A STUDY OF THE 6 DECEMBER 1995 MIDWEST SNOW EVENT: SYNOPTIC AND MESOSCALE ASPECTS

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Abstract

On 6 December 1995, a narrow band of five to ten inches of snow fell from central Nebraska through southwest Iowa into northern Missouri. This event was distinctly mesoscale in nature. The snowfall occurred near and upwind of a surface high-pressure center, and in the absence of a surface cyclone. The primary forcing mechanism was frontogenesis in the middle and upper troposphere near the entrance region of an upper-level jet streak. Cyclonic vorticity advection was not a major factor in this case, and a survey of the 500-mb heights and vorticity and mean relative humidity fields was of little help in forecasting the potential for snow. Because of the mesoscale nature of the system, many traditional snowfall forecasting methods performed poorly in this case.

The performance of the 0000 UTC 6 December 1995 NWS Eta model run leading up to the event is examined, specifically with respect to the location of the upper-level jet, frontogenesis, ageostrophic circulations, and static stability. It is shown that the use of traditional snowfall forecasting methods using the Eta model performed poorly, but the application of non-traditional methods, including frontogenesis and divergence concepts performed well.

1. Introduction

Forecasting winter mesoscale precipitation events can be extremely challenging, particularly the placement, duration, and timing of heavy precipitation amounts over a forecast area. Such small-scale winter events can often exceed the impact of the larger-scale systems in which they occur. In some cases, the early periods of these events can result in numerous traffic accidents over a metropolitan area due to the immediate melting and refreezing of precipitation on roads.

During the period from 1000 UTC to 1700 UTC 6 December 1995, a mesoscale event produced a narrow band of five to ten inches (13-26 cm) of snow from parts of east-central Nebraska through southwest Iowa and northern Missouri (Fig. 1). The event occurred just northwest of a surface high-pressure ridge, in the absence of any low-pressure center at the surface or aloft. This snow event was not well forecast by the National Weather Service (NWS) or private meteorologists, all of whom called for just flurries over the area.

A host of individuals (Sanders and Bosart 1985; Moore and Blakely 1988; Shields et al. 1991; Funk and Moore 1996; Shea et al. 1996) have investigated the various forcing mechanisms (e.g., frontogenesis) and modulating influences (e.g., conditional symmetric instability) with respect to the evolution of mesoscale snow bands. Others, including Uccellini and Kocin (1987), Hakim and Uccellini (1992), and Shea et al. (1996) focused on the merger of the ascending branches from two distinct upper-tropospheric jet streaks in enhancing upward vertical motion and snowfall over a given area. The events presented by Sanders and Bosart (1985), Moore and Blakely (1988), and Shields et al. (1991) each depict frontogenetical forcing as the key mechanism for heavy snow production in the winter storms they studied, while Funk and Moore (1996) and Shea et al. (1996) considered frontogenesis to be only a contributing factor in the presence of other forcing mechanisms. A surface low-pressure center was present in each of the cited events studied, however, no surface low was apparent in this event. In addition, only a single jet streak is identified in this case, unlike Uccellini and Kocin (1987) and Hakim and Uccellini (1992) where the interaction of two jet streaks was critical for the production of heavy snow.

Thus, the goal of this paper is to understand what physical mechanisms likely contributed to upward vertical motion and significant snowfall along a relatively narrow band (20 to 30 km wide) from east-central Nebraska through far northern Missouri. Section 2 will describe the initial meteorological environment that led to the snow event over the area of interest. Sections 3 and 4 will show the various forcing mechanisms contributing to the development of the snow bands, focusing in particular on frontogenetical forcing using from the 6- and 12-h NWS

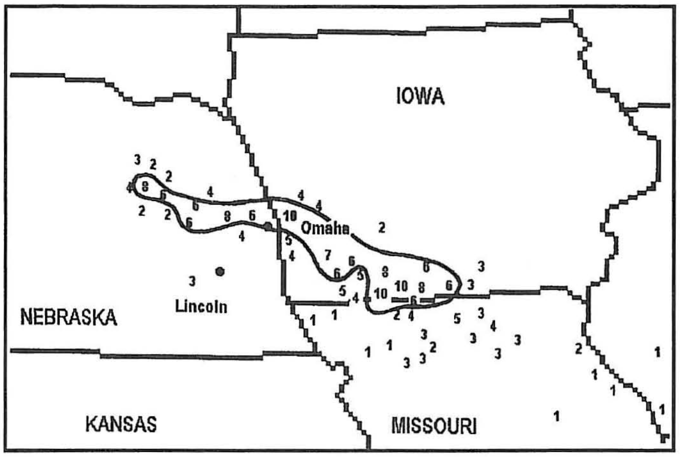


Fig. 1. Total Snowfall (inches) for 6 December 1995. Contoured are amounts of six inches or more.

Eta model forecasts initialized at 0000 UTC 6 December 1995. Section 5 will combine a discussion of the surface observations before and during the snow event, together with an analysis of the NWS WSR-88D radar reflectivity images of the snow bands from Valley, Nebraska (KOAX).

2. Meteorological Environment

The synoptic-scale weather conditions at 0000 UTC 6 December 1995, prior to the onset of the winter precipitation event under consideration are shown in Figs. 2a-d. The central United States was dominated by an area of surface high pressure that extended from eastern Kansas and southeast Nebraska through southern Iowa and the western half of Missouri (not shown). An area of low pressure across the northern Great Lakes, in combination with the high pressure system, channeled west-northwest winds and colder air into the Upper-Mississippi and lower Great Lakes region. Weak southerly flow was noted along the backside of the surface high across the western High Plains.

The 300-mb analysis revealed nearly zonal flow across the western and central United States (Fig. 2a). A large and broad trough was evident across much of the continental U.S. with an embedded short-wave trough moving through the Great Lakes region. A 110-knot jet streak was moving through the base of the trough from eastern Montana through the lower Great Lakes region. The 500-mb short-wave trough over the Great Lakes region was sharper and more well-defined compared to the 300-mb level (Fig. 2b). A strong north-south thermal gradient was detected at the 500-mb level from the northern and central Rockies through the western Great Lakes region. A 130-knot jet streak at the 500-mb level coincided with the strong thermal gradient from the northern plains through the lower Great Lakes. The 500-mb analysis also indicated an area of moisture across the northern and central Rockies, but it is difficult to find any other feature indicative of a short-wave trough in that area. Nearly saturated air was also noted at the 700-mb level from this region eastward into the western High Plains (Fig. 2c). A strong baroclinic zone from the 700-mb trough over the lower Great Lakes region through the north-central Rockies coincided with the area of mid-level moisture. The 850-mb analysis showed predominately northwest flow from the Northern Plains through the lower Great Lakes region (Fig. 2d). Strong cold air advection was evident from the eastern Great Lakes through the Mid-Mississippi Valley region. Nearly all of the Northern and Central Plains were colder than 0°C. In contrast, weak southwest flow detected over the western High Plains indicated return flow and weak warm air advection over western Nebraska through northeast Colorado. The wind field over Nebraska appeared frontogenetic based on the northeast winds in western South Dakota, southwest winds in western Nebraska and northwest winds in eastern Nebraska. In summary, an intense jet streak through much of the depth of the troposphere and associated strong thermal gradient were present over the area of concern.

3. Overview of the 0000 UTC 6 December 1995, 6-h Eta Model Forecast

This section explores the various forcing mechanisms that likely played a role in the generation of the mesoscale snow band. These include: 1) the location of the 300-mb jet streak and its associated transverse ageostrophic circulation, and 2) frontogenetical forcing and its response. It will also be shown that 500-mb vorticity advection was not a useful forecast tool in this case. The forcing mechanisms are diagnosed using the Eta model initialized at 0000 UTC 6 December 1995.

Previous studies (e.g., Hakim and Uccellini 1992; Uccellini and Kocin 1987) have documented the importance of jet streaks in the production of heavy snow. Upward vertical motion occurs in a thermally direct circulation typically in the right entrance region of the jet streak. At 0600 UTC, a 300-mb jet streak (Fig. 3) was forecast across the upper Midwest and lower Great Lakes, from southern Minnesota to Lake Michigan. A cross section generated across central Nebraska at this time (line A-B in Fig. 3) indicated the entrance region of the jet streak between 300 mb and 250 mb at point A near Mitchell, South Dakota (Fig. 4). A thermally direct circulation ("D") was centered near 780 mb near the Nebraska/South Dakota border. In contrast, an indirect circulation ("I") was identified at a higher level between 600-630 mb over southwest Kansas. The ageostrophic wind vectors (see Fig. 4 caption), which combine quasi-geostrophic (QG) frontogenesis and non-QG effects, revealed a broad area of lift across much of central Nebraska and northern Kansas, most notably in the 700-500 mb layer. This was coincident with an increase in snow intensity and coverage over central Nebraska, which occurred between 0600 and 0800 UTC.

One of the more significant factors in the production of the mesoscale snow band was frontogenetical forcing. Its response can be depicted by the convergence of Q_n-vectors. Frontogenesis, by definition, is the intensification of the temperature gradient, and is frequently observed near the entrance region of an upper-tropospheric jet streak (Shields et al. 1991; Shea et al. 1996; Funk 1995). The response to this forcing, in a QG framework, is the development of a thermally direct circula-

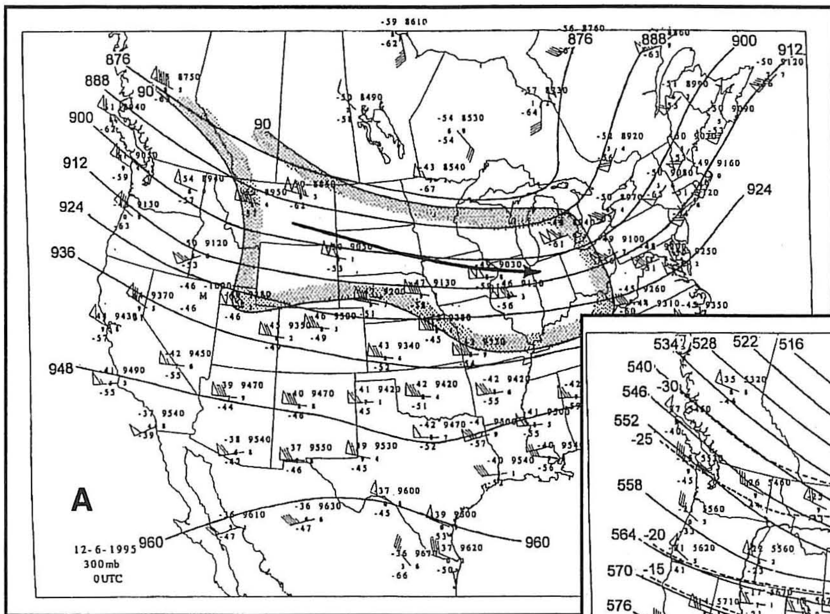


Fig. 2a. 300-mb analysis for 0000 UTC 6 December 1995. Solid contours are heights (dm) and stippled area is wind speeds greater than 90 knots

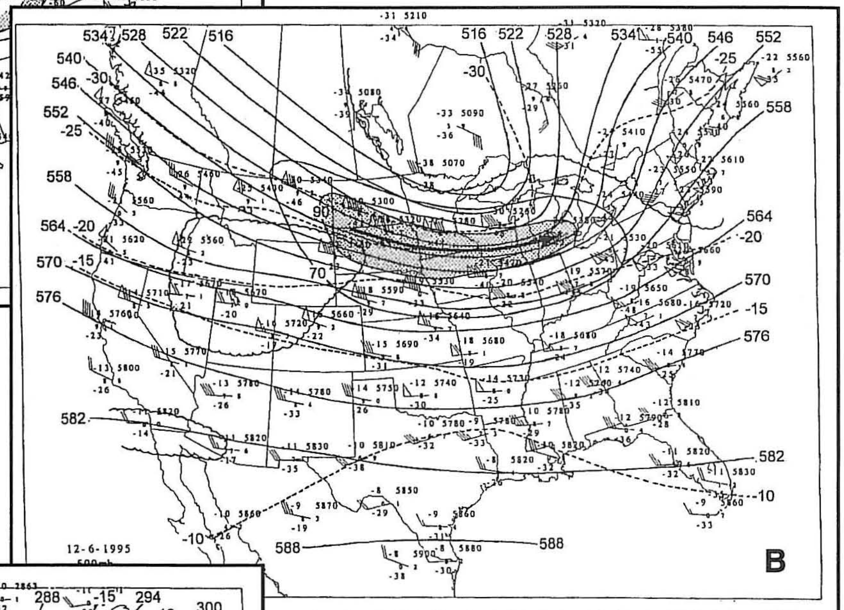


Fig. 2b. 500-mb analysis for 0000 UTC 6 December 1995. Solid contours are heights (dm) and isotherms (°C) are dashed. Scalloped areas are dewpoint depressions < 6 °C. Stippled area is wind speeds greater than 90 knots.

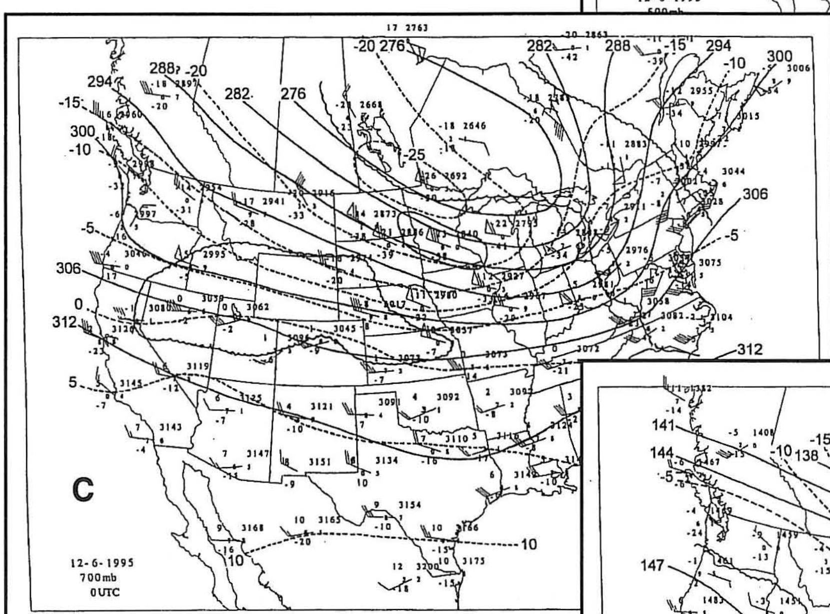


Fig. 2c. 700-mb analysis for 0000 UTC 6 December 1995. Solid contours are heights (dm) and isotherms (°C) are dashed. Scalloped areas are dewpoint depressions < 6 °C.

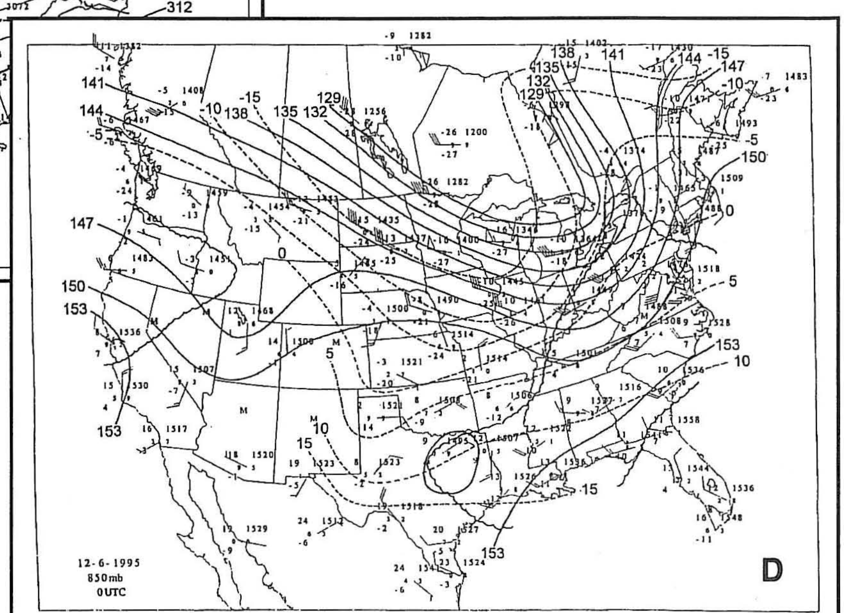


Fig. 2d. 850-mb analysis for 0000 UTC 6 December 1995. Solid contours are heights (dm) and isotherms (°C) are dashed. Scalloped areas are dewpoint depressions < 6 °C.

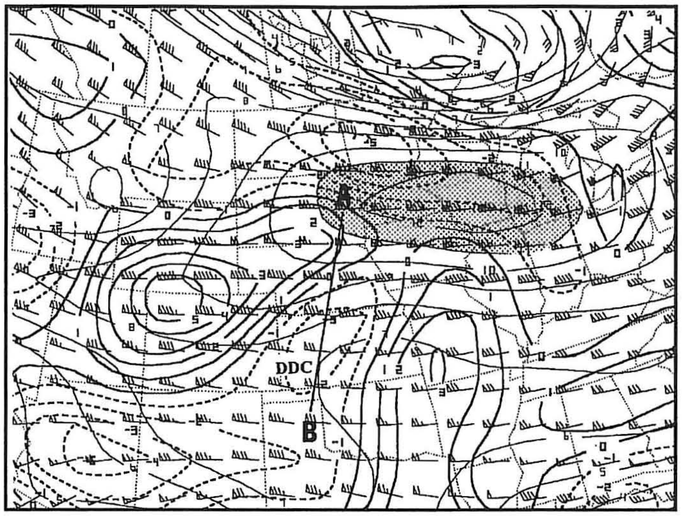


Fig. 3. The Eta model 6-h forecast 300-mb level wind barbs and isotachs (thin solid lines every 10 knots) valid 0600 UTC 6 December 1995. Divergence (10^{-5} s^{-1}) is depicted by thick solid lines and convergence by thick dashed lines. Stippled area is wind speeds greater than 90 knots. DDC is the location of Dodge City, Kansas. The bold line refers to Fig. 4.

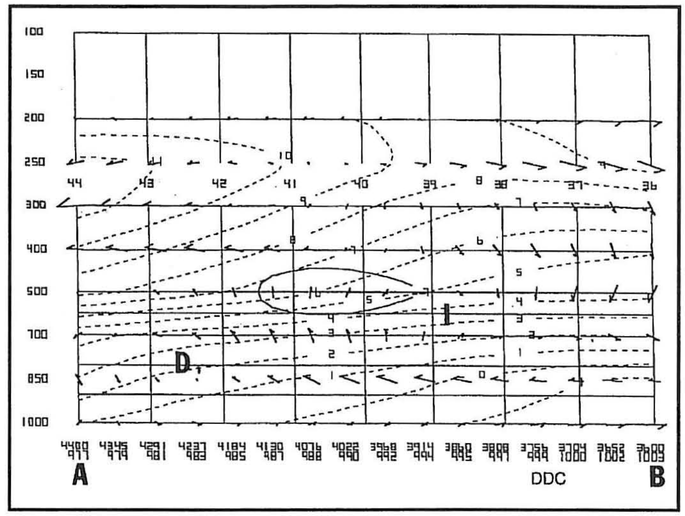


Fig. 4. The Eta model 6-h forecast vertical cross section from "A" to "B" (bold line in Fig. 3) valid 0600 UTC 6 December 1995. Vectors are ageostrophic winds (vector length is proportional to wind speed along the cross section) combined with omega. The center of the direct (indirect) ageostrophic circulation is indicated by "D" ("I"). Dashed lines are isotachs every 10 knots. Solid line encloses area of relative humidity greater than 70%. DDC is the location of Dodge City, Kansas.

tion that will act to weaken the temperature gradient and restore thermal wind balance. To visualize this direct circulation, one need only look at the convergence of the Q_n-vector, that portion of the Q-vector normal to the isotherms.

The 700-500 mb layer mean QG frontogenesis (Fig. 5) from the Eta model showed an axis of frontogenetical forcing that extended from eastern Montana to central Iowa. The QG response to this forcing, shown by the convergence of Q_n-vectors, identifies the region of implied lift extending from central Montana to southeast Iowa.

Additionally, the 500-300 mb layer frontogenesis (Fig. 6) showed an axis of frontogenetical forcing that extended from eastern Montana southeast into northern Iowa. The forcing was not quite as strong as was indicated in the 700-500 mb layer. The convergence of Q_n implies an area of lift over Nebraska, northern Kansas, most of Iowa, and northwest Missouri. These forecast fields suggested that the area of implied lift was relatively deep over Nebraska through southwest Iowa and northwest Missouri.

At 0600 UTC, the region over central Nebraska where the snow band developed was characterized by statically stable air in the unsaturated 700-500mb layer (Fig. 7) with mean lapse rate of 4 - 5 °C km^{-1}. The lapse rate was near neutral in the more moist 500-300 mb layer (Fig. 8), between 7 and 8 °C km^{-1}. Although the 700-500 mb layer was statically stable, a tight lapse rate gradient was evident from northeast to southwest across the area with greater instability farther southwest across southwest Nebraska and western Kansas. A comparison of the 0000 UTC and 1200 UTC 6 December 1995 Omaha soundings (not shown) indicated the entire vertical profile had moistened overnight, thus becoming near neutral through a deep layer of the troposphere above 600 mb.

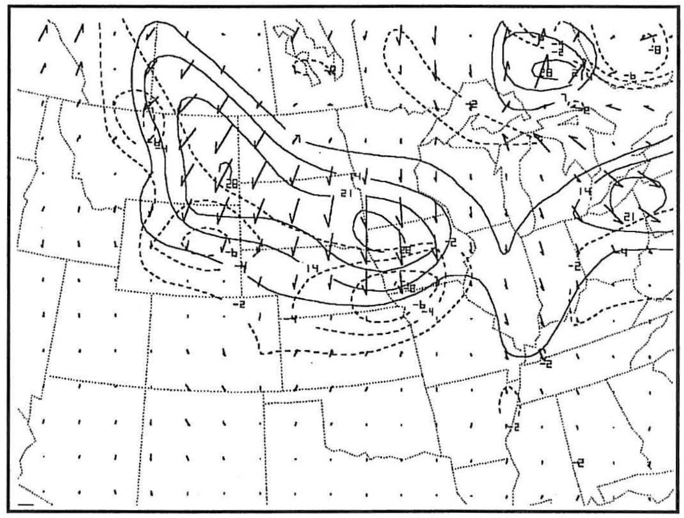


Fig. 5. The Eta model 6-h forecast 700-500 mb layer mean quasi-geostrophic frontogenesis (solid, 10^{-14} Pa^{-1} s^{-1}) and divergence of Q_n (dashed in units of 10^{-19} Pa^{-1} m^{-1} s^{-1}, vector length is proportional to magnitude).

4. Overview of the 0000 UTC 6 December 1995, 12-h Eta Model Forecast

By 1200 UTC, the projected 300-mb jet streak (Fig. 9) had shifted slightly farther east, with the core extending from central Iowa into the southern Great Lakes. However, the overall area of stronger winds extended westward into northern Colorado from the 0600 UTC forecast field suggesting a "back-building" extension of the overall jet core and formation of a small secondary core over northern Colorado. The Eta model predicted a region of strong upper-level divergence within the vicinity of the right entrance region of the upper-level jet

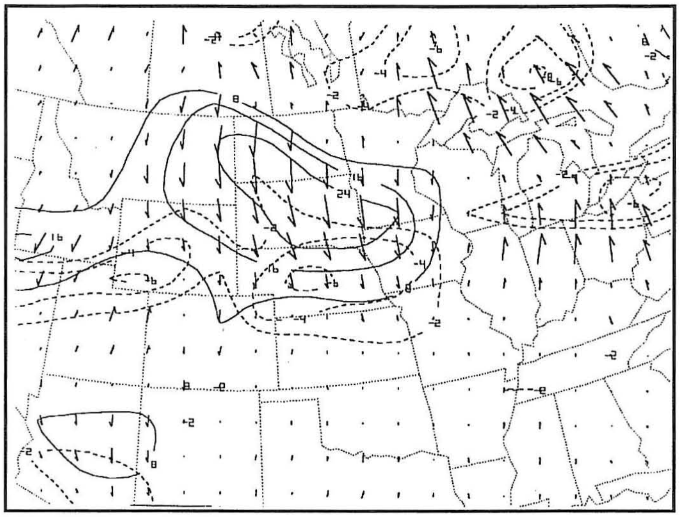


Fig. 6. The Eta model 6-h forecast 500-300 mb layer mean quasi-geostrophic frontogenesis (solid, 10^{-14} Pa^{-1} s^{-1}), and divergence of Q_n (dashed in units of 10^{-19} Pa^{-1} m^{-1} s^{-1}, vector length is proportional to magnitude).

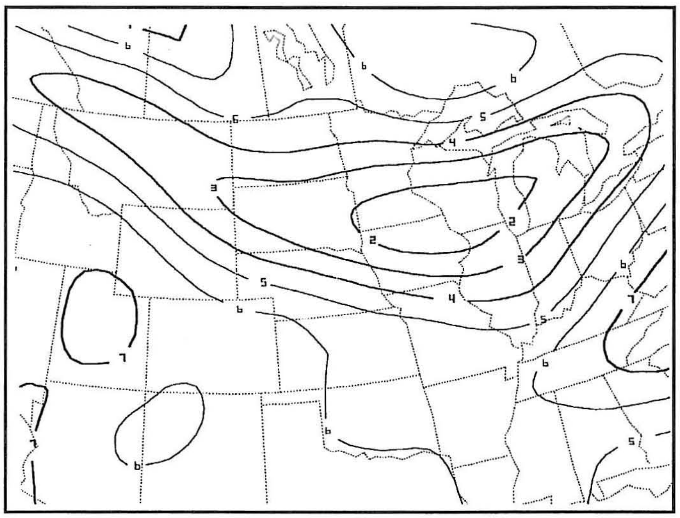


Fig. 7. The Eta model 6-h forecast 700-500 mb layer mean lapse rate contours (°C km^{-1}).

streak from central Nebraska through southwest Iowa and far northwest Missouri. A cross section generated across eastern Nebraska at 1200 UTC (Fig. 10, line C-D in Fig. 9) revealed the entrance region of the jet streak between 300 and 250 mb just to the north of Omaha over northern Iowa. A thermally direct circulation ("D") was noted near 850 mb over western Iowa and an indirect circulation was identified over east central Kansas. The ageostrophic wind vectors showed a broad area of lift from northern Kansas into eastern Nebraska. Although the lift was most pronounced in the 700-300 mb layer, it extended throughout the entire atmospheric column. Note the substantial increase in the magnitude and areal coverage of the rising motion when compared with the 0600 UTC output (Fig. 4). This corresponded well with the rapid development and intensification of the snow band. It is also interesting to note that the area of strong upper-level divergence and associated ageostrophic circulation in this case was associated with a single jet core with a westward extension of higher winds. This type of jet core pattern differs from the distinct dual jet patterns observed by Hakim and Uccellini (1992) and Shea and Przybylinski (1995) in their winter mesoscale events.

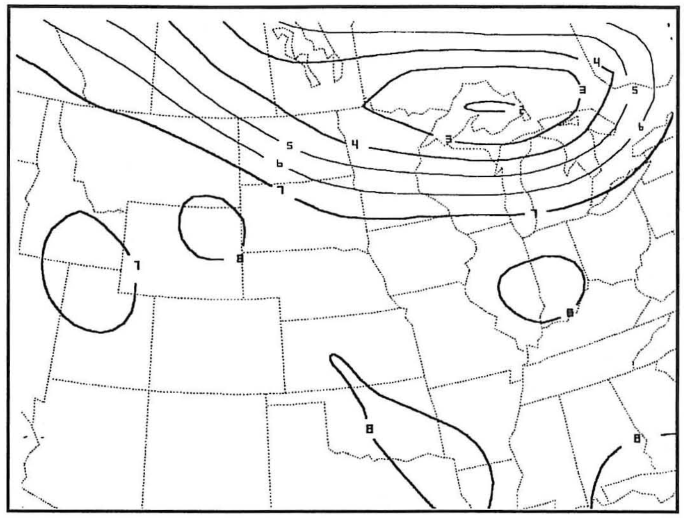


Fig. 8. The Eta model 6-h forecast 500-300 mb layer mean lapse rate contours (°C km^{-1}).

The 12-h forecast, 700-500 mb layer mean QG frontogenesis (Fig. 11) indicated an area of frontogenetical forcing extending from western North Dakota southeast through Iowa. The QG vertical motion response to this forcing is indicated by the band of Q_n-vector convergence in the gradient region of frontogenesis from eastern Montana through central Nebraska and into extreme northern Missouri. The location and alignment of the maximum 700-500 mb region of implied lift coincided with the location of the frontogenetic snow band.

The 12-h forecast, 500-300 mb layer mean QG frontogenesis (Fig. 12) also showed a narrow axis of frontogenetic forcing extending from northeast Nebraska, east into northern Indiana. The Q_n-vector convergence indicated forcing for QG ascent from central Nebraska through northern Missouri and central Illinois. Note that the strength of the Q_n-vector convergence had increased significantly between 0600 and 1200 UTC over the area of concern, implying a deep and pronounced area of lift over southeast Nebraska through northern Missouri and far southern Iowa. The fact that the forcing implied by QG frontogenesis agrees with the vertical motion field depicted by the ageostrophic vectors implies that QG theory explains reasonably well the nature of the vertical motion field in this case.

The 12-h Eta model forecast valid at 1200 UTC showed that the area from eastern Nebraska through northern Missouri was characterized by a nearly neutral lapse rate in the now saturated 700-500 mb and 500-300 mb layers. The 700-500 mb layer lapse rate (Fig. 13) was near 4 °C km^{-1} and the 500-300 mb layer lapse rate (Fig. 14) was between 7 and 8 °C km^{-1}. Examination of the Valley, Nebraska (KOAX) sounding from 1200 UTC 6 December 1995 (not shown) gave credence to the Eta model lapse rates for these layers. The stability of the 700-500 mb layer decreased slightly

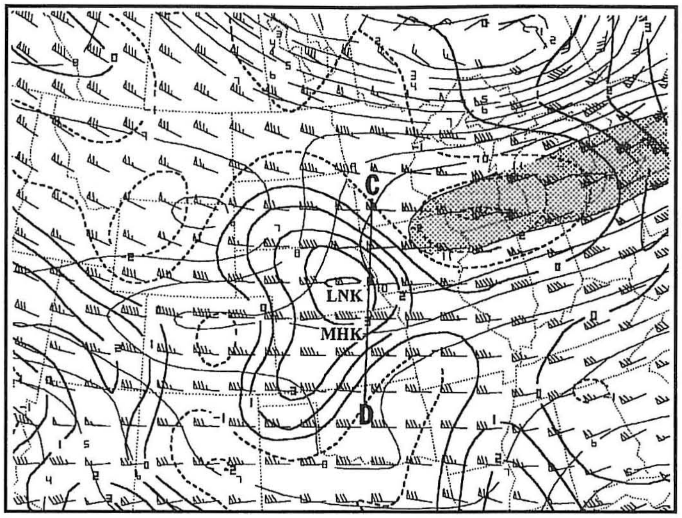


Fig. 9. The Eta model 12-h forecast 300-mb level wind barbs and isotachs (thin solid lines every 10 knots) valid 1200 UTC 6 December 1995. Divergence (10^{-5} s^{-1}) is depicted by thick solid lines and convergence by thick dashed lines. Stippled area is wind speeds greater than 90 knots. LNK and MHK represent the locations of Lincoln, Nebraska and Manhattan, Kansas, respectively. The bold line refers to Fig. 10.

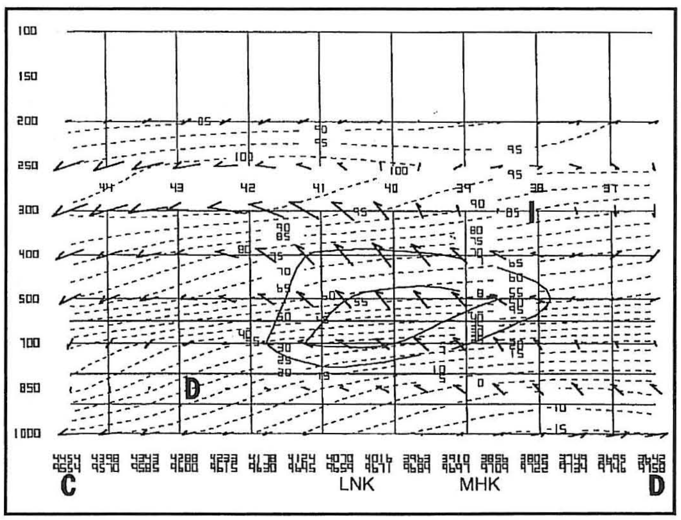


Fig. 10. The Eta model 12-h forecast vertical cross section from "C" to "D" (bold line in Fig. 9) valid 1200 UTC 6 December 1995. Vectors are ageostrophic winds (vector length is proportional to wind speed). Dashed lines are isotachs (kt). The center of the direct (indirect) ageostrophic circulation is noted at "D" ("I"). Solid contours enclose areas of relative humidity ≥70%; innermost contour encloses ≥90% humidities. LNK and MHK represent the locations of Lincoln, Nebraska and Manhattan, Kansas respectively.

between 0600 UTC and 1200 UTC, but the layer remained nearly neutral.

Frequently forecasters will survey the model-generated 500-mb height and vorticity fields and base precipitation forecasts for the presence or absence of positive vorticity advection. The 6-h Eta 500-mb height and vorticity fields (Fig. 15) showed a broad northwesterly flow regime across the Central Plains. A weak short-wave trough was evident (at least in the model forecast fields) moving from the Pacific Northwest into the northern and central

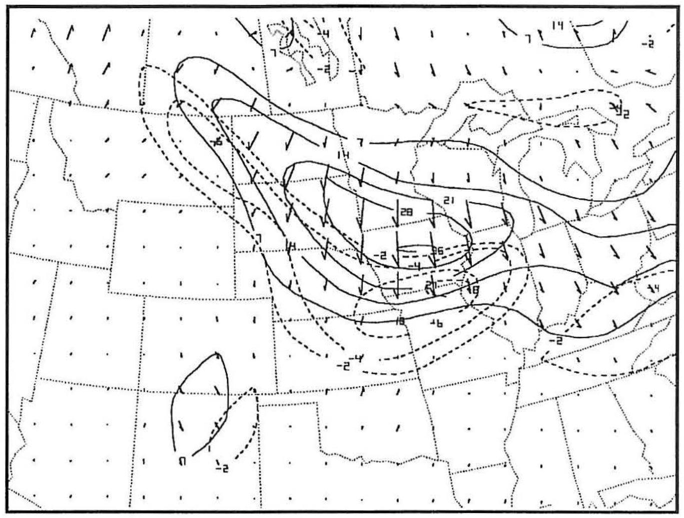


Fig. 11. The Eta model 12-h forecast 700-500 mb layer mean quasi-geostrophic frontogenesis isolines (solid in units of 10^{-14} Pa^{-1} s^{-1}) and divergence of Q_n isolines (dashed in units of 10^{-19} Pa^{-1} m^{-1} s^{-1}, vector length is proportional to magnitude).

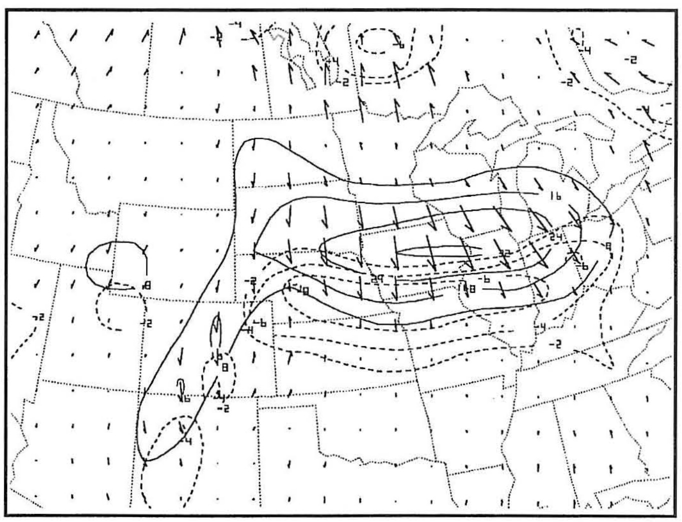


Fig. 12. The Eta model 12-h forecast 500-300 mb layer mean quasi-geostrophic frontogenesis isoloines (solid in units of 10^{-14} Pa^{-1} s^{-1}) and divergence of Q_n isolines (dashed in units of 10^{-19} Pa^{-1} m^{-1} s^{-1}, vector length is proportional to magnitude).

Rockies. The short-wave trough had a "sheared" appearance at first glance, and may not have been of enough significance to alert the forecaster that further in-depth analysis was warranted. The 12-h forecast (Fig. 16) showed the short-wave trough moving into the western High Plains, west of the snow bands. The weak nature of this vorticity maximum, combined with its location well west of the snow bands, and lack of appearance in satellite imagery suggests it was likely not a factor in the development of the snow bands.

Because of the mesoscale nature of this event, several of the traditional snowfall forecasting methods performed poorly in this case. The amount of snow forecast using the Magic Chart (Chaston 1989) was almost negligible over the area of concern, while the Garcia method (Garcia 1994) depicted a maximum snowfall between 2 and 3 inches. These methods rely on detecting the larger-

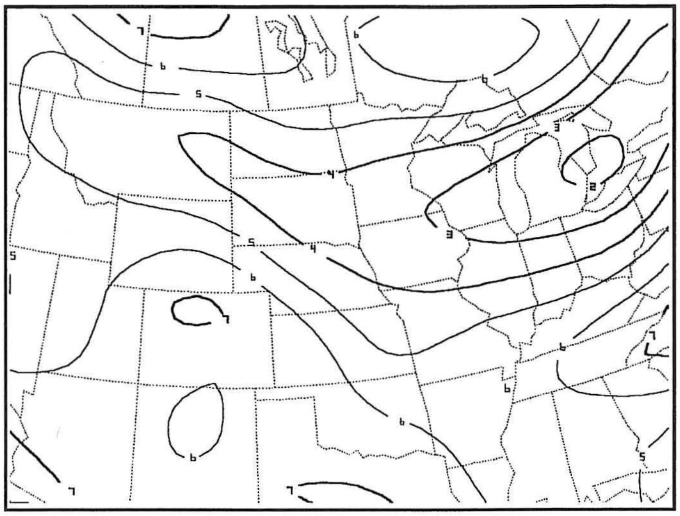


Fig. 13. The Eta model 12-h forecast 700-500 mb layer mean lapse rate contours (°C km^{-1}).

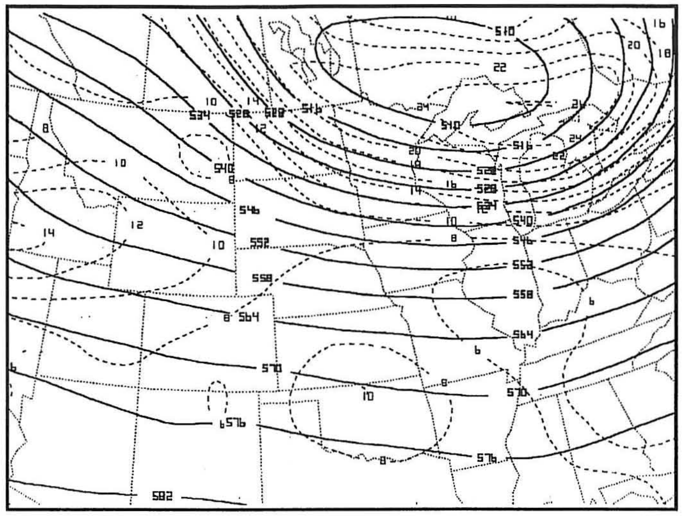


Fig. 15. The Eta model 6-h forecast 500-mb level height contours (dm; solid lines) and absolute vorticity (10^{-5} s^{-1}; dashed lines).

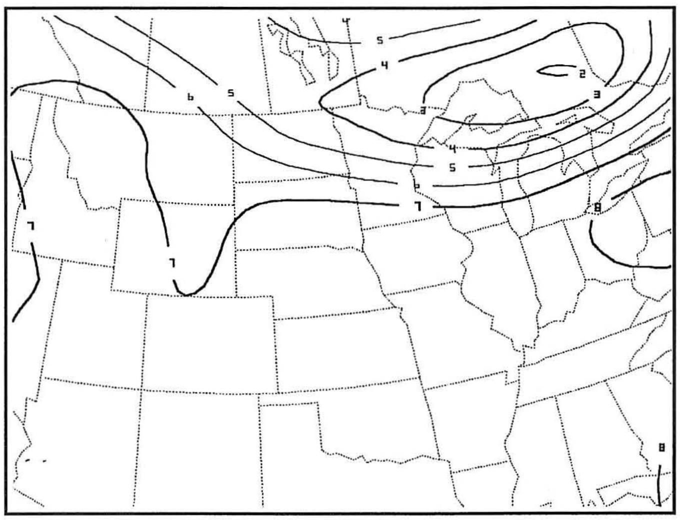


Fig. 14. The Eta model 12-h forecast 500-300 mb layer mean lapse rate contours (°C km^{-1}).

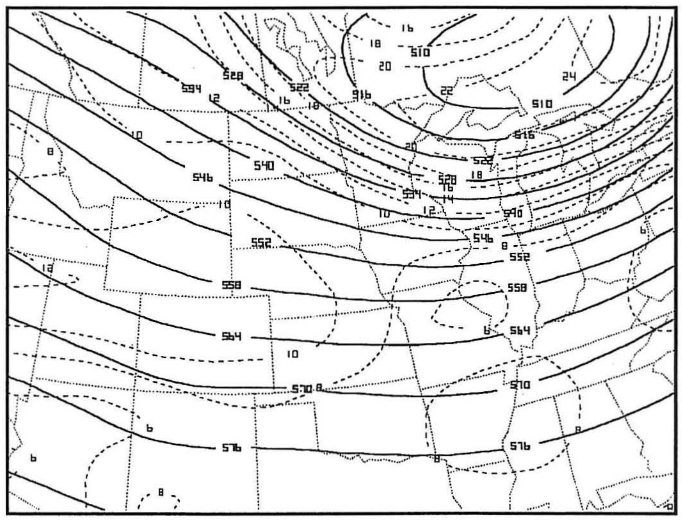


Fig. 16. The Eta model 12-h forecast 500-mb level height contours (dm; solid lines) and absolute vorticity (10^{-5} s^{-1}; dashed lines).

scale vertical motion fields associated with synoptic-scale systems. The smaller-scale vertical motion patterns in this case were best diagnosed using frontogenesis, and could have been easily missed if only traditional methods were used.

5. Surface and Radar Analyses

At 0600 UTC, a large area of surface high pressure (1027 mb) extended from the eastern Dakotas through Missouri and eastward into central Kentucky (Fig. 17a), while a weak area of low pressure stretched across Wyoming and Colorado. Surface winds over western Nebraska and western South Dakota showed an easterly component while a southerly flow was noted across eastern Colorado through southern Nebraska. Both the surface high and low pressure systems were responsible for a southerly flow of air from the Texas Panhandle region through southern Nebraska. Note the col in north central Nebraska with the axis of dilatation evident west to east across northern Nebraska. Three-hour pressure tendency fields showed 2.0 - 4.0 mb falls from northern Colorado through southwest Nebraska southward into western Kansas (Fig. 17b).

One distinct band and two smaller mesoscale precipitation bands evolved shortly after 0600 UTC across eastern Nebraska, southwest Iowa and northwest Missouri. The first and perhaps most interesting mesoscale event was the growth of a narrow but intense precipitation band approximately 15 to 20 km wide and over 200 km long. As early as 0755 UTC (Fig. 18a), WSR-88D reflectivity images from Valley, Nebraska (KOAX) showed the beginning of this nearly solid band pattern comprised of 20 dBZ and greater echoes northwest of the radar site (band "A"). This feature was embedded within the lighter precipitation that extended from 80 km west to nearly 220 km west-northwest of KOAX.

The surface analyses at 0900 UTC (Fig. 17c) showed the high pressure area moving southeast and stretching from northern Missouri through central Kentucky.

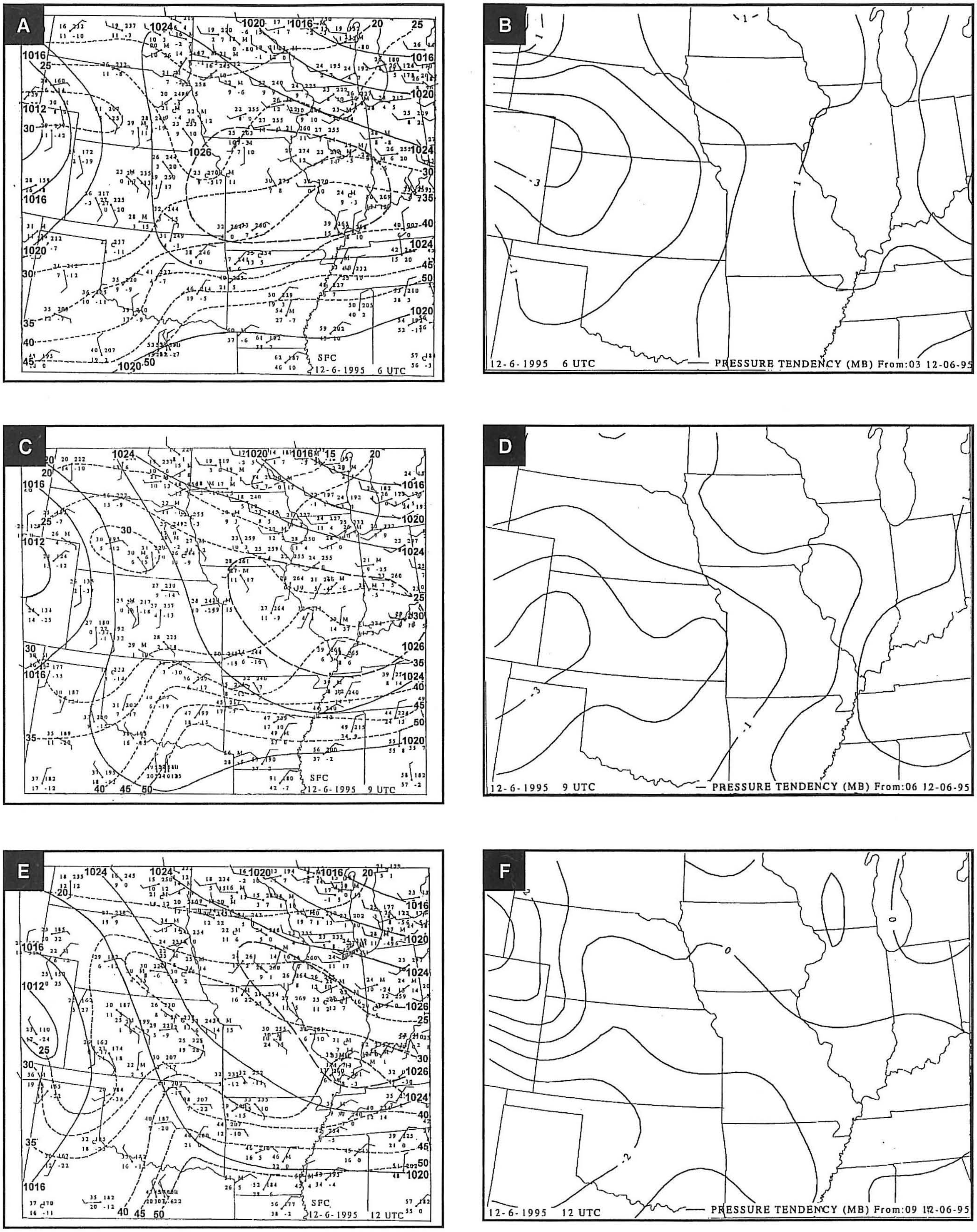
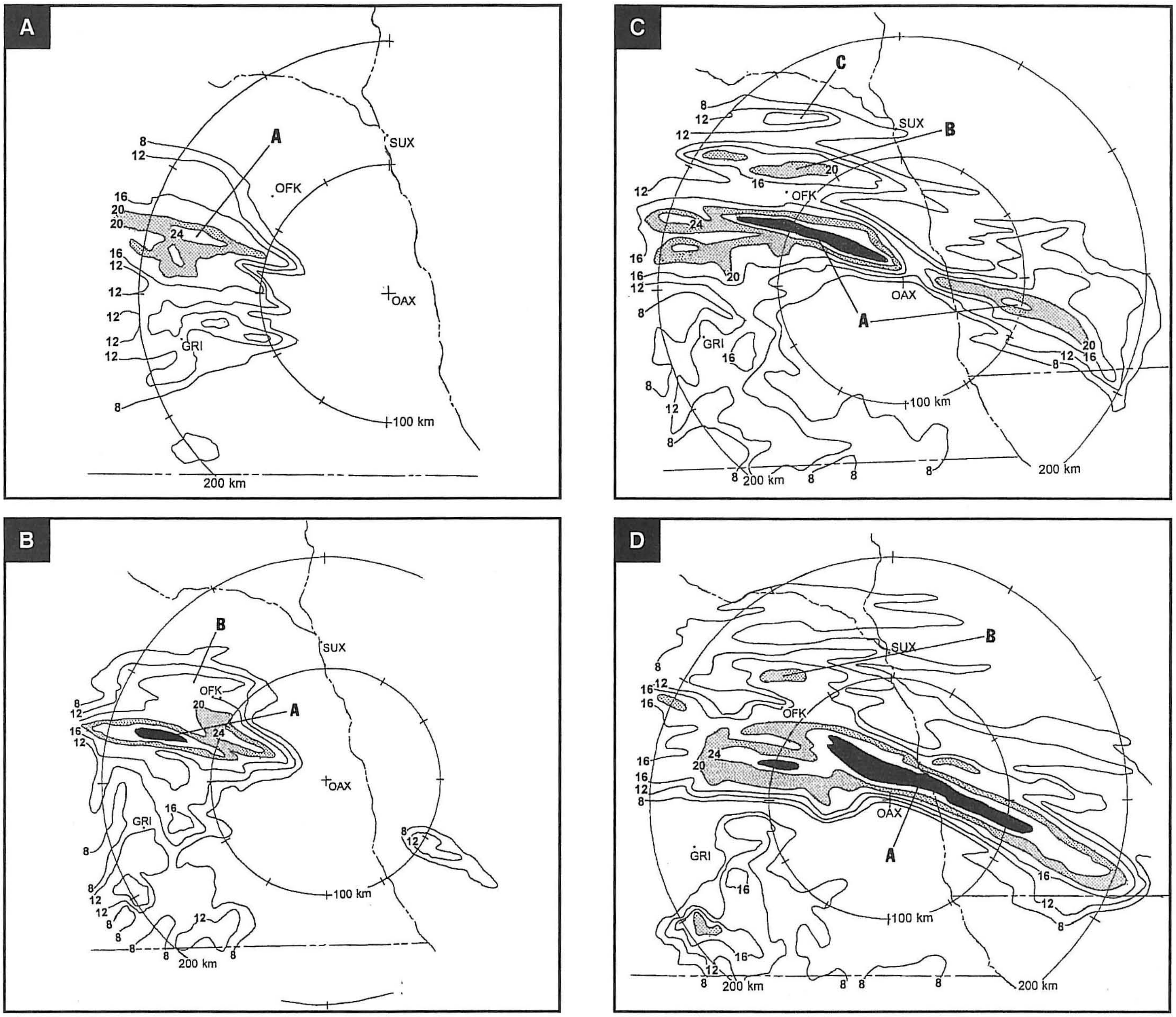


Fig. 17. Sea-level pressure isobars (solid, mb) and surface temperature isotherms (dashed, °F) at (a) 0600 UTC, (c) 0900 UTC, and (e) 1200 UTC and surface pressure tendencies (mb-3h^{-1}) at (b) 0600 UTC, (d) 0900 UTC and (f) 1200 UTC..



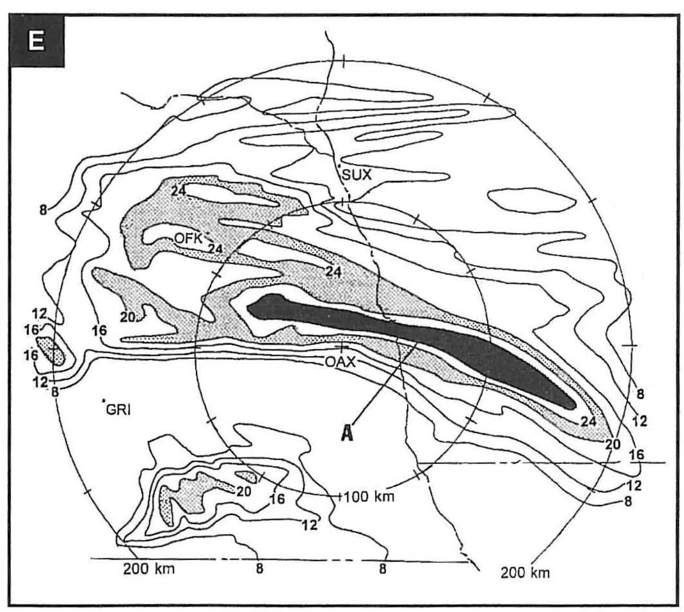


Fig. 18. WSR-88D reflectivity images at 0.5° elevation angle from Valley, Nebraska (OAX) for the time periods (a) 0755 UTC, (b) 0853 UTC, (c) 0951 UTC, (d) 1049 UTC, and (e) 1147 UTC. The reflectivity factor values are given in dBZ. Values of 20-23 dBZ are stippled and 28 dBZ and greater are shaded. Labels A, B, and C denote separate reflectivity bands. SUX is Sioux City, Iowa. OFK and GRI are Norfolk and Grand Island, Nebraska, respectively.

Surface wind fields continued to show easterly flow across central and western Nebraska while a light southeast flow was noted across eastern and southeast sections of the state. The low pressure center over eastern Colorado was associated with three-hour pressure falls of 2.0 to 3.0 mb (Fig. 17d). The surface low was displaced well southwest of the snow band, not in close proximity and south of the snow as usually observed in classic winter storms undergoing organized cyclogenesis.

Band "A" had intensified by 0853 UTC (Fig. 18b) with reflectivity values exceeding 28 dBZ. At 0900 UTC, surface reports under the highest reflectivity echoes revealed visibilities at or below 3/4 statute miles. A second weaker banded pattern (band "B") was evident north, and nearly parallel, to band "A". Light snow was associated with band "B". Southwest of the radar site, a large area of very light unorganized precipitation persisted from Grand Island, Nebraska to the Nebraska-Kansas state line.

At 0951 and 1049 UTC (Figs. 18c and 18d), reflectivity values of 24 dBZ and greater associated with band "A" expanded in areal coverage, and extended from south central Iowa through OAX, and northwestward to 50 km west-southwest of Norfolk, Nebraska (OFK). Surface reports over parts of eastern Nebraska reported visibilities below 1/2 statute mile. Two other weaker bands (bands "B" and "C") were located to the north (north of OFK and west of Sioux City Iowa), oriented nearly parallel to band "A" at 0951 UTC. These bands were about 25 to 30 km apart and were moving to the east. Band "C" was short-lived while band "B" was still evident north of OFK at 1049 UTC. All three bands occurred in a frontogenetical environment across eastern Nebraska and western Iowa. This type of precipitation pattern is similar to observations recorded by Shields et al. (1991) where primary and secondary banded precipitation features were present in a frontogenetical environment. In contrast, precipitation south of band "A" continued to show a more uniform appearance over parts of southeast Nebraska and far northeast Kansas. It is unclear based on available data why this was the case.

At 1200 UTC (Fig. 17e), the surface high-pressure system continued to move southeastward and extended from southeast Iowa through the lower Ohio Valley region. The surface ridge axis extended northwestward from southeast Iowa through southeast South Dakota. Surface winds were generally from the west or west-southwest over eastern South Dakota through far northeast Nebraska. The surface thermal gradient had tightened over eastern Nebraska and was oriented parallel to the snow bands, an indication of surface frontogenesis. The surface low in east central Colorado remained well southwest of the area. Strongest three-hour (0900-1200 UTC) pressure falls were detected from southeast Colorado through the Texas and Oklahoma Panhandle regions with magnitudes reaching 2.0 to 3.8 mb (Fig. 17f).

It is interesting to note that surface winds at 1200 UTC were blowing from the east through north or northeast across east central Nebraska to northwest Missouri. Specifically, Omaha, Nebraska, reported north-northeast winds of 10 kt. Even over north central Missouri, surface winds were from the northeast at 10 kt. This area was located south and west of the surface ridge axis. Additionally, the three-hour pressure tendency (0900 - 1200 UTC) showed a slight pressure rise over east-central Nebraska. The surface winds at 1200 UTC and weak pressure rise over parts of east-central Nebraska and northwest Missouri may be a surface reflection of the thermally direct circulation in the vicinity of the entrance region of the 300-mb jet streak.

Similar to that at 1049 UTC, the 1147 UTC reflectivity image (Fig. 18e) continued to depict band "A" extending 200 km southeast of OAX, along the Iowa-Missouri state line, through just north of OAX and westward to 100 km northwest of OAX. Reflectivity values of 28 dBZ and greater persisted within band "A". Snowfall beneath band "A" continued to reduce visibilities to 1/2 statute mile or less at most locations. Low visibilities affected the traveling public and the aviation community. The resulting instrument flight rules (IFR) conditions decreased air traffic flow and caused delays and cancellations of flights at Omaha (OMA). Further north (near and north of OFK) multiple weaker and smaller bands of precipitation, where maximum reflectivity reached 24 dBZ, persisted through 1147 UTC. By 1400 UTC, snowfall amounts of five to ten inches (13-26 cm) had been recorded across parts of eastern Nebraska, southwest Iowa and far northern Missouri.

6. Conclusion

This paper examined a significant mesoscale snow event that proved to be quite a forecast challenge for the operational community. The heavy snow occurred in a very narrow band within a seven-hour period. This type of mesoscale precipitation event poses a greater forecast challenge than the classic events involving major surface cyclogenesis. Moreover, it can dramatically impact communities that are recipients of the snow.

In the case presented here, traditional pattern-recognition forecast methodologies including those based on 500-mb positive vorticity and/or vorticity advection and its relationship to surface low-pressure centers failed as useful forecast tools. Nonetheless, there are tools available, some already well documented, that aid the forecaster in developing a better strategy for diagnosing the key physical processes responsible for these mesoscale events. Even with the limitations of quasi-geostrophic theory, QG frontogenesis proved to be the useful tool in providing evidence that there was synoptic-scale support for this event. It is critical that forecasters know what tools to use and how to apply physical concepts to better understand and predict these events.

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