BAND ON THE RUN

Chasing the Physical Processes Associated with Heavy Snowfall

BY CHARLES E. GRAVES, JAMES T. MOORE, MARC J. SINGER, AND SAM NG

On the afternoon of 10 November 1998, much of southeastern South Dakota and the surrounding area was digging itself out from under a foot of snow. The snowfall was spread over several states; however, the heaviest totals were found in pockets around Sioux Falls, South Dakota (FSD; Fig. 1). The impressive snowfall near Sioux Falls was accompanied by nearly five hours of thunder and lightning during the most intense period of snowfall (1100–1600 UTC). The extratropical cyclone (ETC) responsible for creating the heavy snow and blizzard conditions in parts of South Dakota and Minnesota was of historic magnitude with a central mean sea level pressure (MSLP) of 964 hPa at its peak over Duluth International Airport at 2035 UTC on 10 November [National Climatic Data Center (NCDC) 1998]. The clarity of the features in this early season snowstorm makes it a good candidate for illustrating the common characteristics of synoptic-scale processes often found with heavy banded snowfall in the central United States.

To examine the main physical processes attending this deep system, both observed surface data and initialized upper-air data from the Rapid Update Cycle (RUC) II model are used. The major synoptic features at the time of most intense snowfall (1500 UTC) are the focus of this study; however, some analyses from nine hours earlier (0600 UTC) are shown to illustrate the dynamic development of this exceptionally strong ETC.

The system initially formed to the lee side of the Rocky Mountains and moved eastward across Colorado and Kansas early on 9 November. It then turned northeastward and intensified rapidly as it moved through eastern Nebraska into Minnesota. At 0600 UTC 10 November, the ETC was located in eastern Nebraska and had a central MSLP of 984 hPa (Fig. 2a). The surface analysis reveals a warm front extending eastward ahead of the system through Missouri and two cold fronts pinwheeling southward from the center of low pressure. The dual cold-front structure at this time is supported by the presence of two wind shift lines (not shown) and two distinct thermal gradients, as illustrated by the packing of the isentropes in Fig. 2a.

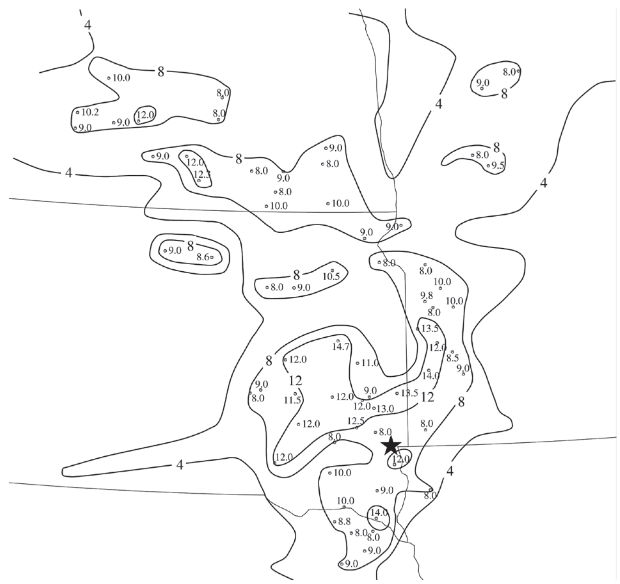

FIG. 1. The 48-h snowfall isohyet analysis in inches for the period ending 1200 UTC 11 Nov 1998, based upon the NCDC cooperative observer network. Snowfall reports of less than 8 inches are not displayed. A star indicates Sioux Falls, SD.

By 1500 UTC the system had moved into southern Minnesota and the central MSLP had dropped to 967 hPa (Fig. 2b); most of this 17-hPa pressure fall occurred in the last six hours. It was during this rapid intensification phase that snowfall rates became sig-

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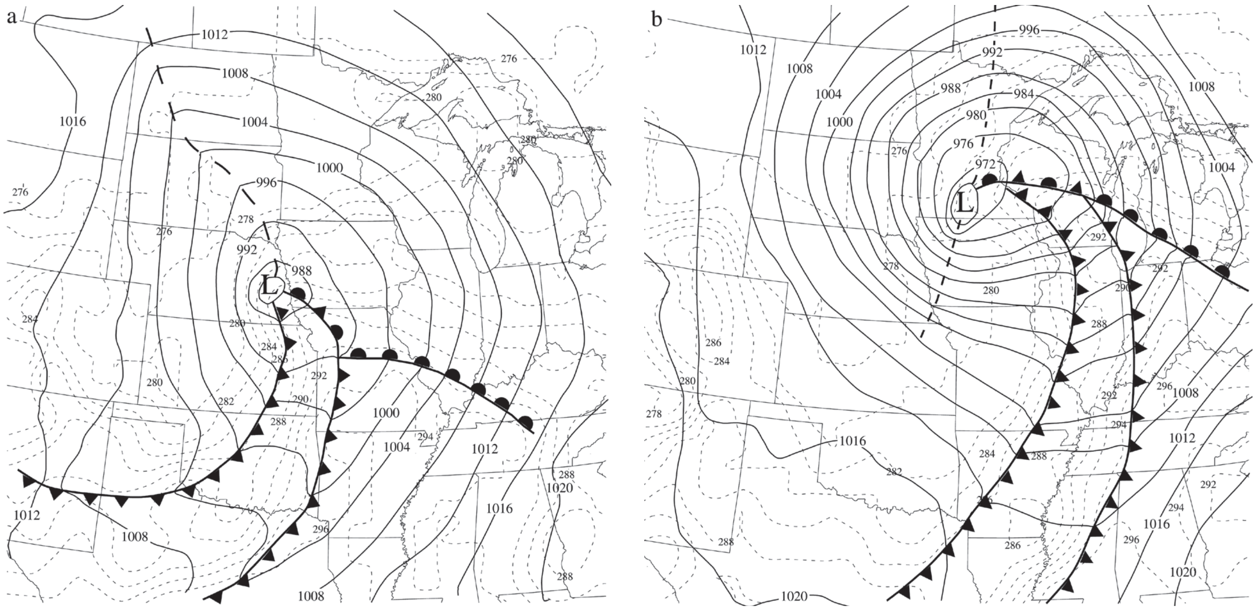

Fig. 2. Surface analysis for (a) 0600 and (b) 1500 UTC 10 Nov 1998. Solid lines are subjectively analyzed isobars (in hPa) and dashed lines are objectively analyzed isentropes (in K) from the RUC-II initialized data.

nificant in the vicinity of FSD. The occluded front was located within the thermal ridge at the surface extending from eastern Wisconsin to south-central Minnesota. The dual cold frontal structure was even more pronounced at this time, judging from the two separate regions of thermal packing south of the cyclone center. At this time, an area of moderate to heavy snowfall was occurring in South Dakota, as indicated by the Weather Surveillance Radar-1988 Doppler (WSR-88D) reflectivity from FSD (Fig. 3). The banded area of heavy snow extended from FSD to the northwest and was approximately 30 km wide, illustrating the narrow nature of the band. This significant snowband was located west of the surface low and was not directly associated with any surface fronts. The majority of the stations north of the surface low and east of the inverted trough reported rain, while most of the stations west of the inverted trough reported snow.

A high-amplitude, midtropospheric (500 hPa) trough was located southwest of the surface low at 0600 UTC (not shown) over western Kansas. By 1500 UTC the trough had lifted to the northeast and became a closed low over the Minnesota–Iowa border as implied by the circulation indicated in both the IR and water vapor imagery (Fig. 4). During the same time period at 300 hPa, a 70 m s^{-1} cyclonically curved jet streak had rounded the base of the upper-level trough, and by 1500 UTC it stretched from northeastern Oklahoma to northwest Illinois coincident with the dry slot indicated in Fig. 4b. Consequently, the surface low was located in the left-exit region of a strong cyclonically curved, upper-level jet—a prime location for upper-level divergence and synoptic-scale upward motion.

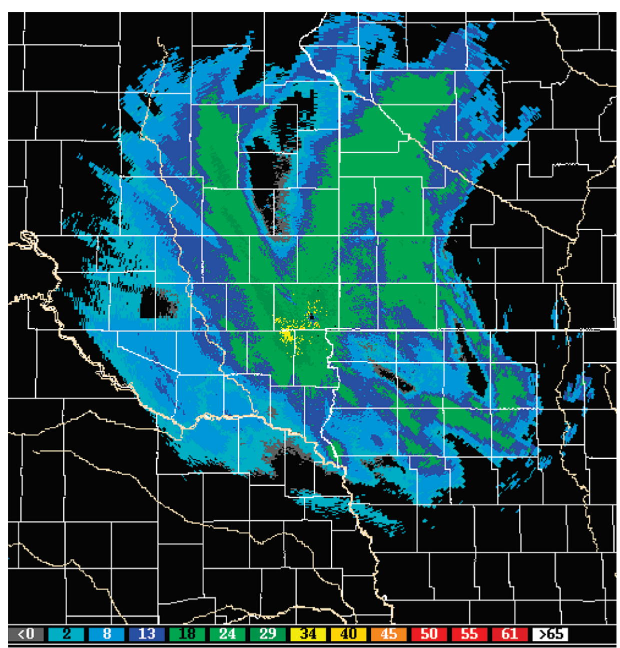

Fig. 3. WSR-88D radar reflectivity pattern for 0.5° elevation at 1504 UTC 10 Nov 1998 at Sioux Falls, SD. The legend on the bottom of the figure indicates the reflectivity color scale in dBZ.

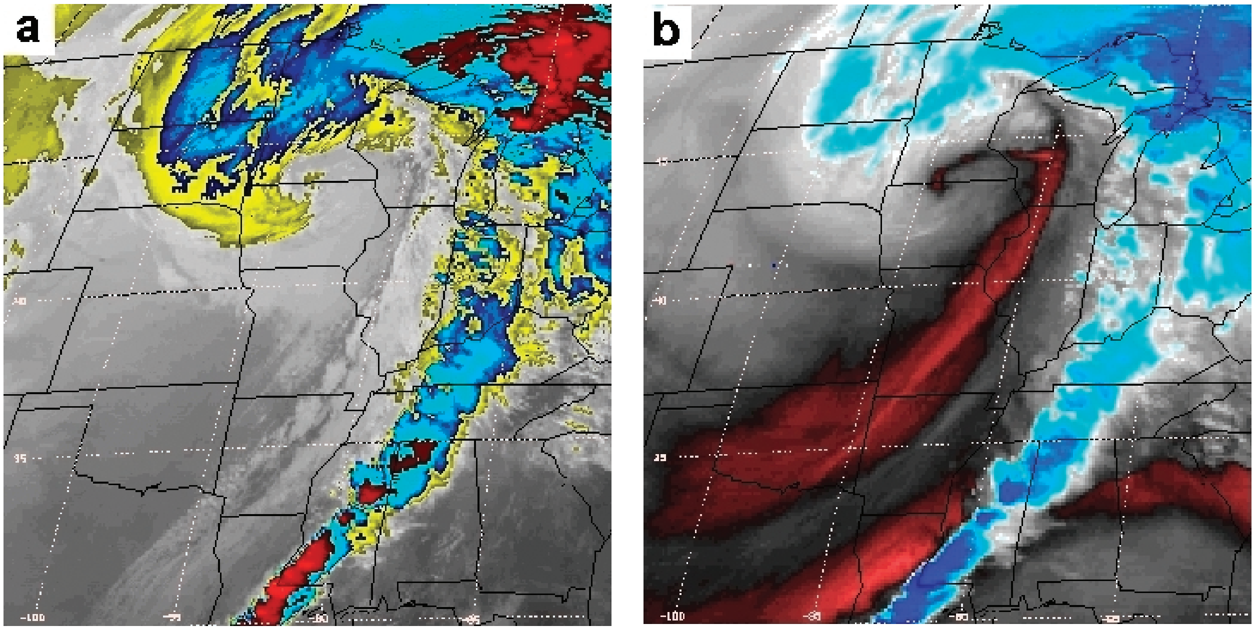

Fig. 4. *GOES-8* (a) infrared and (b) water vapor satellite images valid 1515 UTC 10 Nov 1998. In (a) the coldest cloud tops are indicated in red; in (b) the driest air is indicated in red.

In the lower-tropospheric levels, a southerly low-level flow was transporting warm moist air to the north-northwest of the occluded system. With cold air in place to the north, this warm air advection enhanced the thermal gradient north of the ETC. A plan view of frontogenesis, computed over the 800–600-hPa layer at 0600 UTC (Fig. 5a), reveals two regions where the horizontal thermal gradient was strengthening. The southernmost axis of frontogenesis, located over Oklahoma and west Texas, was associated with the second westernmost cold front. The second region of frontogenesis, associated with the warm air transport to the northwest of the low, was centered over north-central Nebraska. By 1500 UTC (Fig. 5b), the frontogenesis zone associated with the second cold front had translated eastward, while the northern frontogenesis region had weakened slightly and elongated into an axis extending from north-central Minnesota to southeastern South Dakota, northwest of the cyclonic circulation. The presence of a persistent area of frontogenesis, as noted above, is associated with a direct thermal circulation (DTC). The heavy snowfall observed to the northwest of this ETC was consistent with the enhanced, mesoscale-sloped ascent associated with the DTC from the warm to cold side of the frontogenetical zone.

The *Geostationary Operational Environmental Satellite (GOES-8)* IR satellite image at 1515 UTC (Fig. 4a) reveals a classic comma-shaped pattern in the clouds. The narrow band of clouds from Kentucky through Mississippi and Louisiana was associated with strong convective activity along the cold front. Warm, moist air streamed north and west of the low, turning cyclonically as it ascended into the Minnesota–South Dakota region. The *GOES-8* water vapor image (Fig. 4b) highlights the streak of dry air (indicated by the red band) wrapping into the system from southwest of the occlusion. The dry airstream moved northeastward from Oklahoma into eastern Iowa and then split, with one branch found across Wisconsin and the other spiraling just south of the cyclone center, along the Iowa–Minnesota border. These two satellite imagery perspectives illustrate the juxtaposition of two critical airstreams that contributed to the heavy snowfall bands in South Dakota. The warm, moist airstream, known as the warm conveyor belt (WCB; Carlson 1980), rises as it moves cyclonically to the northwest, forming a trough of warm air aloft (trowal; Martin 1998). For this event, evidence of the trowal is seen as an axis of high equivalent potential temperature (θ_e) wrapping into western Minnesota at 650 hPa at 1500 UTC (Fig. 6a). The second midtropospheric airstream, known as the dry conveyor belt (DCB), is best depicted in Fig. 4b as the dry slot on the water vapor imagery. This DCB consists of cold, dry air that has a recent history of descent as it subsides from the upper levels of the troposphere. The region where these two conveyor belts

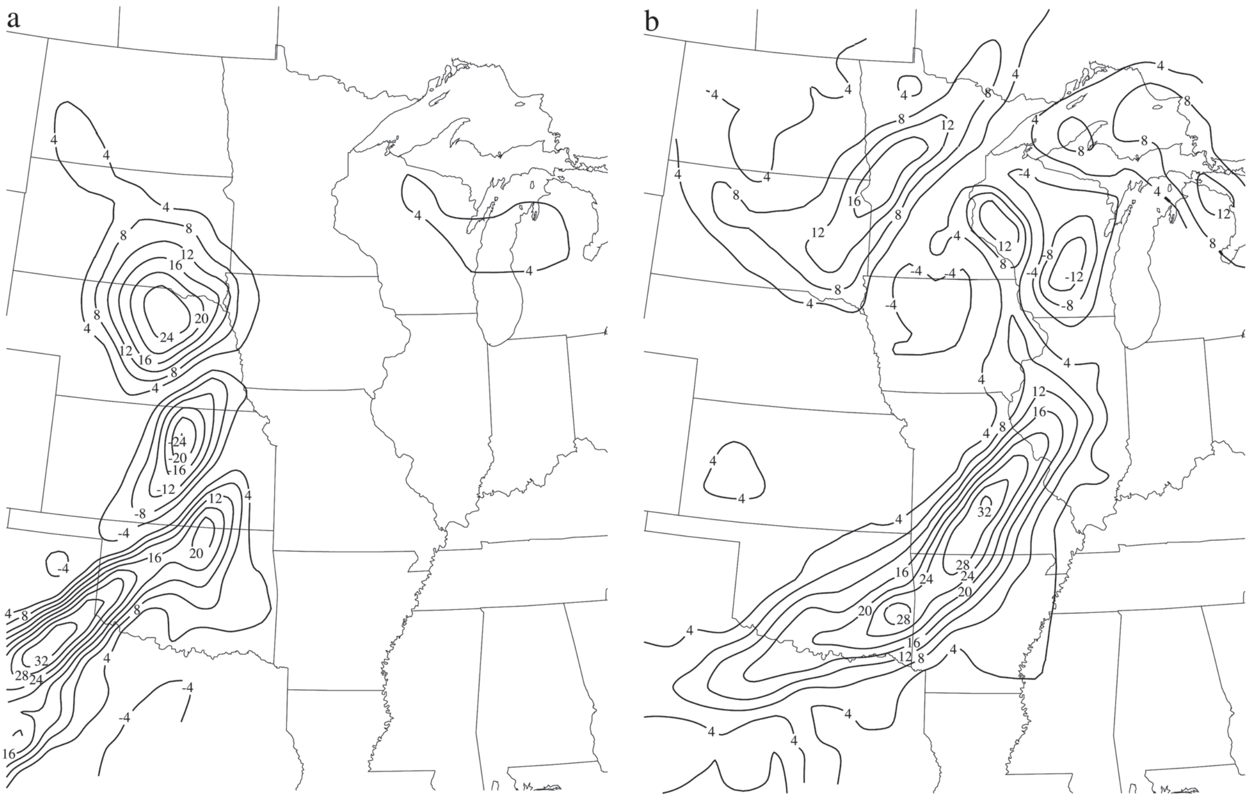

Fig. 5. Frontogenesis for the 800–600-hPa layer in K (100 km 3 h)$^{-1}$ computed from RUC-II initialized data at (a) 0600 and (b) 1500 UTC 10 Nov 1998.

overlapped was over south-central Minnesota; cold dry air aloft overlays warm, moist air below. This thermodynamic configuration, in the presence of strong vertical wind shear, reduces atmospheric stability, often resulting in a region of slantwise or even upright potential instability. These regions can be diagnosed using a parameter called equivalent potential vorticity (EPV; Schultz and Schumacher 1999). Essentially, saturated air parcels undergoing pseudoadiabatic ascent in a region of negative EPV will experience a slantwise (or upright) acceleration, from the warm to cold air. Regions of negative EPV tend to form where the atmosphere is destabilizing due to differential temperature and moisture advection (Nicosia and Grumm 1999). A large area of negative EPV formed along the westernmost cold front at 1500 UTC (Fig. 6b) and was associated with a significant region of upright convection. However, the region of negative EPV associated with the heavy snow formed to the north of the ETC, from southwest Wisconsin into most of Minnesota, in the region where the DCB overlaid the WCB.

It was the interaction of these critical processes: tightening of the midtropospheric thermal gradient (i.e., frontogenesis) and the associated DTC; destabilization resulting from the overlaying of two contrasting airstreams (or conveyor belts); and the synoptic-scale ascent of warm, moist air within the cyclonically turning trowal, that synergistically enhanced the production of snow. Moreover, other researchers (e.g., Emanuel 1985) have shown that frontogenesis in the presence of weakly stable to unstable air (i.e., near zero to negative EPV) results in an enhanced slantwise lift on the warm side of the DTC, producing heavier snowfall rates within the larger shield of snowfall.

Observational and theoretical studies continue to examine the spatial and temporal evolution of these processes and their role in generating banded, heavy snowfall. Incorporating this knowledge into mesoscale numerical models will lead to more accurate snowfall prediction. Then, in the near future, although residents of Sioux Falls may not enjoy digging out from under a foot of snow, at least they'll know when it's coming!

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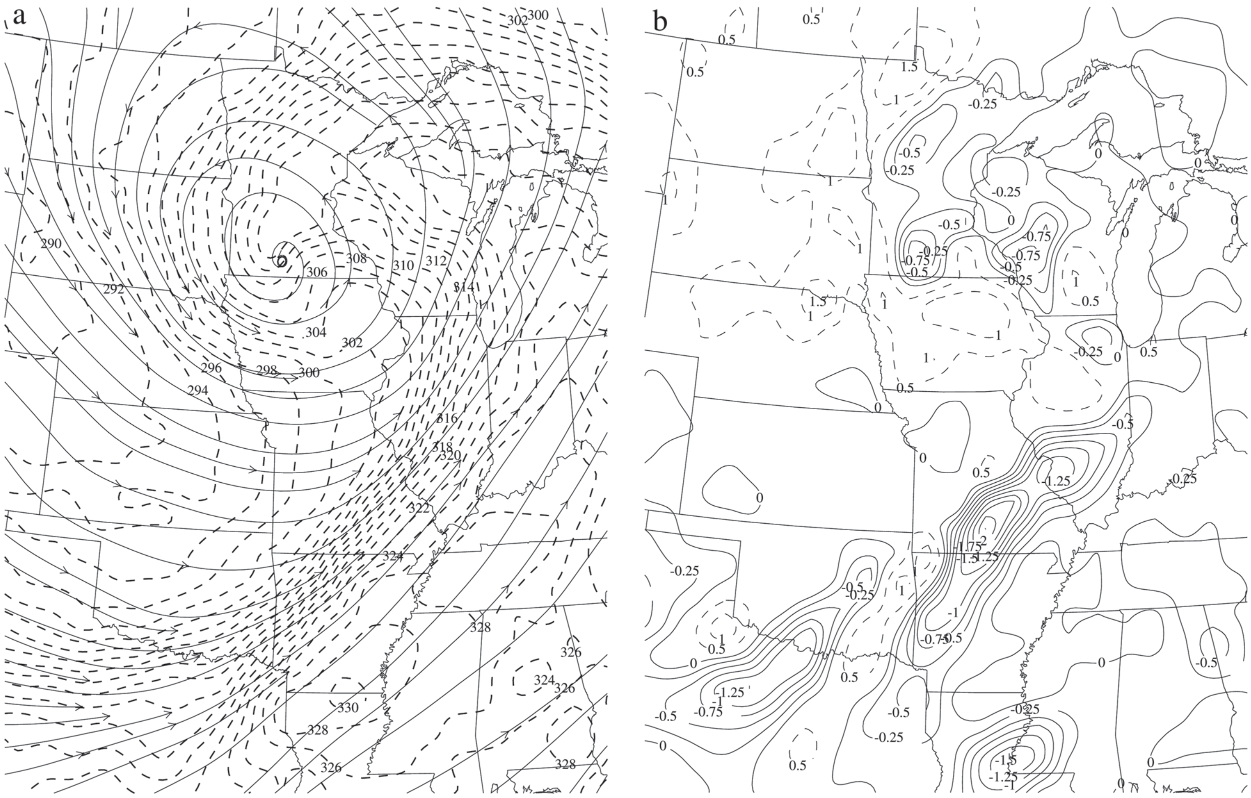

Fig. 6. (a) Streamlines and equivalent potential temperature (θ_e; dashed lines) at 650 hPa, and (b) EPV (10^{-6} m^2 K s^{-1} kg^{-1}) at 600 hPa at 1500 UTC 10 Nov 1998, computed from RUC-II initialized data. Solid lines depict negative EPV values, while dashed lines depict positive values of EPV.

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FOR FURTHER READING

Carlson, T. N., 1980: Airflow through midlatitude cyclones and the comma cloud pattern. *Mon. Wea. Rev.*, **108,** 1498–1509.

Emanuel, K., 1985: Frontal circulations in the presence of small moist symmetric stability. *J. Atmos. Sci.,* **42,** 1062–1071.

Martin, J. E., 1998: The structure and evolution of a continental winter cyclone. Part I: Frontal structure and the occlusion process. *Mon. Wea. Rev.,* **126,** 303–328.

NCDC, 1998: *Storm Data.* Vol. 40, No. 11, 139 pp.

Nicosia, D., and R. Grumm, 1999: Mesoscale band formation in three major northeastern United States snowstorms. *Wea. Forecasting,* **14,** 346–368.

Schultz, D. M., and P. N. Schumacher, 1999: The use and misuse of conditional symmetric instability. *Mon. Wea. Rev.,* **127,** 2709–2732.