A PV-streamer's role in a succession of heavy rain-producing MCSs over the central U. S.

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Abstract. A PV-streamer at 250 hPa, moving over the west central United States 25 June - 5July, 1999 was visible on water vapor imagery as a narrow, elongated dark band. It sparked a series of mesoscale convective systems (MCSs) on successive days, producing heavy precipitation from Nebraska eastward and southeastward toward the coast along the Gulf of Mexico. The MCSs began as the PV-streamer moved off the central Rocky Mountains onto the Great Plains where it interacted with a surface front and a low-level jet. Each convective system interrupted the PV-streamer, and low and mid level vorticity accumulated along the front. One of the MCSs, which occurred 28 June 1999, is examined in detail.

1 Introduction

Forecasting excessive precipitation is a major problem yet to be solved. Operational numerical weather forecast models alone cannot do it; it remains a forecaster's art. Doswell et al. (1999) suggest that forecasters use an ingredient based technique that takes into account a number of factors affecting the likelihood of heavy precipitation.

Mesoscale Convective Systems (MCSs), often a source of excessive precipitation, are also difficult to forecast for both NWP models and human forecasters. Mesoscale convective systems (MCSs) are often responsible for a large percentage of the growing season's precipitation in the Central United States when they recur as serial outbreaks (Fritsch et al., 1986); and some of these extreme events can lead to serious flooding. Forecasting MCSs is also an ingredient based process that has some quantitative and theoretical basis.

In a study of MCSs occurring in the warm seasons of 1990, 1991 and 1992, Augustine and Caracena (1992) found that several precursors foreshadowed the occurrence of MCSs over the central U.S. The pre-MCS environment is characterized by a low-level jet transporting moisture toward a frontogenetic frontal boundary at 850 hPa, in an area where the troposphere is being destabilized by the approach of a short wave trough.

Several recent publications suggest using water vapor satellite imagery to analyze atmospheric flow patterns and patterns of upper level potential vorticity (PV). Martin et al. (1999) use mushroom shapes to interpret kinematic properties of the corresponding tropospheric flow. Morgenstern and Davies (1999) discuss the role of PV-streamers, appearing as dark bands in satellite water vapor imagery, in organizing heavy precipitation events in the Alps. They hypothesize that a region of ascent in the left forward flank of such anomalies may act as a trigger for convection, and further, that a dynamical interplay between orography, diabatic heating associated with convection and the upper PV-streamer, dynamically organize a resulting terrain-bound, heavy precipitation.

Rodgers et al. (1988) found that a long-lived dark band appearing in the GOES water vapor satellite imagery (6.7 microns) was associated with a sequence of four Mesoscale Convective Complexes (MCCs). One of these, occurring the evening and night of 19-20 May 1983, was "an enormous, quite deadly MCC". The dark band, which they called a "dry slot," represented pronounced dryness in the mid to upper troposphere, and was also associated with an upper level wind maximum and deformation zone, probably emerging from the subtropics. They speculated that the enhanced flow ventilated storms forming in the path of the dry slot and that the midlevel part of the dry airflow fed storm downdrafts.

2 A long-lived PV-streamer

For a week following 26 June 1999, a PV-Streamer that had emerged over the central Rocky Mountains was associated

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with a series of MCSs over the central US that formed from initial convection in the lee of the mountains. The total precipitation for 27 June-2 July 1999 shows the impact of these convective systems over Kansas and neighboring states (Fig. 1) from all the MCSs originating in the High Plains and foothills of the Rocky Mountains. Subsequent diurnal cycles of convective systems propagated further east and southeast bringing heavy rain to the Atlantic coast where over 330 mm fell in extreme southeastern South Carolina (not shown).

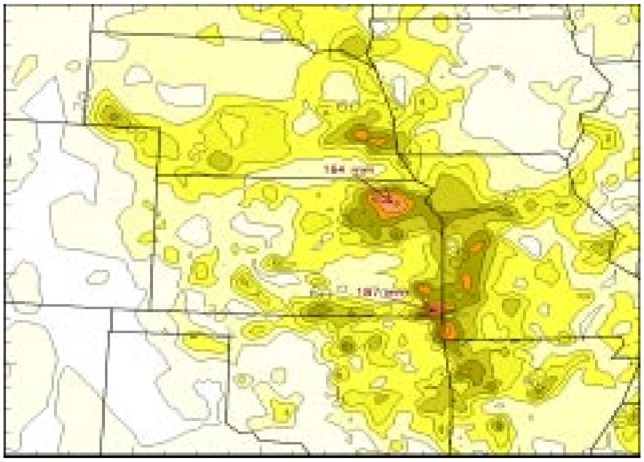


Fig. 1. An analysis, using triangulation, of precipitation for the preiod 27 June - 2 July 1999 based on surface 24 h gauge observations taken at 1200 UTC each day.

We analyzed the PV-streamer using Eta model (described by Black, 1994) initial and 6 h forecast fields for the whole period, as well as some RUC2 (40 km) initial fields for selected times (Benjamin et al., 1998). Although the Eta model output was originally available on a grid having 32 km horizontal resolution and in an Eta coordinate system, for convenience we used a version interpolated to a coarser (80-km,19-level) Continental United States grid version 212 (CONUS-212) grid. The coarser, interpolated Eta model's resolution of the PV-streamer compared well to the RUC2 analyses at selected times, although the RUC2 analyses showed more detail.

The PV-streamer discussed here originated from a pool of potential vorticity that was extruded and sheared off from a low latitude trough in a deformation field over the southeastern Pacific at the margins of a continental ridge. The PV-streamer followed a track parallel and to the south of a series of short wave troughs in the flow over the northern U.S. (Fig. 2a).

To compare the results with satellite imagery, PV analyses at 250 hPa were overlaid on corresponding GOES 8 water vapor images for the whole period of interest. The results showed that the PV-streamer overlapped the narrow dark band on the satellite imagery, with a slight offset in its axis to the north. Because of space limitations, we present only one such analysis for, 28 June 1999 1200 UTC (Fig. 2a and 2b).

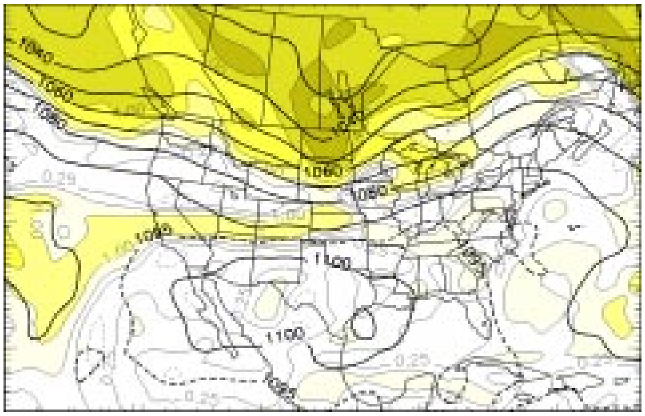
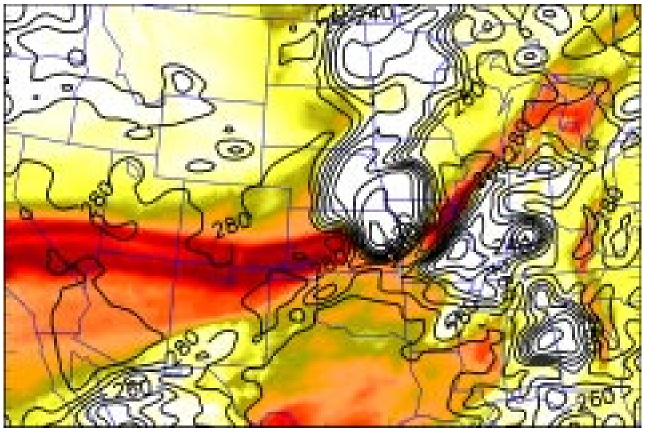


Fig. 2a. A 250 hPa analysis of potential vorticity (shaded, K kg^{-1} s^{-1} 1 0^{-6}) and height field based on the 1200 UTC 28 June 1999, 32 km Eta initial analysis interpolated to an 80 km horizontal grid.



ig. 2b. A GOES 8 water vapor image for 1215 UTC 28 June 1999 on which are superposed contoures of the cloud top temperaturecomputed from the orresponding 11 micron IR GOES 8 satellite image. Note that the PV-reamer is visualized here as a dark band.

We found mature MCSs positioned relative to the PV-streamer in two ways. Type-one MCSs (as in Fig. 2b) formed directly in the path of the PV-streame,r intercepting and interrupting the flow of potential vorticity. Type-two MCSs formed to one side of the PV-streamer and pushed it aside (not shown). Although the latter type produced impressive looking anvils, the type one systems produced more severe weather and greater amounts of precipitation.

3. Analysis of a Type-one storm

The MCS of 28 June 1999, a type one event that is analyzed here, formed from storms that produced millions of dollars in damage from tornadoes, hail and high winds in Wyoming, Colorado, Nebraska and Kansas. Subsequently, these storms aggregated to form a large MCS that propagated rapidly into eastern Kansas and western Missouri, producing millions of dollars in flash flood damage in the Kansas City metropolitan area.

3.1 Meteorological conditions

The first storms formed the evening of 27 June along the foothills of the Rocky Mountains in Wyoming in response to initially strong, low-level upslope flow of moist air around a large high pressure area centered over western Kansas which by 0600 UTC had turned parallel to the terrain contours (Fig. 3). A short wave trough approached the northern Rocky Mountains to the north of the storm genesis area, as a PV-streamer approached the same area from the west (Fig. 2a).

Note that by 0600 UTC the winds which had been more southeasterly earlier, had become southerly in western Nebraska and westerly in eastern Wyoming (Fig. 3).

Low-level frontogenesis 28 June 1999 0600 UTC (Fig.3) indicates a area ripe for organized convection over northeastern Kansas. Here there is also a strong low-level flow of moisture directly against a strengthening frontal boundary. According to the study of Augustine and Caracena (1992) one would expect to find organized convection in norhteastern Kansas and parts of adjoining states.

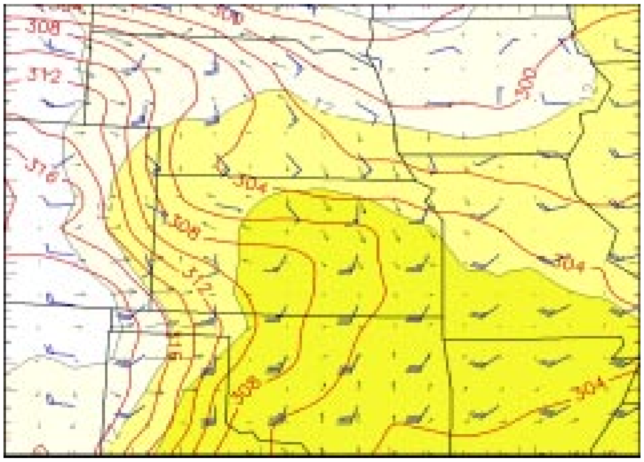


Fig. 3. An analysis of temperature (K), mixing ratio (g/kg)and wind vectors (a full barb repesents 5 m^{-s} and a half barb, half this amount) for a surface 50 hPa less than the surface pressure, and an analysis of 850 hPa Q-vectors (small arrows having a maximum value of 3.8 x 10^{-12} $s^{-1}kg^{-1}$) from the Eta initial fields for 28 June 1999 1200 UTC.

3.2 Radar history

A national composite radar image for 0000 UTC 28 June 1999 indicates that supercell storms were moving over the High Plains of Wyoming and Nebraska, and a loosely organized MCS was propagating south over extreme eastern Kansas and western Missouri (Fig. 4a).

By 0600 UTC, a prominent squall line was propagating into northeast Colorado as a second line to the north in Nebraska was beginning to diminish (Fig. 4b). The MCS over extreme eastern Kansas and Missouri continued to propagate to the south. A new line of convection was beginning to ignite in extreme northeastern Kansas.

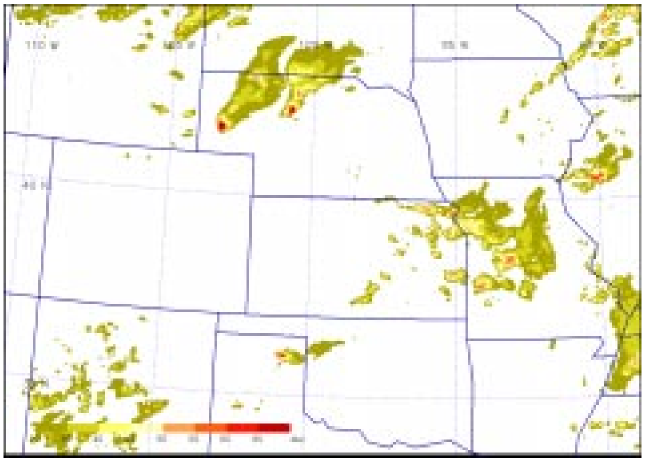


Fig. 4a. A portion of the composite national radar analysis for 0000 UTC 28 June 1999.

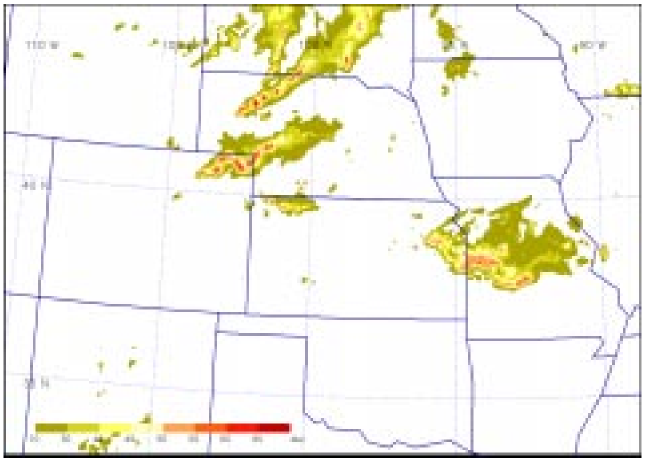


Fig. 4b. A portion of the composite national radar analysis for 0600 UTC 28 June 1999.

By 0900 UTC, the three convective bands over the High Plains had merged and the most intense storm echoes in this storm complex had shifted to the southeastern quadrant of the storm (Fig. 4c). A second convective system continued its southerly course across Missouri.

By 1200 UTC the storm that had formed over the High Plains had propagated into eastern Kansas and its echo had formed into a mature, comma shape (Fig. 5). At this time, this storm had nearly overtaken the older MCS that continued to propagate southward over Missouri. The comma tail subsequently grew into an expanding squall line that produced wind damage in Missouri, as the comma head brought flash flooding to the Kansas City area. A comparison of the position of the PV-streamer at 250 h Pa in the 1200 UTC initial Eta model analysis (Fig. 2a) and the national radar analysis for this time (Fig. 5) reveals a prominent potential vorticity maximum to the west of the radar comma head.

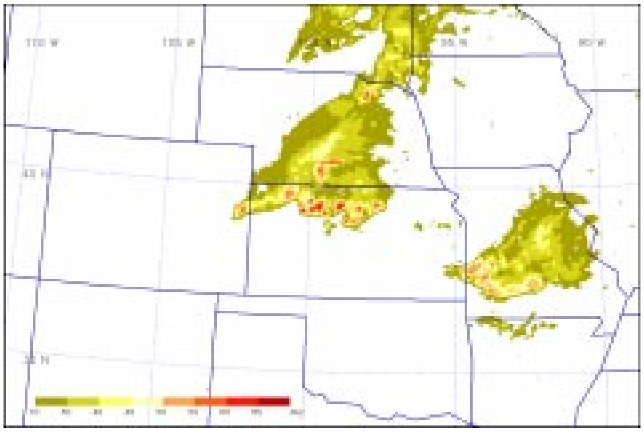


Fig. 4c. A portion of the composite national radar analysis fo 0900 UTCr 28 June 1999.

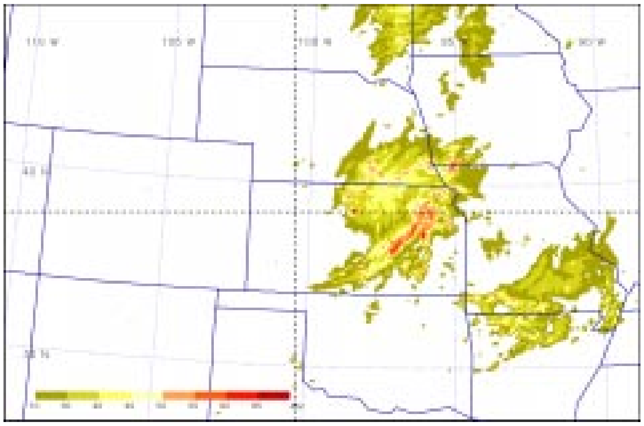


Fig. 5. A portion of the composite national radar analysis for 1200 UTC 28 June 1999. The dashed vertical and horizontal lines indicate the locations of vertical south-north and west-east cross sectional analyses.

3.3 Organization of the storm

Vertical west-east (Fig. 6a) and south-north (Fig. 6b) cross sections depict vorticity and potential temperature fields relative to the storm. Note that a vertical vortex has formed from the top to bottom of the troposphere to the west side of the storm. A weak connection has formed also between upper-level and lower-level potential vorticity (Fig. 7) corresponding to absolute vorticity in Fig. 6a, but the connection is not as strong as it is for vorticity. The PV-streamer analyzed from RUC2 model initial fields for 28 June 1999 12000 UTC when plotted against a background of the GOES 8 11 micron cloud top temperature and wind observations (Fig. 8) has the potential vorticity maximum penetrating into the storm anvil, whereas actual observations show an anticyclonic turning of the winds in the anvil suggesting that the PV-streamer should terminate at the anvil edge.

The observations used in initiating RUC2 could provide for a higher resolution analysis of the model that that seen here, especially if a 20 km grid were used instead of a 40 km grid. The analysis scheme, however, would have to be tuned to the mesoscale as well as the synoptic scale.

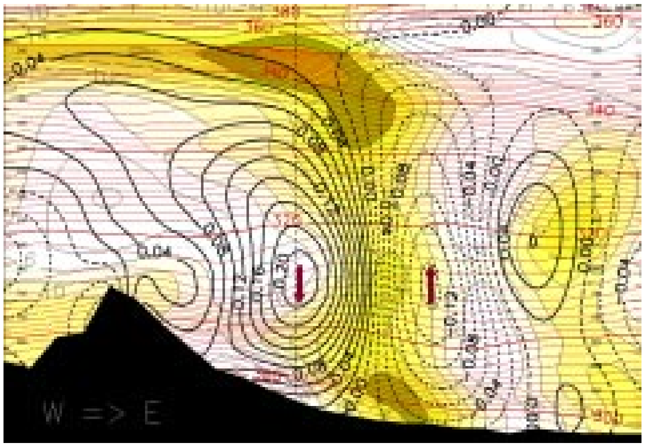


Fig. 6a. A composite analysis of initial Eta model fields along the vertical west-east cross section shown in Fig. 5 as a horizontal dashed line. Absolut vorticity is depicted in shaded contours (10^{-5} sec^{-1}), vertical motion in heavy solid (downward) and dashed (upward) contours (Pa s^{-1}), and potential temperature as thin almost horizontal contours (K).

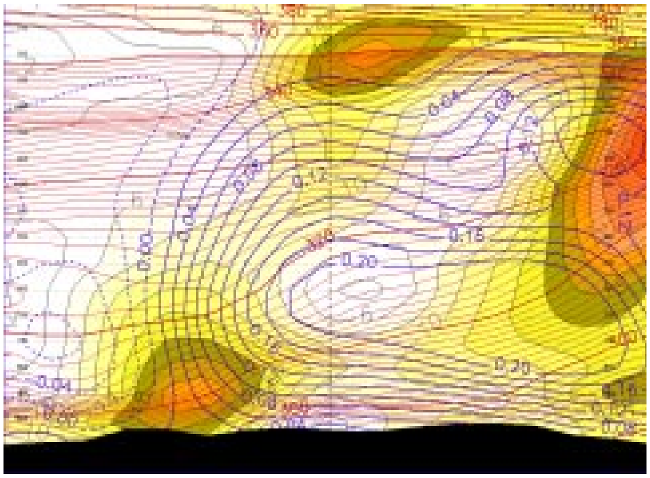


Fig. 6b. As in Fig. 6a except for a south-north cross section (along the vertical dashed line in Fig. 5.).

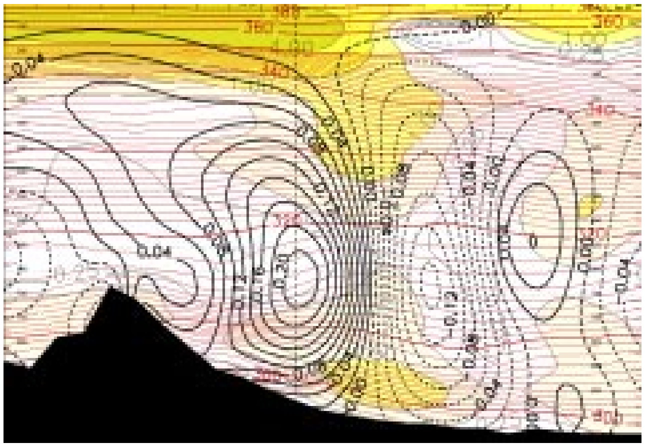


Fig. 7. As in Fig. 6a caption, except potential vorticity (10^{-6} m^2 K kg^{-1} s^{-1}) instead of absolute vorticity.

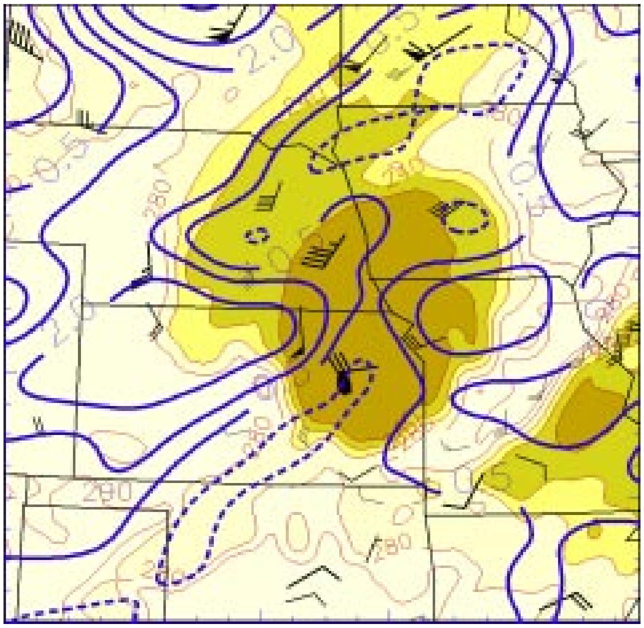


Fig. 8. A contour plot of 250 hPa PV ($m^2\ 10^{-6}$ K kg^{-1} s^{-1}) computed from RUC2 initial fields for 1200 UTC 28 June 1999 superposed on a contour plot of cloud top temperature (shaded) computed from the GOES 8 11 micron image for 1215 UTC. Observed wind vectors minus the storm propagation velocity of (25.4, -2.8) m s^{-1} from soundings (large and bold), profilers (smaller and bold), and aircraft (smallest) are plotted in meteorological notation for 1200 UTC.

4. Conclusions

4.1 Analysis of the PV-streamer

A PV-streamer was analyzed in both 32 km Eta and 40 km RUC2 model initial fields for a period of over a week extending from late June into early July 1999. Although the Eta model fields were interpolated to a grid of 80 km horizontal resolution, and the RUC2 output was used at a full 40 km resolution, the two sets of analyses captured the PV-streamer with details corresponding to the different resolutions.

4.2 Dynamical mechanisms

The PV-streamer appears to have played a dual role in the type-one MCS discussed here, in both initiating and organizing the MCS that formed over the High Plains overnight on 28 June 1999. Emerging over the central Rocky Mountains, the PV-streamer acted jointly as a jet streak and PV-anomaly aloft. Uccellini (1980) suggests that such an emerging jet streak acts to enhance the low-level jet and lee cyclogenesis. Hoskins et al. (1985) suggest that a PV-anomaly aloft tends to induce low-level cyclogenesis which is intensified by low-level warm advection. In the case of a PV-streamer both the Uccellini and Hoskins mechanisms would have acte in concert.

Once formed, convection interacted further with the PV-streamer aloft. First, the PV-streamer and associated jet streak ventilated the anvil. Secondly, the anvil was a source of negative vorticity and vertical momentum transfer that replaced and blocked the PV-streamer forcing the streamer to deform in three dimensions. The PV-streamer was a source of vorticity aloft. Lee cyclogenesis was a source of low-level vorticity. The convection itself was a source of midlevel vorticity.

A comparison of the vertical distribution of potential vorticity in a west-east cross section at 0000 UTC (not shown) with the distribution later at 1200 UTC suggests that potential vorticity has subsided to the southwest of the storm anvil to a level just above 500 hPa. This subsidence represents a stretching of the column thereby simultaneously lowering the dry static stability and increasing the vorticity. Once connected from top to bottom of the troposphere, a vertical column of vorticity would have tended to organize and perpetuate the storm.

The low-level storm inflow was directed cyclonically ahead of the storm's gust front in a spiral over a warm front, against an opposing thermal gradient, lifting the storm inflow and gradually destabilizing this layer. Convergence from the strong gust front provided an abrupt lift that initiated free convection producing a squall line. Mid-level moisture detrained from this squall line, wrapped further around the opposing thermal gradient in the mid and upper troposphere in the circulation to the north of the imbedded vortex. This led to slant convection in the anvil, enhancing the vertical transport of low-level and mid-level momentum further strengthing the blocking action of the anvil aloft. Dry mid-level air was formed into a rear inflow jet that intensified the squall line downdraft, increasing the low-level convergence along the gust front.

4.3 Precursors

Low-level frontogenesis at 850 hPa both at 0000 UTC (not shown) and 0600 UTC (indicated in two areas where Q-vectors have components pointing parrellel to the potential temperature gradient in Fig. 3) signaled the possibility of organized convection. The stronger of these frontogenetic regions (over northeastern Kansas) also had a low-level jet directed at the strengthening frontal boundary, satisfying the criteria of Augustine and Caracena (1992) as precursors of organized convection. In this case, the precursors anticipated the formation of an MCS by about 12h.

A few supercell storms were sparked in the weaker frontogenetic area in the lee of the Rocky Mountains, which grew and merged into squall lines. Here the low-level flow was transporting moisture first northwestward, then later, almost parallel to the thermal gradient. In this case, orography and not frontal lifting destabilized the low-level flow.

By 1200 UTC, the series of squall lines emanating from the High Plains had amalgamated into a large MCS that had propagated into the stronger frontogenetic region over eastern Kansas and western Missouri. Here there was a rapid expansion and maturing of the MCS.

4.4 Need for follow-up studies

The results presented here strongly suggest that there is a dynamical connection between PV-streamers and organized convection. Other studies have noted similar occurrences of organized convection associated with “dry slots” and PV-streamers. In the series that we examined, MCSs formed along the path of the dark band, or PV-streamer, the strongest MCSs blocking the path of the PV-streamer.

We have presented some physical hypotheses that need to be tested by numerical modeling. Diagnostic analyses, such as those presented here, are insufficient in themselves to make definitive connections, but are useful for generating hypotheses to be further tested.

We are in the process of using fine scale, non-hydrostatic, numerical models to simulate the formation of the MCS case presented here, and to study the role of the associated PV-streamer in organizing that convection. By varying the strength of the PV-streamer and the amount of boundary layer moisture present in the initial model fields, we hope to determine how critical the enhanced values of potential vorticity aloft are in organizing convection, and what role the convection played in modfying the PV-streamer. This is very much a scale interaction problem.

In the present study we have not attempted to tap the less conventional data sources available for better defining atmospheric states either for initializing the model or for diagnosing its behavior. In the future, we hope to be able to assimilate additional obeservations from aircraft, profilers, and Doppler radar network retrieving the mass fields from the higher resolved kinematic fields.

In this study, we have investigated the role of a PV-streamer that passed almost orthogonal to the continental divide. We will continue to search for incidences of PV-streamers having different orientations relative to the Rocky Mountains. Perhaps cases can be found where PV-streamers emerge almost parallel to the mountain chain producing a series heavy rains and flash flooding along the foothills.

5. References

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6. Acknowledgements

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