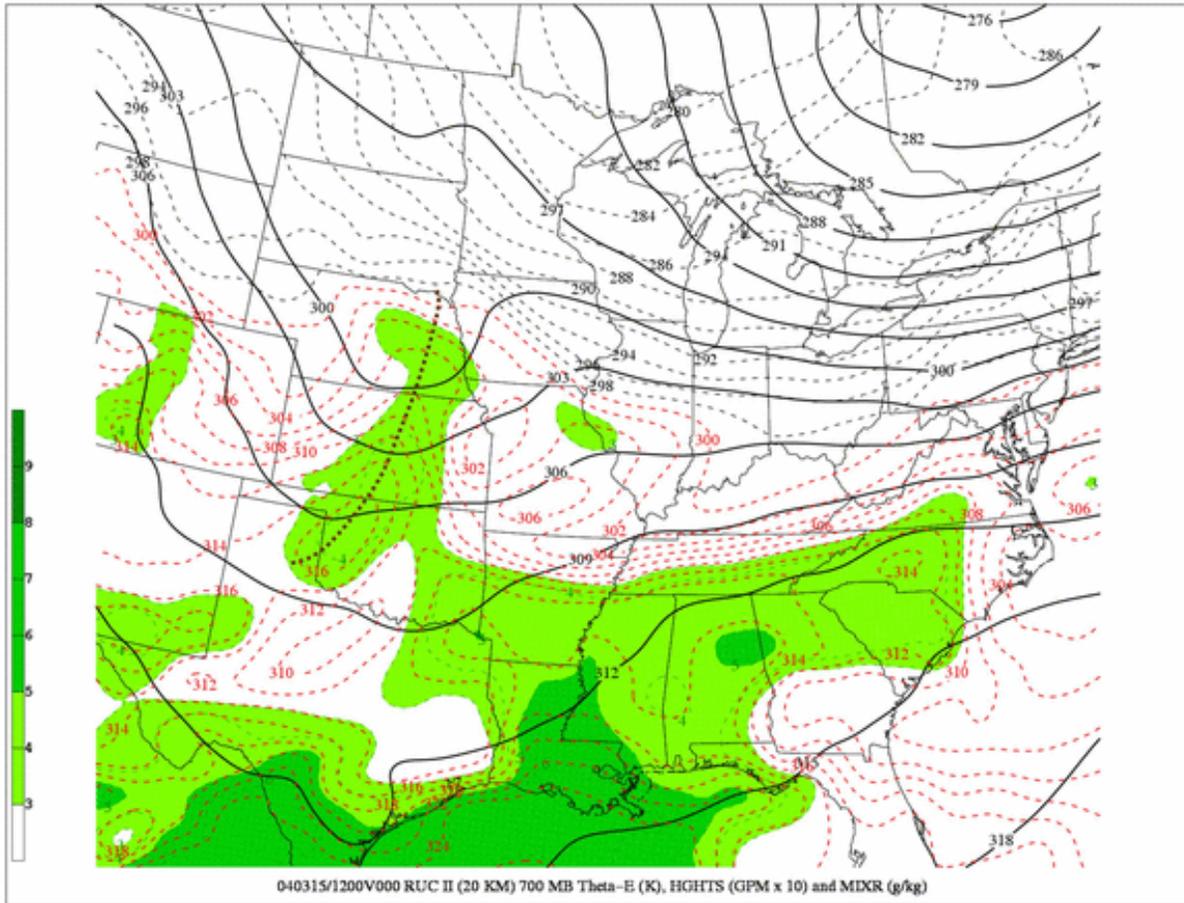
**Figure 5.** Animation of objectively analyzed upper-air observations from 0000 UTC 15 March 2004 to 1200 UTC 16 March 2004. (top left) 300-hPa heights (gpm \* 10) in solid black lines, wind vectors (kts), and wind speed (shaded, kts); (top right) 500-hPa heights (gpm \* 10) in solid black lines, wind vectors (kts), and absolute vorticity ( $10^{-5} \text{ s}^{-1}$ ) in dashed black lines and shaded; (bottom left) 700-hPa heights (gpm \* 10) in solid black lines, wind vectors (kts), wind speed (shaded, kts), and temperature ( $^{\circ}\text{C}$ , dashed red contours represent positive values and dashed blue contours represent zero and negative values); (bottom right) 850-hPa heights (gpm \* 10) in solid black lines, wind vectors (kts), wind speed (shaded, kts), and temperature ( $^{\circ}\text{C}$ , dashed red contours represent positive values and dashed blue contours represent zero and negative values). Note that the animation is limited to the html version of this paper, and only the most pertinent image (1200 UTC 15 March 2004) of the animation is given in the PDF version.



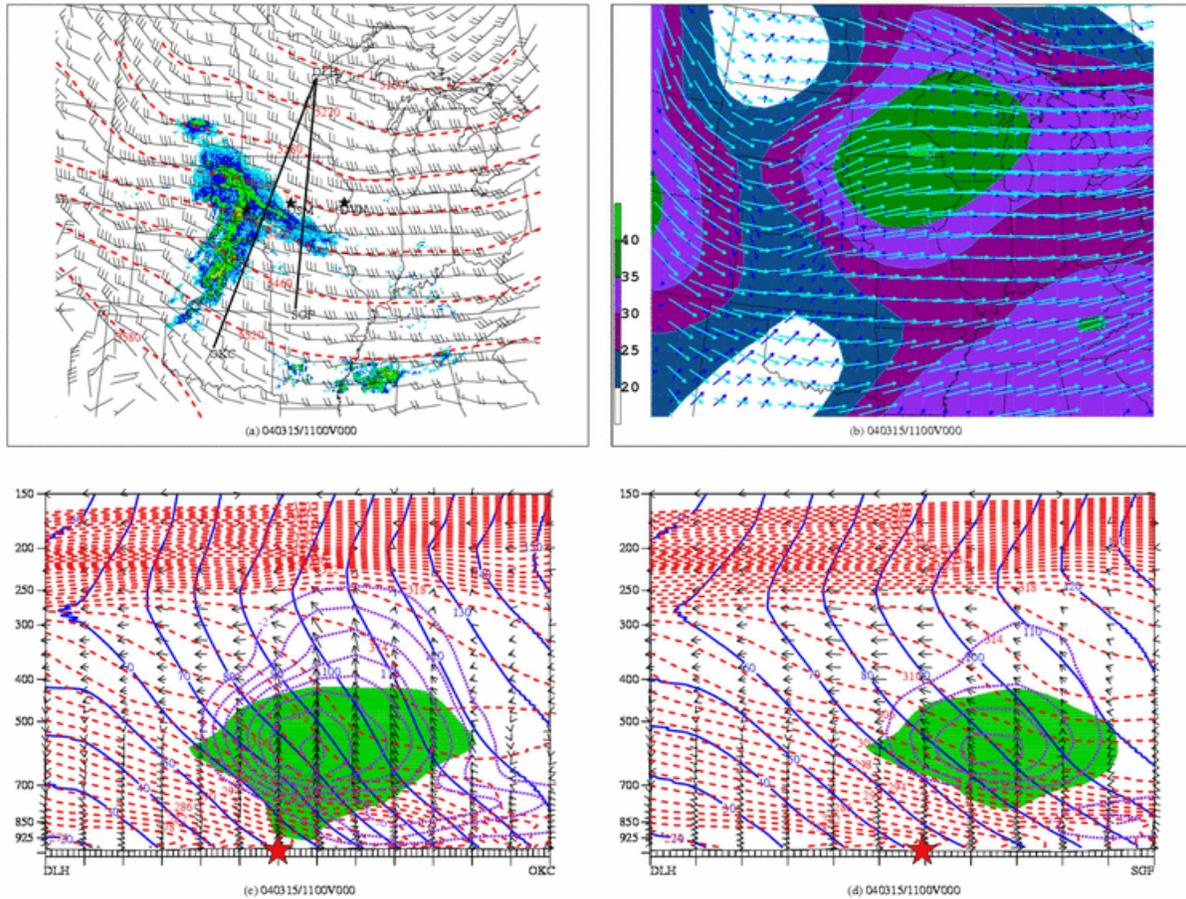
**Figure 6.** Animation of 20-km RUC 300-hPa divergence from 0000 UTC 15 March 2004 to 1200 UTC 16 March 2004: heights (gpm \* 10) in solid black lines, wind vectors (kts), and wind speed (shaded, kts), and divergence ( $10^{-5} \text{ s}^{-1}$ ) in red dotted lines. Note that the animation is limited to the html version of this paper, and only the most pertinent image (1200 UTC 15 March 2004) of the animation is given in the PDF version.



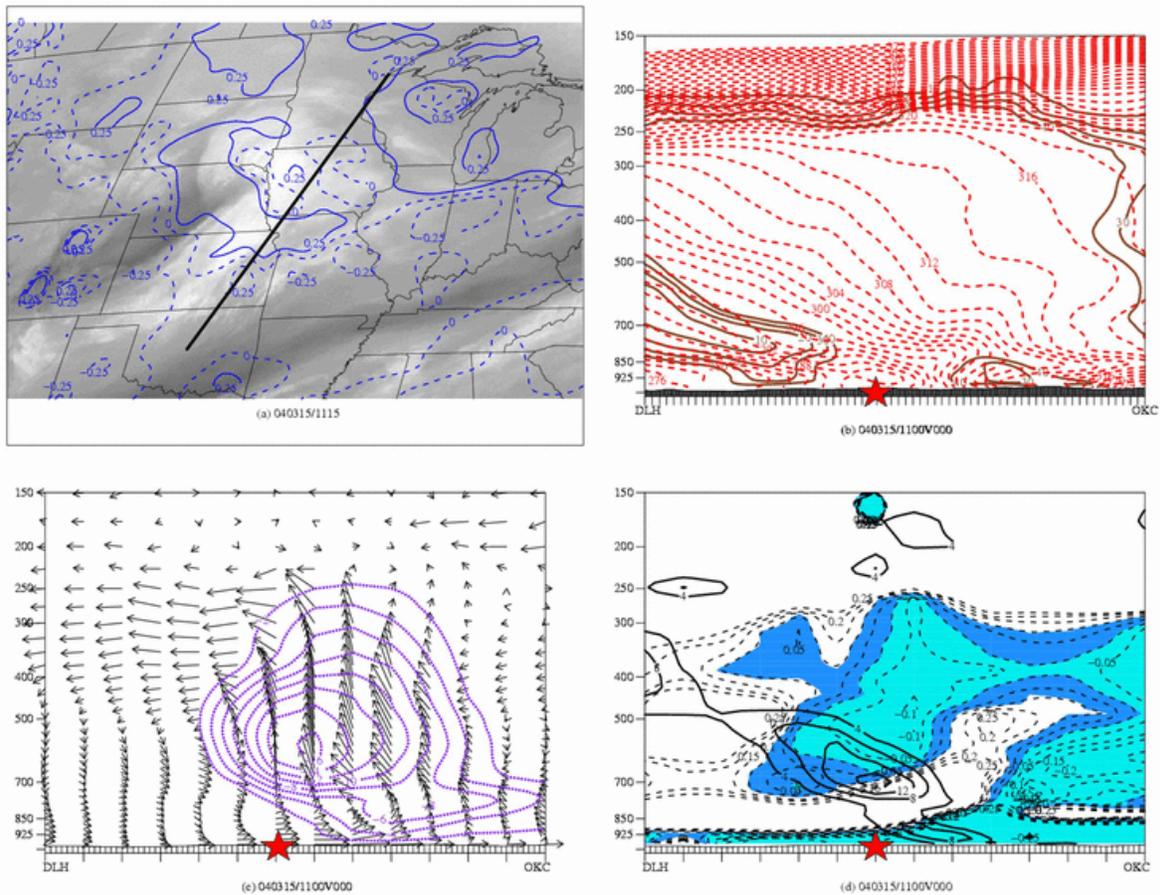
**Figure 7.** Animation of 20-km RUC (filtered to 80-km) Q vectors from 0000 UTC 15 March 2004 to 1200 UTC 16 March 2004. 500-300 hPa Q vectors ( $\text{K m}^{-1} \text{s}^{-1}$ ) in black arrows and convergence ( $10^{-14} \text{ K m}^{-2} \text{s}^{-1}$ ) in solid red lines (negative values contoured to represent divergence). Note that the animation is limited to the html version of this paper, and only the most pertinent image (0000 UTC 16 March 2004) of the animation is given in the PDF version.



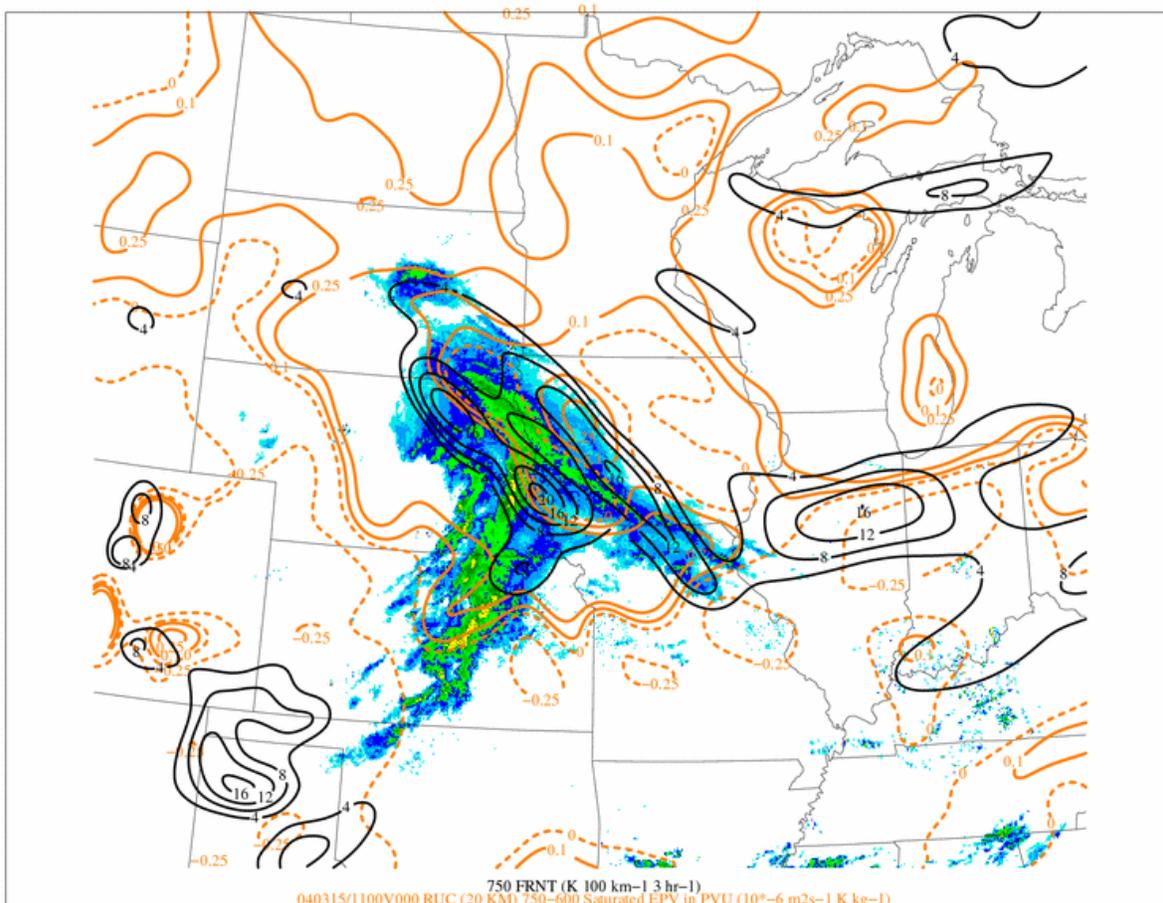
**Figure 8.** Animation of moisture and the TROWAL signature (brown dotted line) from 0600 UTC 15 March 2004 to 1200 UTC 15 March 2004 using 20-km RUC data. 700-hPa heights (gpm \* 10) in solid black,  $\theta_e$  (K) in dashed lines (300 K and greater are red), and mixing ratio ( $\text{g kg}^{-1}$ ) shaded green every unit. Note that the animation is limited to the html version of this paper, and only the most pertinent image (1200 UTC 15 March 2004) of the animation is given in the PDF version.



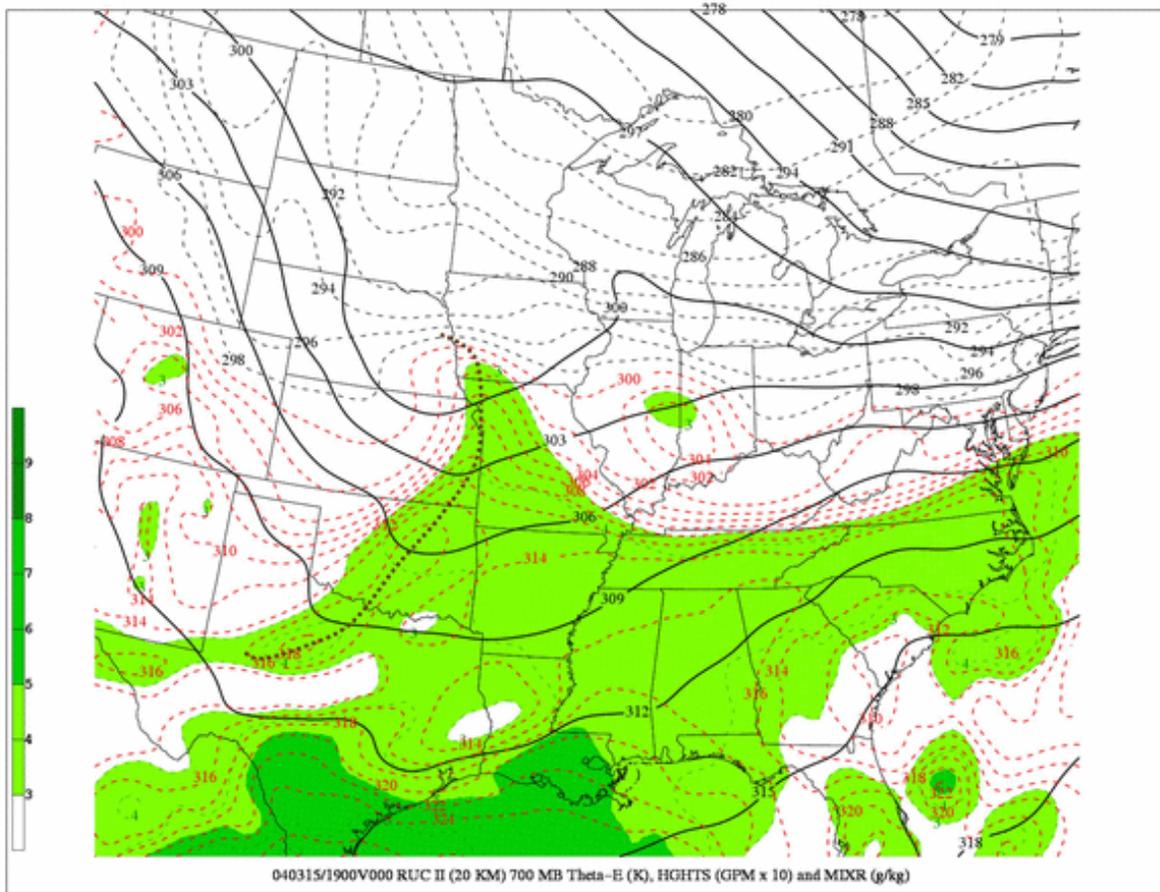
**Figure 9.** Animation of 4-panel graphic from 0600 UTC 15 March 2004 to 1200 UTC 15 March 2004 using 20-km RUC data: (top left) 1000–500-hPa thickness (gpm) in dashed red lines, thermal wind vectors (black), NEXRAD Level III composite reflectivity, and solid black lines that show the orientations of cross sections from Duluth, MN (DLH) to Oklahoma City, OK (OKC), and from DLH to Springfield, MO (SGF); (top right) 300–850-hPa wind shear ( $s^{-1}$ , shaded), 300-hPa wind vectors ( $m s^{-1}$ , dark blue), and 850-hPa wind vectors ( $m s^{-1}$ , light blue); (bottom left) cross section from DLH to OKC of  $\theta_e$  (K, red dashed lines), absolute geostrophic momentum ( $m s^{-1}$ , solid blue lines), relative humidity ( $> 80\%$  shaded green), and omega ( $\mu bar s^{-1}$ , purple dotted lines); (bottom right) cross section from DLH to SGF of the same fields as in the bottom left. The red star at the bottom of the cross sections denotes the location of Des Moines, IA. Note that the animation is limited to the html version of this paper, and only the most pertinent image (1100 UTC 15 March 2004) of the animation is given in the PDF version.



**Figure 10.** Animation of 4-panel graphic from 0600 UTC 15 March 2004 to 1200 UTC 15 March 2004 using 20-km RUC data: (top left) GOES-12 water vapor imagery and 750–600-hPa EPV in PV units ( $10^{-6} \text{ m}^2 \text{ s}^{-1} \text{ K kg}^{-1}$ ) in solid blue lines with negative values dashed, and the solid black line shows the orientation of the cross section from DLH to OKC [during 0000–1200 UTC 16 March 2004 this changes to DLH to SGF]; (top Right)  $\theta_{es}$  (K, dashed red lines) and relative humidity (< 40% solid brown lines); (bottom left) ageostrophic circulation vectors ( $\text{m s}^{-1}$ , black arrows) and omega ( $\mu\text{bar s}^{-1}$ , purple dotted lines); (bottom right) frontogenesis ( $\text{K } 100 \text{ km}^{-1} \text{ } 3 \text{ h}^{-1}$ , solid black lines) and EPV in PV units ( $10^{-6} \text{ m}^2 \text{ s}^{-1} \text{ K kg}^{-1}$ , black dashed lines with negative values shaded light blue and 0.0–0.1 shaded darker blue). The red star at the bottom of the cross sections denotes the location of Des Moines, IA. The static image for the PDF version of the paper is from 1100 UTC 15 March 2004.

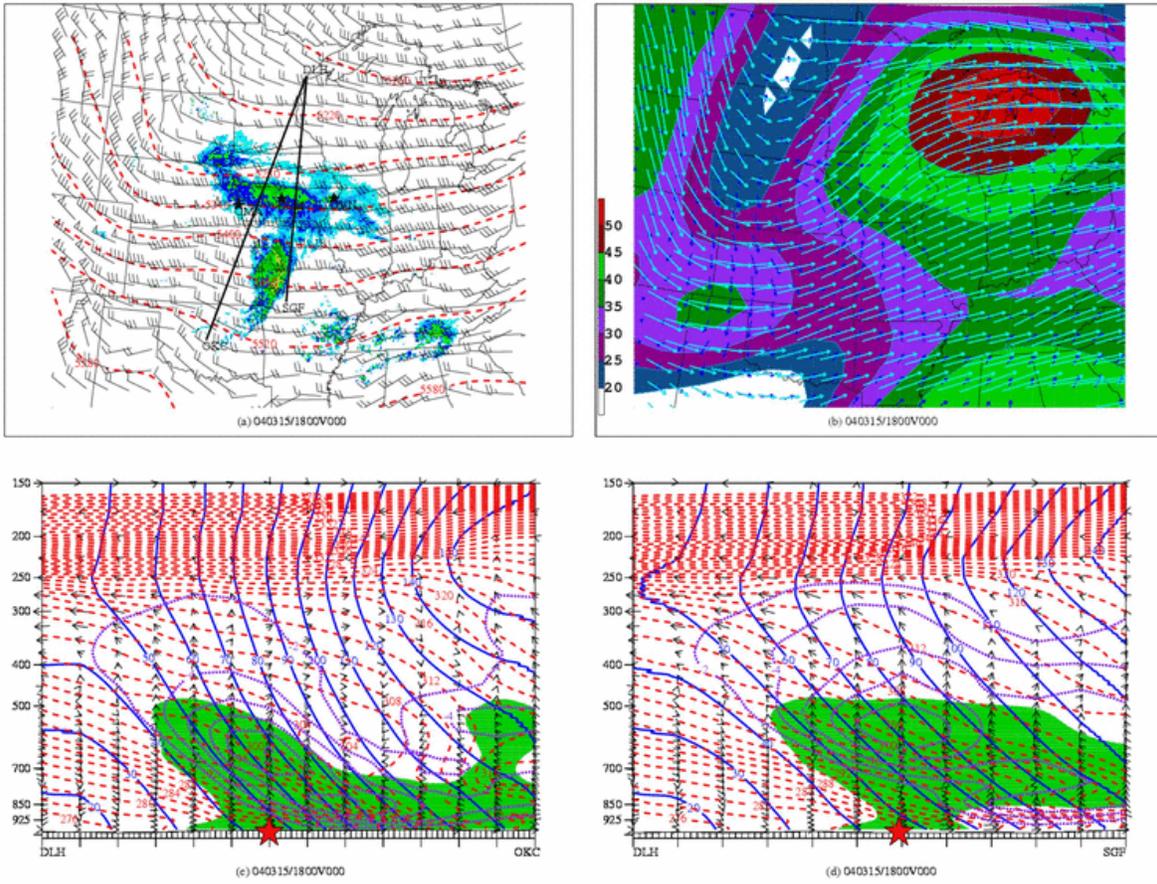


**Figure 11.** Animation of 20-km RUC frontogenesis, EPV, and NEXRAD Level III composite reflectivity from 0600 UTC 15 March 2004 to 1200 UTC 12 March 2004. 750-hPa frontogenesis ( $\text{K } 100 \text{ km}^{-1} \text{ 3 h}^{-1}$ ) in solid black lines and 750–600-hPa EPV in PV units ( $10^{-6} \text{ m}^2 \text{ s}^{-1} \text{ K kg}^{-1}$ ) in orange solid lines with negative values dashed. The static image for the PDF version of the paper is from 1100 UTC 15 March 2004.

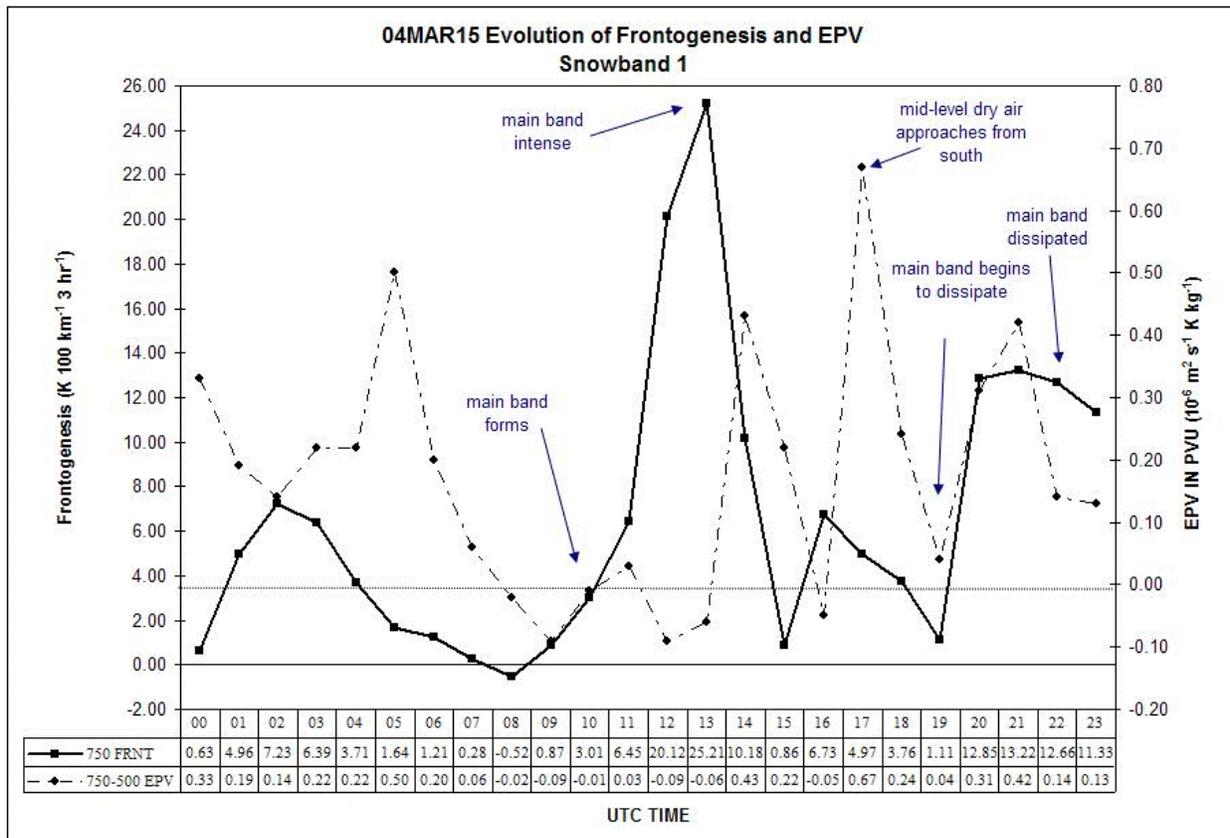


**Figure 12.** Same as Fig. 8 except from 1200 UTC 15 March 2004 to 1900 UTC 15 March 2004. The static image for the PDF version of the paper is from 1900 UTC 15 March 2004.

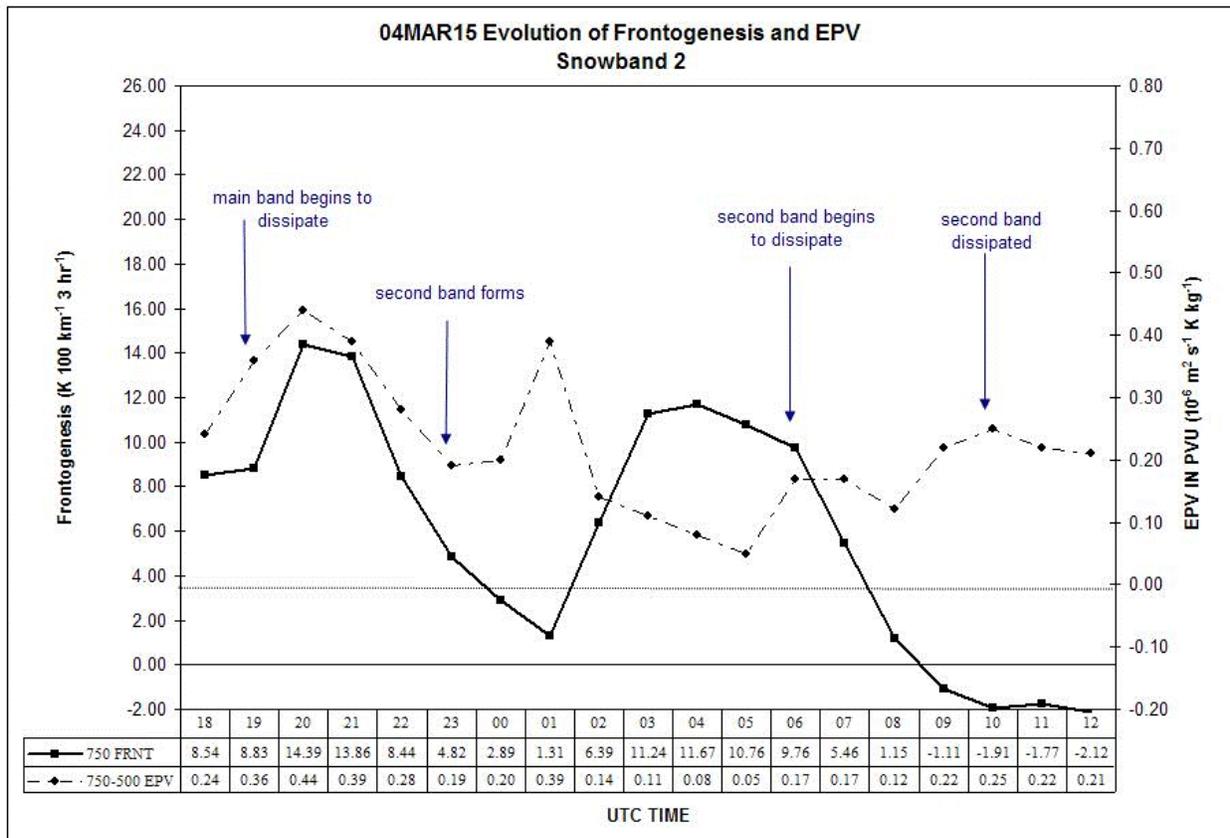




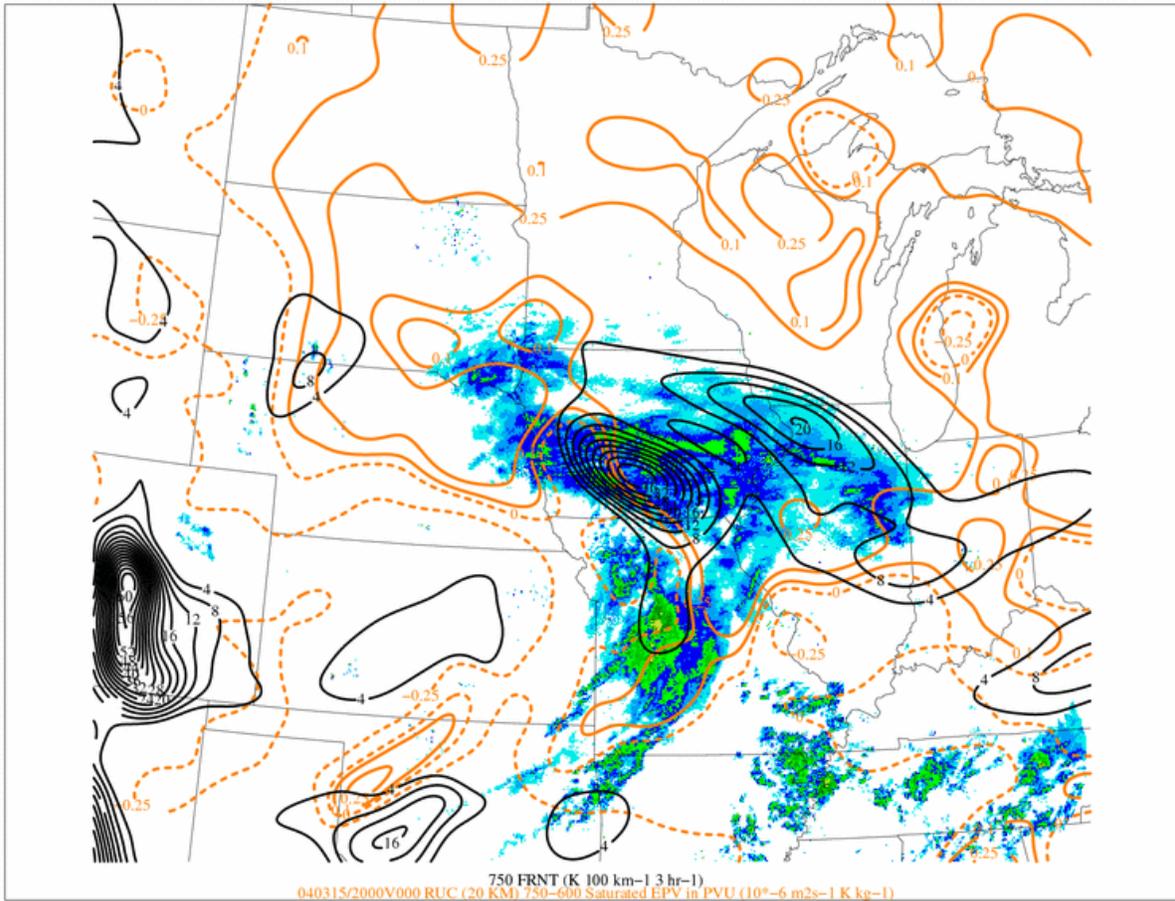
**Figure 14.** Same as Fig. 9 except from 1200 UTC 15 March 2004 to 1900 UTC 15 March 2004. The static image for the PDF version of the paper is from 1800 UTC 15 March 2004.



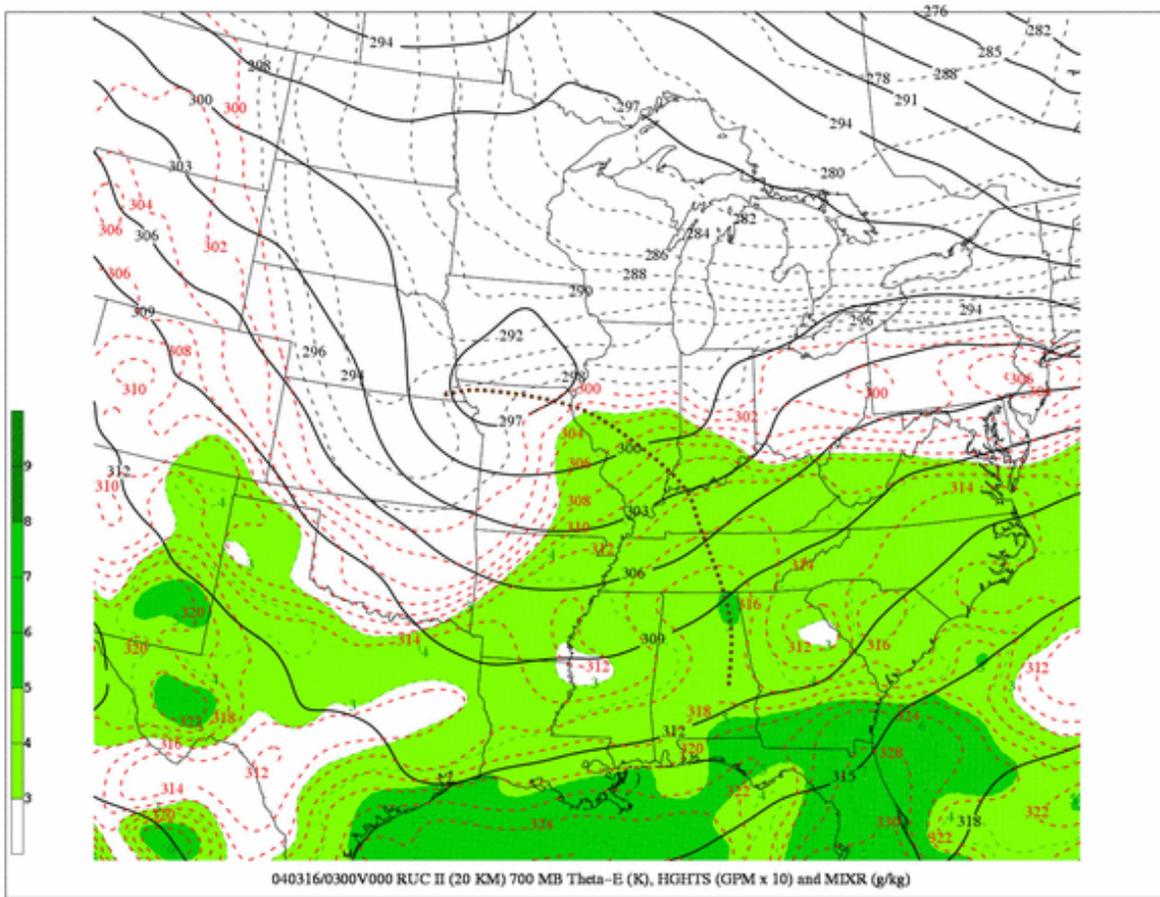
**Figure 15.** Evolution of frontogenesis ( $\text{K } 100 \text{ km}^{-1} 3 \text{ h}^{-1}$ ) in solid black lines and EPV in PV units ( $10^{-6} \text{ m}^2 \text{ s}^{-1} \text{ K kg}^{-1}$ ) in dashed black lines across the snowband. Points were obtained from radar imagery at 1800 UTC 15 March 2004 to compute the average evolution.



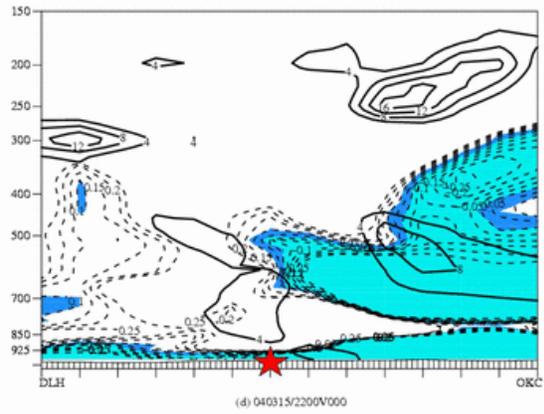
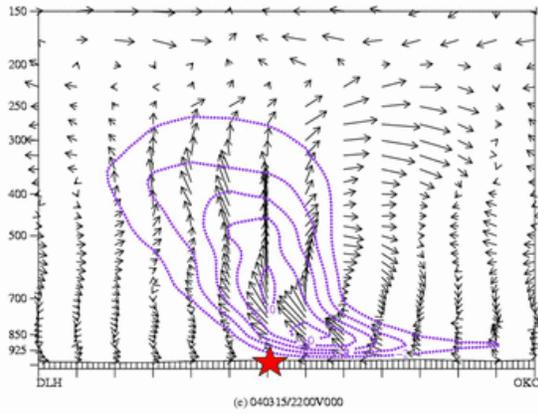
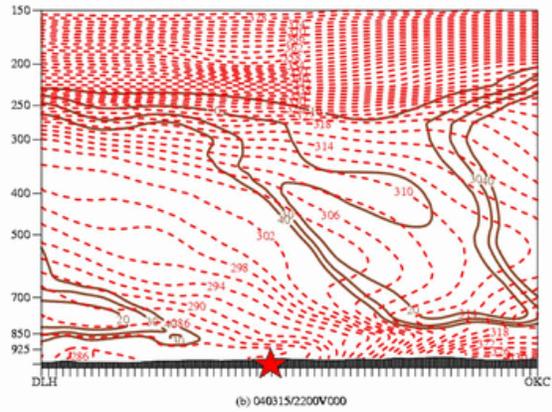
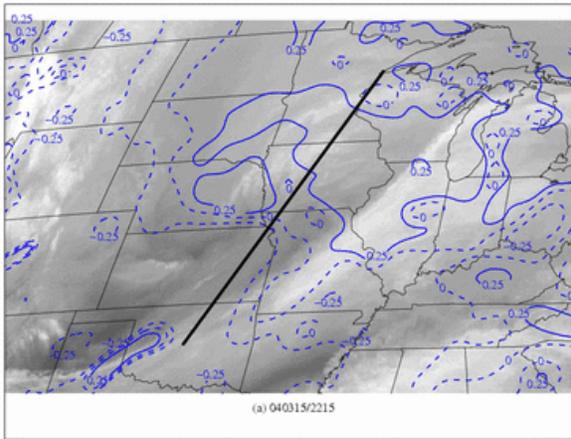
**Figure 16.** Same as Fig. 15 except points were obtained from radar imagery at 0500 UTC 16 March 2004.



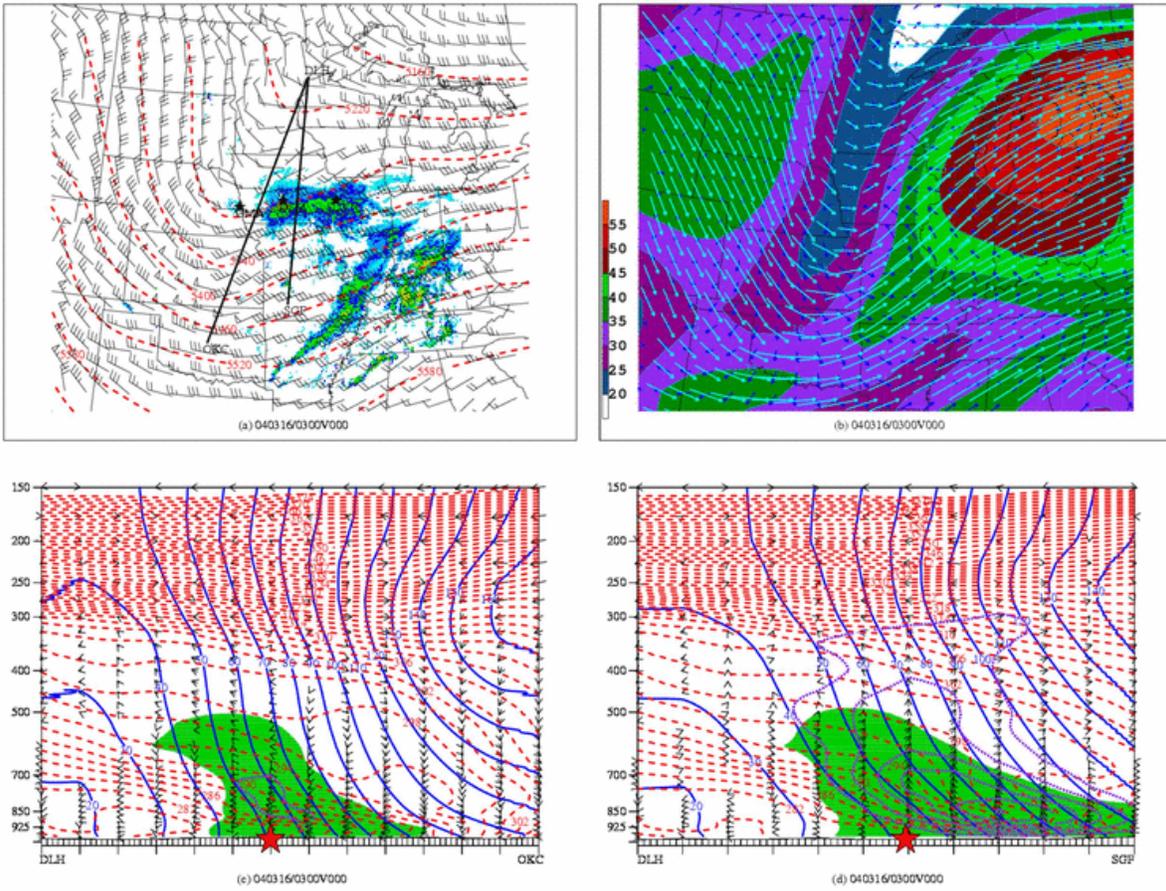
**Figure 17.** Same as Fig. 11 except from 1900 UTC 15 March 2004 to 1200 UTC 16 March 2004. The static image for the PDF version of the paper is from 2000 UTC 15 March 2004.



**Figure 18.** Same as Fig. 8 except from 1900 UTC 15 March 2004 to 1200 UTC 16 March 2004. The static image for the PDF version of the paper is from 0300 UTC 16 March 2004.



**Figure 19.** Same as Fig. 10 except from 1900 UTC 15 March 2004 to 1200 UTC 16 March 2004. Cross section taken from DLH to SGF substituted from 0000 UTC 16 March 2004 to 1200 UTC March 16 2004. The static image for the PDF version of the paper is from 2200 UTC 15 March 2004.



**Figure 20.** Same as Fig. 9 except from 1900 UTC 15 March 2004 to 1200 UTC 16 March 2004. The static image for the PDF version of the paper is from 0300 UTC 16 March 2004.

## **Appendix A – Methodology to plot the evolution of the snowband.**

1. Choose the time just before band dissipation
  - a. To map out the first band, 1800 UTC was chosen
  - b. To map out the second band, 0500 UTC was chosen
2. Use GARP or another display program to display radar imagery
3. Choose ten latitude and longitude pairs across the band which will represent points
4. Use GEMPAK programs gdpoint and gdlist to find the value of frontogenesis and EPV at each point.
  - a. The value of frontogenesis and EPV is found for every hour
  - b. The result is ten points with values for every hour from 0000–2300 UTC 15 March 2004 and from 0000 –1200 UTC 16 March 2004
  - c. The layer average of 750–500 hPa was chosen for EPV instead of 750–600 hPa, because a deeper layer accounted for any variation in the depth of the EPV layer
5. Obtain the average value of frontogenesis and EPV for each hour by averaging the ten points for each hour
6. Plot the average evolution (i.e., the average value for each hour)
7. See table below for more clarification
  - a. The second band began to experience significant dissipation after 0500 UTC
  - b. Ten latitude and longitude pairs were used across the band using radar imagery
  - c. The values of frontogenesis and EPV were found from 1800 UTC 15 March 2004 to 1200 UTC 16 March 2004
  - d. The values of the ten points were averaged for each hour
  - e. The average values were plotted to give the evolution for the band

**Table A1.** The 20-km RUC 750-hPa frontogenesis and 750–500 hPa EPV values at ten points across the band for each hour. Points were obtained at 0500 UTC 16 March 2004 before band dissipation. The average value for each hour in bold is plotted as the average evolution.

<b>Ten points obtained at 20040316/0500</b>											
<b>750 FGEN</b>	<b>one</b>	<b>two</b>	<b>three</b>	<b>four</b>	<b>five</b>	<b>six</b>	<b>seven</b>	<b>eight</b>	<b>nine</b>	<b>ten</b>	<b>Mean</b>
0315/1800	7.91	17.67	10.09	9.26	-7.36	-4.27	0.43	8.39	17.84	25.42	<b>8.54</b>
0315/1900	12.74	23.53	14.84	12.55	2.58	0.65	3.42	4.64	5.10	8.22	<b>8.83</b>
0315/2000	18.74	34.18	34.05	21.76	8.32	2.98	5.01	4.79	6.37	7.74	<b>14.39</b>
0315/2100	3.68	29.17	35.86	30.28	13.21	6.83	5.17	3.69	3.78	6.92	<b>13.86</b>
0315/2200	-9.64	10.35	22.90	21.81	11.21	5.74	8.35	5.05	3.89	4.73	<b>8.44</b>
0315/2300	-16.70	-7.10	13.25	16.75	11.23	9.56	6.18	3.21	6.23	5.55	<b>4.82</b>
0316/0000	-11.82	-9.13	5.04	7.33	14.62	10.07	5.10	3.32	2.77	1.57	<b>2.89</b>
0316/0100	-5.61	-4.82	-1.55	4.63	14.39	5.75	0.40	-2.70	0.26	2.37	<b>1.31</b>
0316/0200	-0.06	7.06	6.83	9.27	13.33	7.43	7.15	3.85	5.55	3.51	<b>6.39</b>
0316/0300	5.28	12.73	16.17	21.64	17.44	12.82	8.65	6.34	7.05	4.32	<b>11.24</b>
0316/0400	4.88	11.86	23.56	20.55	16.90	12.21	10.08	7.53	6.22	2.95	<b>11.67</b>
0316/0500	7.63	11.30	20.05	21.34	18.06	10.99	8.91	3.86	2.29	3.19	<b>10.76</b>
0316/0600	5.74	9.85	16.39	21.44	16.53	10.54	7.20	4.07	4.00	1.86	<b>9.76</b>
0316/0700	3.21	10.32	8.69	11.03	6.30	6.54	2.15	2.96	1.52	1.85	<b>5.46</b>
0316/0800	-4.63	3.42	2.84	3.87	1.59	1.37	0.81	1.00	0.24	0.97	<b>1.15</b>
0316/0900	-8.97	0.64	1.77	1.25	-0.40	-0.74	-1.19	-1.86	-1.03	-0.62	<b>-1.11</b>
0316/1000	-9.49	-0.81	-0.67	-0.59	-1.09	-1.69	-1.86	-1.08	-1.08	-0.72	<b>-1.91</b>
0316/1100	-3.08	-2.32	-2.10	-2.55	-1.60	-1.85	-1.86	-1.47	-1.09	0.21	<b>-1.77</b>
0316/1200	-3.36	-4.01	-3.56	-3.35	-1.46	-2.25	-1.28	-1.24	-0.38	-0.35	<b>-2.12</b>
<b>Ten points obtained at 20040316/0500</b>											
<b>750-500 EPV</b>	<b>one</b>	<b>two</b>	<b>three</b>	<b>four</b>	<b>five</b>	<b>six</b>	<b>seven</b>	<b>eight</b>	<b>nine</b>	<b>ten</b>	<b>Mean</b>
0315/1800	0.4	0.44	0.44	0.44	0.42	0.3	0.08	-0.01	-0.08	0.02	<b>0.24</b>
0315/1900	0.15	0.21	0.28	0.35	0.4	0.47	0.47	0.45	0.43	0.44	<b>0.36</b>
0315/2000	-0.05	0.12	0.47	0.57	0.74	0.7	0.61	0.53	0.38	0.33	<b>0.44</b>
0315/2100	0.13	0.29	0.53	0.62	0.54	0.47	0.31	0.28	0.32	0.38	<b>0.39</b>
0315/2200	-0.04	0.03	0.18	0.32	0.47	0.4	0.37	0.36	0.35	0.38	<b>0.28</b>
0315/2300	0.36	0.23	0.14	0.14	0.11	0.19	0.17	0.15	0.15	0.25	<b>0.19</b>
0316/0000	0.4	0.27	0.14	0.13	0.11	0.11	0.13	0.16	0.23	0.34	<b>0.20</b>
0316/0100	0.53	0.47	0.43	0.44	0.49	0.42	0.37	0.33	0.25	0.18	<b>0.39</b>
0316/0200	0.26	0.25	0.25	0.19	0.07	0.04	0.03	0.04	0.06	0.17	<b>0.14</b>
0316/0300	0.17	0.13	0.16	0.11	0.01	0.04	-0.02	-0.01	0.14	0.41	<b>0.11</b>
0316/0400	0.125	-0.02	-0.06	-0.05	-0.01	0.03	0.07	0.12	0.25	0.38	<b>0.08</b>
0316/0500	0.22	0.04	-0.08	-0.11	0.05	0.01	0.04	0.06	0.1	0.13	<b>0.05</b>
0316/0600	0.33	0.16	0.04	-0.03	-0.03	0.11	0.16	0.2	0.31	0.42	<b>0.17</b>
0316/0700	0.37	0.26	0.14	0.05	0.04	0.08	0.11	0.14	0.22	0.28	<b>0.17</b>
0316/0800	0.3	0.22	0.12	0.04	0.1	0.07	0.06	0.07	0.1	0.12	<b>0.12</b>
0316/0900	0.34	0.31	0.27	0.2	0.13	0.17	0.15	0.16	0.21	0.28	<b>0.22</b>
0316/1000	0.26	0.24	0.24	0.22	0.21	0.22	0.21	0.22	0.28	0.38	<b>0.25</b>
0316/1100	0.2	0.25	0.3	0.26	0.27	0.2	0.16	0.17	0.2	0.21	<b>0.22</b>
0316/1200	0.27	0.35	0.38	0.33	0.21	0.18	0.08	0.06	0.1	0.19	<b>0.21</b>