TWO CASE STUDIES OF QUASI-STATIONARY CONVECTION DURING THE 1993 GREAT MIDWEST FLOOD

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Abstract

Two examples of quasi-stationary convective systems responsible for extreme rainfall events were examined to determine the atmospheric processes favorable to their formation and to test an experimental method of predicting their subsequent movement. The study was performed using gridded analyses from the NWS National Centers for Environmental Prediction Regional Data Assimilation System (RDAS) (DiMego et al. 1992), Rapid Update Cycle Surface (RUCS) analyses and gridded ETA model forecasts (Black 1994). One of the quasi-stationary convective systems investigated led to heavy rains across the Raccoon and Des Moines rivers that left much of the Des Moines, Iowa area without potable water, the other produced serious flooding just south of Kansas City, Missouri. During each case, the strongest potential buoyant energy (instability) and low-level moisture convergence were located on the western side of the initial convection that eventually developed into the mesoscale convective system (MCS). The strongest low-level winds and moisture transport were also located on the western side of the convective systems. As a result, the formation of new cells on the western flank of the storm apparently offset the movement of the individual cells within the MCS, leading to a period of quasi-stationary convection. During the Des Moines event, rapid changes in the mass and wind fields led to a dramatic increase in the low-level moisture convergence over western Iowa and eastern Nebraska, leading to the generation of new convective cells on the back edge of the MCS resulting in the period of quasi-stationary convection. A method for predicting the motion of mesoscale convective complexes (MCCs), based on concepts documented in Corfidi et al. (1996), was adapted and tested for use with gridded model output data. The results suggest that the technique can be used effectively in an operational setting and might help forecasters anticipate times when quasi-stationary convection is likely.

1. Introduction

Mesoscale convective systems (MCSs) produce a large portion of warm season rainfall over the Great Plains (Fritsch et al. 1986). When these MCSs are slow moving or quasi-stationary, they often produce heavy rains and flash flooding (Chappell 1986). Unfortunately, the movement of MCSs remains difficult to forecast since it is dependent on the characteristics of the larger scale environment, the synoptic scale forcing and on the rates and locations that cells form and dissipate within the developing system (Chappell 1986). This paper investigates the meteorological conditions that were associated with periods of quasi-stationary convection on 9 and 10 July 1993 using gridded RDAS and RUCS analyses, ETA model forecasts and the PC-GRIDDS diagnostic package (Petersen 1992). The study was

conducted to: 1) see how well each of the cases met the conditions that Chappell (1986) suggested would be favorable to produce quasi-stationary convection, 2) see if high temporal resolution surface data and related diagnostic fields could be used to help identify when a period of "backbuilding" or quasi-stationary convection might be anticipated, and 3) test a new method of predicting periods of quasi-stationary convection (Corfidi et al. 1996).

2. Quasi-Stationary Convective Events and Estimates of MCS Motion

A number of researchers have noted that it is convenient to think of the motion of a convective system as the sum of the mean velocity of the cells making up the system and the propagation velocity due to the formation of new cells along the periphery of the storm (Newton and Katz 1958; Newton and Newton 1959; and Chappell 1986). MCS propagation may slow or accelerate depending on which flank of the system is undergoing new cell growth. Convective systems may become stationary when new cells form on a system's flank and oppose the mean cell motion. "Backbuilding" occurs when new cells form on the upwind side of the system faster than the mean wind can move the individual cells from their initial location. Quasi-stationary systems often occur when a storm moves east of the area of highest instability and to the east of the axis of the low-level jet. This positions the strongest low-level moisture convergence and potential buoyant energy on the western side of the MCS so rapid cell generation can occur on the rear flank of the system to oppose the mean cell motion (Chappell 1986). Along the leading edge of the system, where in many cases the environment is more stable and less favorable for convection, rapid cell dissipation occurs (Maddox 1983; and Chappell 1986).

Corfidi et al. (1996) have used these ideas to develop a vector method that can help predict the future movement of the most convectively active areas within mesoscale convective systems. These regions, called meso-beta elements (MBEs) correspond to the area within a complex with radar intensities of level 3 or greater on the manually digitized radar (MDR) composite radar chart and are generally associated with the coldest cloud tops in the enhanced infrared imagery and also with the heaviest rainfall (McAnelly and Cotton 1986). In Corfidi et al. (1996), MBE movement was determined by plotting the centroid of their hourly positions from the MDR composite charts during the life cycle of the system. The speed and direction of the MBE movement were then calculated by subjectively drawing a line of best fit from the beginning to the end of each event (Corfidi et al. 1996).

The approach used by Corfidi and his colleagues is based on several assumptions. First, it assumes that the vector describing the mean wind between 850 and 300 mb is a good approximation of the mean velocity of the cells making up the system. This assumption is supported by studies of radar echoes (Brooks 1946; and Byers and Braham 1949) that indicated that individual convective cells move approximately with the mean wind. More recently, Merritt and Fritsch (1984) found that the 850-300 mb mean wind vector approximated the mean cell movement within 10 degrees during MCC genesis. They defined the "cloud layer" mean wind using the formula introduced by Fankhauser (1964):

$$V_{CL} = \frac{V_{850mb} + V_{700mb} + V_{500mb} + V_{300mb}}{4} \qquad (1)$$

Corfidi et al. (1996) used Merritt and Fritsch's data set to assess the correlation between the 850-300 mb "cloud layer" mean wind and cell motion. They found high correlations between the movement of the cells as noted by radar operators on the MDR composite radar charts and the 850-300 mean wind (equation 1) during the period of MCS generation (correlation coefficients of .71 for speed and .76 for direction).

Another Merritt (1985) finding is the basis for the second assumption used in the technique. Merritt noted that a vector opposite to the low-level jet is a good approximation to the propagation component of MBE movement. For the 103 events used in Merritt's study, Corfidi et al. (1996) established that there was a strong correlation (.84 if two outliers were ignored) between the vector directed opposite the low-level jet and the propagation direction of the MBE.

Finally, Corfidi et al. (1996) assumed that the magnitude of the propagation vector was approximately given by the strength of the low-level jet. They argue that the faster the low-level jet, the stronger the low-level convergence should be and that this should promote faster growth of new cells leading to more rapid upstream propagation of the MBE. Therefore, the magnitude of storm propagation should be strongly modulated by the low-level jet.

Based on these three assumptions, Corfidi et al. (1996) developed a conceptual model of MBE movement as the sum of the mean flow of the cloud layer (V_{CL}) and the propagation component (V_{PROP}) with the magnitude and direction of V_{PROP} assumed to be equal and opposite to those of the low-level jet (V_{LLJ}) (Fig. 1). If the conceptual model is valid, the difference between V_{LLJ} and V_{CL} should provide a skillful forecast of MBE movement (V_{MBE}),

$$\dot{V}_{MBE} = V_{CL} - V_{LLJ} \qquad (2)$$

We will refer to such estimates of V_{MBE} as Corfidi, Merritt and Fritsch (CMF) vectors.

Applying this simple relationship to observed data, Corfidi et al. found a correlation coefficient of .80 between the predicted MBE speed and the observed MBE speed. They noted that the scheme tended to underpredict the speed by about 1 kt or 0.5 m s^{-1}. A similar but slightly lower correlation was found for the direction of the MBE movement.

The CMF vector approach is well suited for the operational environment because of its simplicity and ease of calculation. The technique can easily be adapted for use by forecasters in a PC or workstation environment using the PC-GRIDDS (Petersen 1992) or GEMPAK (des Jardins et al. 1991) diagnostic packages to calculate and display CMF movement vectors. A routine to determine the exact level and intensity of the low-level jet (LLJ) was not available so the 850-mb wind was
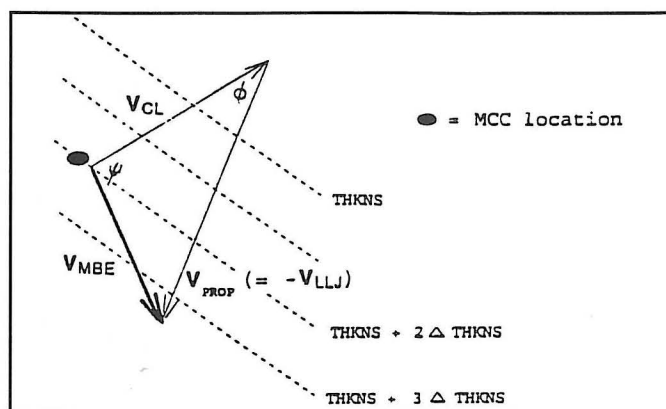

Fig. 1. Conceptual model of MBE movement (V_{MBE}) as the vector sum of the mean flow in the cloud layer (V_{CL}) and the propagation component (V_{PROP}). The magnitude and direction of V_{PROP} are assumed to be equal and opposite to those of the low-level jet (V_{LLJ}). The angles phi and psi are used to calculate the magnitude and direction of V_{MBE} given observed values of V_{CL} and V_{LLJ}. Dashed lines (labeled THKNS) indicate a typical relationship of the 850-300 mb thickness pattern to the environmental flow and MBE movement during MCC events (from Corfidi et al. 1996).

substituted for it. However, the LLJ can sometimes differ significantly from the 850-mb winds (Weber 1976) suggesting that the use of 850-mb winds to approximate the LLJ in the CMF vector method may introduce significant errors.

Therefore, the Corfidi et al. (1996) data set was used to investigate how the correlation coefficients would be changed if 850-mb wind vectors were substituted for the vectors representing the low-level jet. The authors first tried to replicate the work of the original investigators and found slightly lower, but still relatively high correlation coefficients for the speed (.78) and direction (.74) of the MBE. The authors then substituted the 850-mb winds for the low-level jet (V_{LLJ}) to calculate a new set of correlation coefficients for the speed and direction. The correlation coefficient was slightly higher for direction (.75), but was lower for speed (.52) suggesting that using the 850-mb winds as a substitute for the low-level jet would provide a rough estimate of the MBE movement (especially for direction). It also suggested to the authors that the method would work best if various levels between the boundary layer and 700 mb were checked for the strongest winds before assigning a vector to the low-level jet.

The CMF method for estimating MBE motion was applied to the two cases using F00 gridded RAFS analyses and ETA model forecasts valid at 0000 UTC and 1200 UTC to determine if the method could correctly forecast a period of quasi-stationary convection. During both cases, the 850-mb winds closely approximated the direction and magnitude of the LLJ suggesting each case would provide a fair test of the method.

3. The Des Moines Flash Flood Event, 9 July 1993

a. Overview

The stage was set for a frontal or meso-high type, heavy rainfall event (Maddox et al. 1979) early on 8 July 1993 when a convective system that tracked across Iowa and produced up to 1.5 inches of rain enhanced the thermal gradient across the state. This boundary was evident as an arc-shaped convective band on the composite radar chart at 1800 UTC (not shown)

and surface temperature field (not shown). The first cells that were associated with the next convective system formed over western Iowa and appeared as a small low-top convective cell on the 2131 UTC 8 July 1993 enhanced infrared image (Fig. 2a). Convection continued to grow over Iowa during the next couple of hours consolidating into a MBE (Fig. 2b). By 0201 UTC new convection developed to the west of the initial Iowa MBE (Fig. 2c) resulting in a nearly stationary MBE from 0001 UTC (Figs. 2b, 3a) through 0501 UTC (Figs. 2d, 3b) over western and central Iowa where more than 7 inches of rain fell over portions of the Raccoon and Des Moines River Basins.

The Des Moines heavy rainfall event shared many of the characteristics found for heavy rainfall-producing MCCs by Maddox et al. (1979) and Merritt and Fritsch (1984). An east-west oriented front was aligned across Iowa (Fig. 4). Precipitable water values at 0000 UTC 9 June across Nebraska and western Iowa were higher than the average value (around 1.62 in.) found by Maddox et al. (1979) for frontal or meso-high type events (Fig. 4). K indices, in the upper 30s to low 40s

(not shown) and lifted indices, in the −4 to −6 range (Fig. 5), were also similar to those found by the earlier studies. Throughout the day, 850-mb winds of 30 to 40 kt (Fig. 5) were associated with a broad area of warm advection, and moisture transport across Kansas, eastern Nebraska and southwestern Iowa resulting in an area of moisture convergence over eastern Nebraska at 0000 UTC 9 June (Fig. 6). Veering of the winds with height was found in the lowest 700 mb, while the vertical speed shear was rather weak (not shown). All the above factors suggested that MCC development was likely.

The environmental conditions were also consistent with those isolated by Chappell (1986), who noted that development of quasi-stationary MCSs often occurs as convective systems move to the east of the axis of greatest convective instability, the axis of the low-level jet and the strongest mass and moisture convergence. In these situations, the rear flank of the MCS is the favored location for new cell formation, particularly in flow characterized by veering winds with height and low-level warm advection. For the Des Moines MCS, the axis of highest equiva-
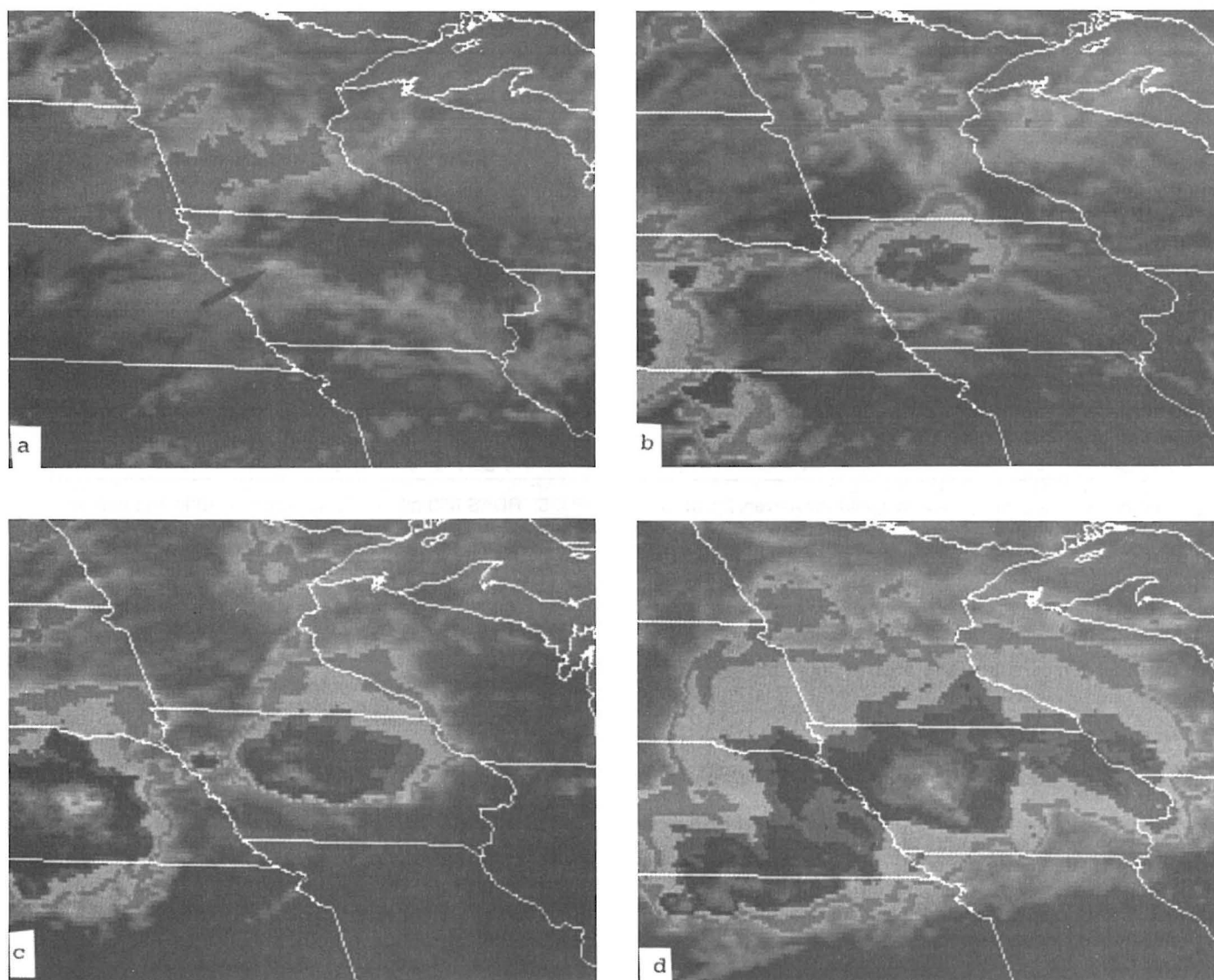

Fig. 2. Enhanced infrared imagery, a) valid 2131 UTC 8 July 1993 with arrow denoting location of initial convection, b) valid 0001 UTC 9 July 1993, c) valid 0201 UTC 9 July 1993 and d) valid 0501 UTC 9 July 1993.
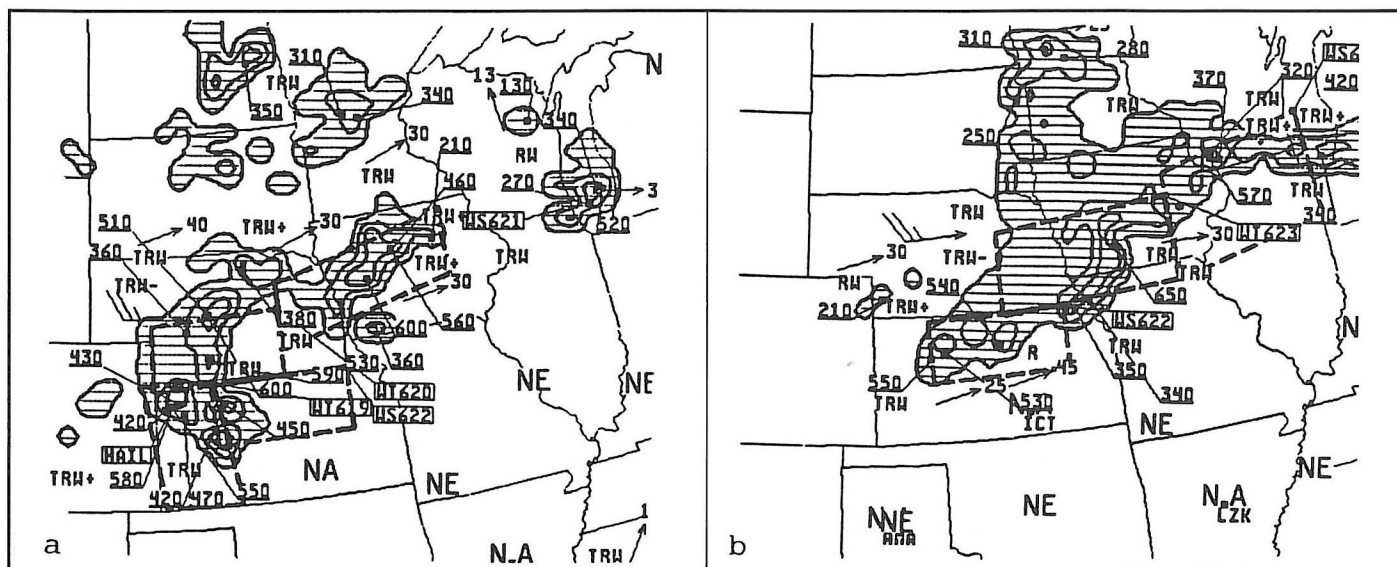
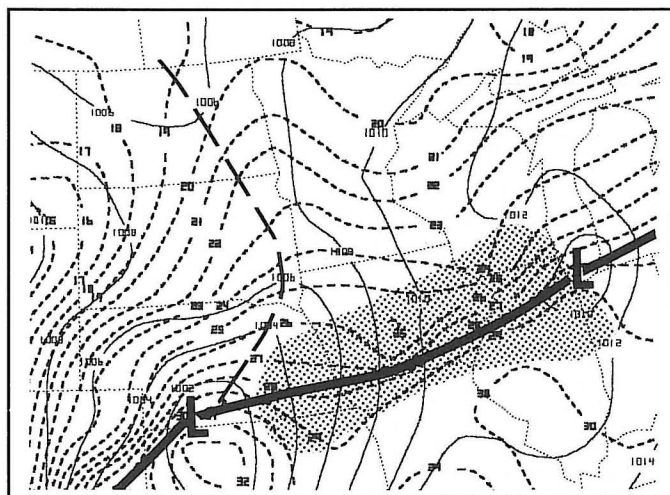Fig. 3. Composite radar imagery for 9 July 1993, a) 0035 UTC and b) 0535 UTC.

Fig. 4. RDAS mean sea-level pressure (solid lines, every 2 mb), 982 sigma level temperatures (dashed, every 1°C), precipitable water (values equal or greater than 1.80 in. shaded), front (thick line) and trough (dashed line) valid at 0000 UTC 9 July 1993.
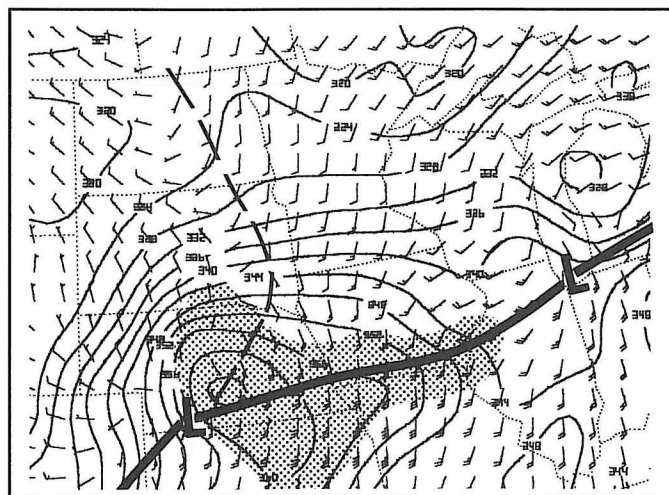

Fig. 5. RDAS 850-mb winds (full barb = 10 kt and half barb = 5 kt), equivalent potential temperature (solid, every 4° K), lifted index (values less than −8 shaded), front (thick line) and surface trough (dashed) valid at 0000 UTC 9 July 1993.

lent potential temperatures and area of most unstable lifted indices (Fig. 5) were located to the west of the initial convection and the axis of strongest 850-mb winds at 0000 UTC 9 July (Fig. 5) was positioned to maintain strong moisture convergence (Fig. 6) along the rear flank of the initial convective system (Fig. 2a).

Another factor that favored heavy rainfall was the orientation of mean winds (V_{CL}) which were directed somewhat toward the colder, more stable air to the north (Fig. 7). The resulting cell motion directed toward colder air during the early stages of convective development would leave a quasi-stationary boundary undisturbed by the translation of existing convection across the boundary (Chappell 1986). Such movement, instead of disrupting the boundary and forcing it southward, would allow the downdraft and resulting outflow from the convection to reinforce the thermal gradient along the front (Chappell 1986).

b. The "backbuilding" stage

Westward propagation of the Des Moines MCS occurred during a period of rapid changes in the surface moisture convergence field that coincided with rapid changes of the mass and wind fields. Initial development of a surface wave along the quasi-stationary boundary between 2100 UTC and 0000 UTC was indicated by both surface pressure falls and increases in surface relative vorticity over eastern Nebraska (Figs. 8a and b). By 0300 UTC the area of pressure falls had shifted into Iowa and an area of pressure rises had developed over Kansas (Fig. 8c) in association with the weak surface wave now over southeastern Nebraska (Figs. 9a through c).

The development and eastward movement of this surface pressure wave were accompanied by important changes in low-level moisture convergence. At 2100 UTC, weak low-level
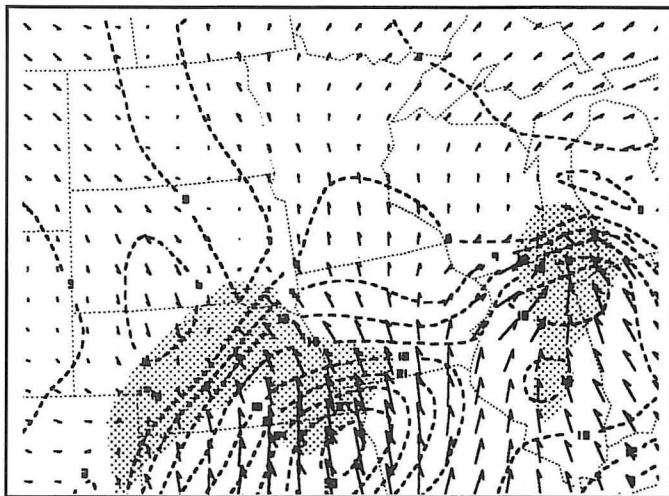
Fig. 6. RDAS 1000-850 mb layer mean moisture transport vectors (arrows), magnitude of moisture transport (dashed, interval 3 × 10^{-2} m s^{-1}) and moisture flux divergence (negative values of −4 × 10^{-7} s^{-1} are shaded) valid 0000 UTC 9 July 1993 where moisture transport is defined as the flux of mixing ratio.
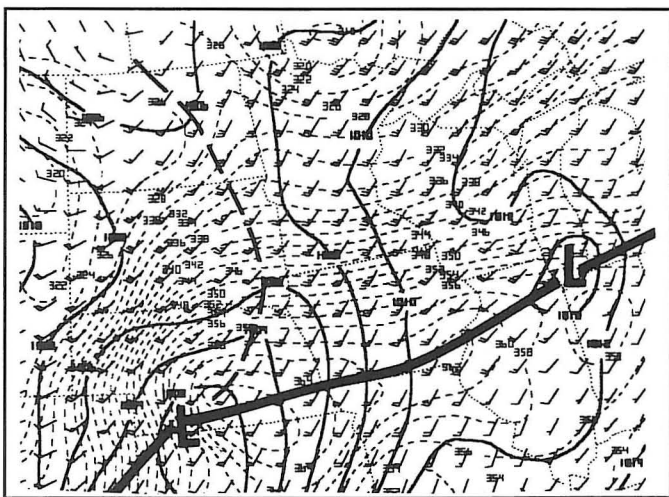

Fig. 7. RDAS 850-300 mb layer mean wind (full barb = 10 kt, half barb = 5 kt), mean sea level pressure analysis (solid, interval = 4 mb), 982 sigma level equivalent potential temperature (dashed every 2°K), front (thick line) and trough (dashed line).

moisture convergence was present over north-central Iowa where a few convective cells started to develop (Fig. 9a). From 2100 to 0300 UTC, the moisture convergence strengthened over western Iowa and eastern Nebraska (Figs. 9b and c) in response to the developing surface wave over Nebraska. Satellite imagery for this period indicates that new cells developed within the area of strong moisture convergence west of the initial cluster of convection (Fig. 2c). Therefore, the MCS and associated MBE held almost stationary from 0001 UTC to 0501 UTC (Figs. 3a and b) as new cell formation to the west offset cell motion. By 0600 UTC, strong pressure rises had shifted into the western half of Iowa (Fig. 8d), signaling a period of rapid eastward movement of the MCS. By this time, the strongest moisture convergence had shifted into southern Iowa

(Fig. 9d). By 0900 UTC (not shown), the remains of the weakening MCS had moved into eastern Iowa ending the heavy rain over Raccoon and Des Moines River Basins.

The period of upstream propagation that led to a period of quasi-stationary convection between 0000 UTC and 0500 UTC 9 July appears to be related to changes that were taking place in pressure, wind and low-level moisture convergence fields. Of more importance to forecasters, the increase in moisture convergence appeared to precede a period when new cell formation led to quasi-stationary convection. Doswell (1982) notes the observation that low-level moisture convergence usually precedes the initiation of convection.

Another area of strong moisture convergence was located over extreme northeast Iowa, southwestern Wisconsin and northern Illinois (Figs. 9a and b). However, no convective system developed within this area. There were several reasons to suspect that no quasi-stationary convective system would develop within this area of moisture convergence. The air mass across the region was much more stable than over eastern Nebraska (Fig. 5). Secondly, the surface pressure wave was moving east of the region suggesting that the strongest moisture transport and moisture convergence would also be shifting to the east. Finally, the moisture convergence (especially its areal extent) decreased across northern Iowa and southwestern Wisconsin between 2100 and 0000 UTC (Figs. 9a and b) and increased across eastern Illinois supporting the idea that the convergence would continue to shift to the east.

The thermodynamic environment over eastern Nebraska and western Iowa was clearly more favorable to the development of convection than over eastern Iowa and Illinois where the air mass was more stable (Fig. 5). The convection inhibition (CIN) on the Omaha (OVN) sounding (Fig. 10) indicated there was a cap or lid present at 1200 UTC 8 July (Colby 1983; Bluestein and Jain 1985). The CIN at Dodge City, Kansas (not shown) was considerably higher than at Omaha so the CIN increased as you moved westward across Kansas and Nebraska. Bluestein and Jain (1985) have suggested that backbuilding of convection may result from a variation in strength of the low-level inversion that caps the moisture. They reason if the inversion and cap are stronger upstream along a boundary than downstream, then the convective temperature will be reached later in the day. The cap may have helped to concentrate the potential buoyant energy by preventing multiple updrafts and convection earlier in the day resulting in greater potential buoyant energy being available later in the day when the cap was finally overcome by diurnal heating, differential temperature advection and the upward motion (Carlson et al. 1983; Doswell 1985). By 0000 UTC 9 July (Fig. 10), the CAPE upstream at OVN (Omaha, Nebraska) had risen to 3630 J kg^{-1} indicating that intense updrafts were likely in the area of strengthening moisture convergence across eastern Nebraska and western Iowa.

Current high temporal resolution data sets such as the RUC surface and upper air analyses combined with the ability to display derived fields such as moisture flux convergence provide forecasters with a valuable tool for short range forecasting of quasi-stationary rainfall events. Forecasters should anticipate the possibility of backbuilding or quasi-stationary convection when surface data indicates moisture convergence is developing or strengthening upstream in a region where there is also strong potential buoyant energy.

c. Estimates of MCS MBE movement

The CMF method for estimating MBE motion described in Section 2 was applied to archived gridded RDAS analysis valid 0000 UTC 9 July 1993 (Fig. 11a) to determine if it would signal
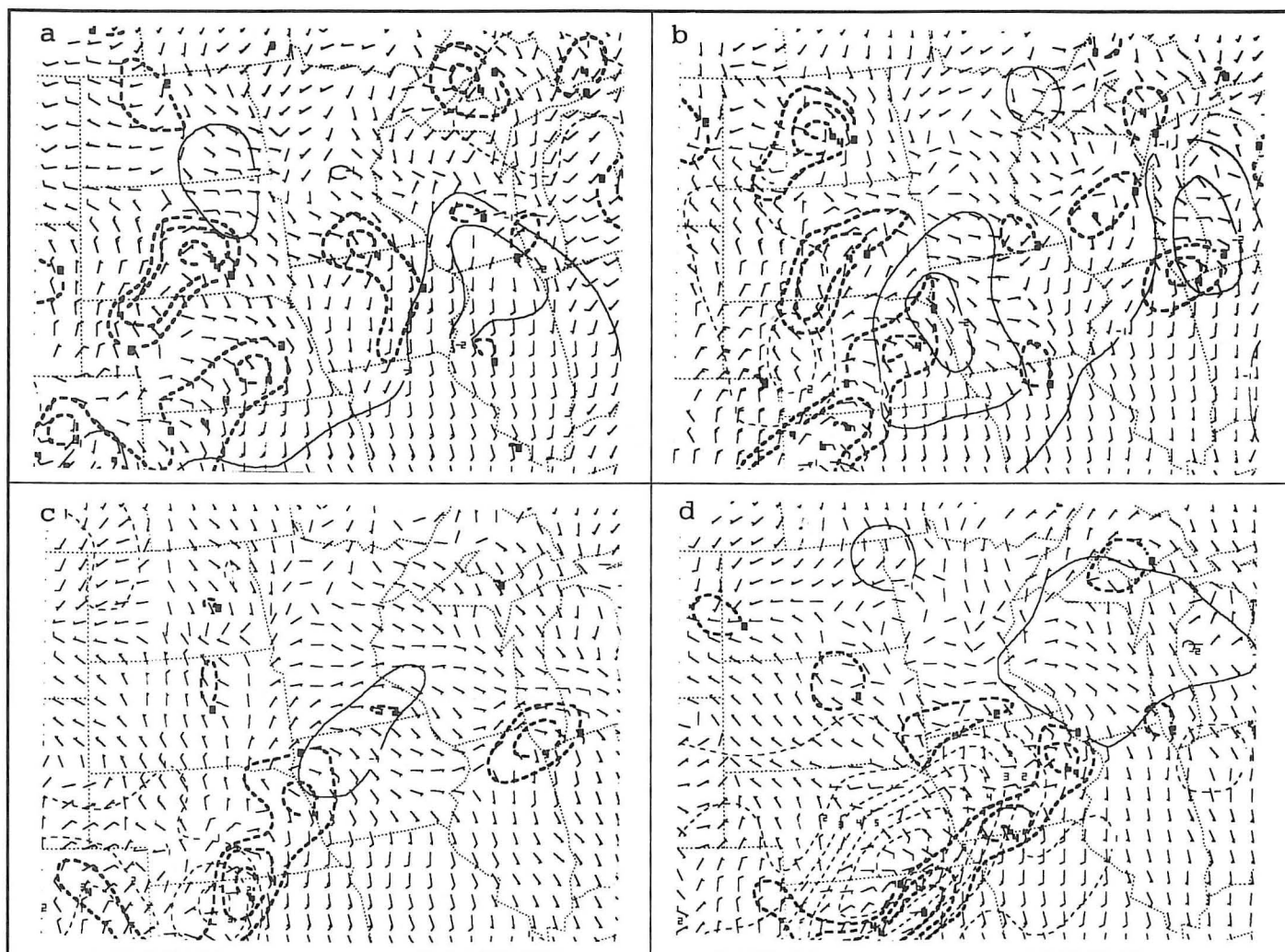
Fig. 8. RUCS surface winds, relative vorticity (dashed, only positive values are depicted, interval = 2 × 10⁻⁵s⁻¹) and pressure rises (solid) and falls (thin dashed) with contour interval of 2 mb, valid at a) 2100 UTC 8 July 1993, b) 0000 UTC 9 July 1993, c) 0300 UTC 9 July 1993, and d) 0600 UTC 9 July 1993.

the period of quasi-stationary convection that occurred between 0000 and 0600 UTC (Figs. 2b and d). The method suggested that any convective system that developed in western Iowa or eastern Nebraska would move slightly north of east at 15 to 20 kt during the 12-hour period ending at 1200 UTC 9 July (Fig. 11a) The 12-hour movement of the MCS was difficult to determine from the satellite and radar imagery. By 1200 UTC there were two apparent MCSs, one that weakened and tracked into eastern Iowa and another that had propagated southward and southwestward into Kansas (not shown). The CMF method using only the 0000 UTC RAFS analysis never anticipated such complex movement and gave no indication that the MCS would hold stationary between 0000 UTC and 0500 UTC.

Corfidi (personal communication) acknowledges there are several factors that can lead to errors when applying the technique. 1) The role the thermodynamic environment plays in modulating the propagation was not factored into the technique. This can sometimes be a significant shortcoming. 2) The correlations developed by Corfidi were established using 12-hour movement of the MBEs. The technique, therefore, may not signal a period of westward propagation that offsets the movement of the individual cells that lasts considerably less than 12

hours (i.e., 6 hours or less). 3) The technique fails to account for rapid non-diurnal changes of the wind field. Rapid changes in either the upper- or lower-level wind field could significantly change the movement vectors in a short period of time.

At least two of these factors may have been present during the Des Moines case. As noted in Section 3b, rapid changes where occurring in the pressure and wind fields. In addition, the period of quasi-stationary convection lasted only 6 hours.

To determine if increased temporal resolution might compensate for the limitation imposed by using only the 12-hourly analyses, ETA model forecasts were investigated. The CMF method was applied to forecasts from the 1200 UTC 8 July 1993 ETA model run to see if the model's ability to forecast changes in the wind field would improve the CMF estimates of MBE movement. The vector wind field using the 18-h ETA forecast valid 0600 UTC 9 July 1993 illustrates this point (Fig. 11b). The magnitudes of the vectors over most of Iowa were generally 5 kt or less suggesting that the MCS would be slow moving as it crossed Iowa. The direction of the vectors varied across Iowa and suggested that any convection over central Iowa would move slowly to the north or east. The CMF technique appeared to provide useful information that might
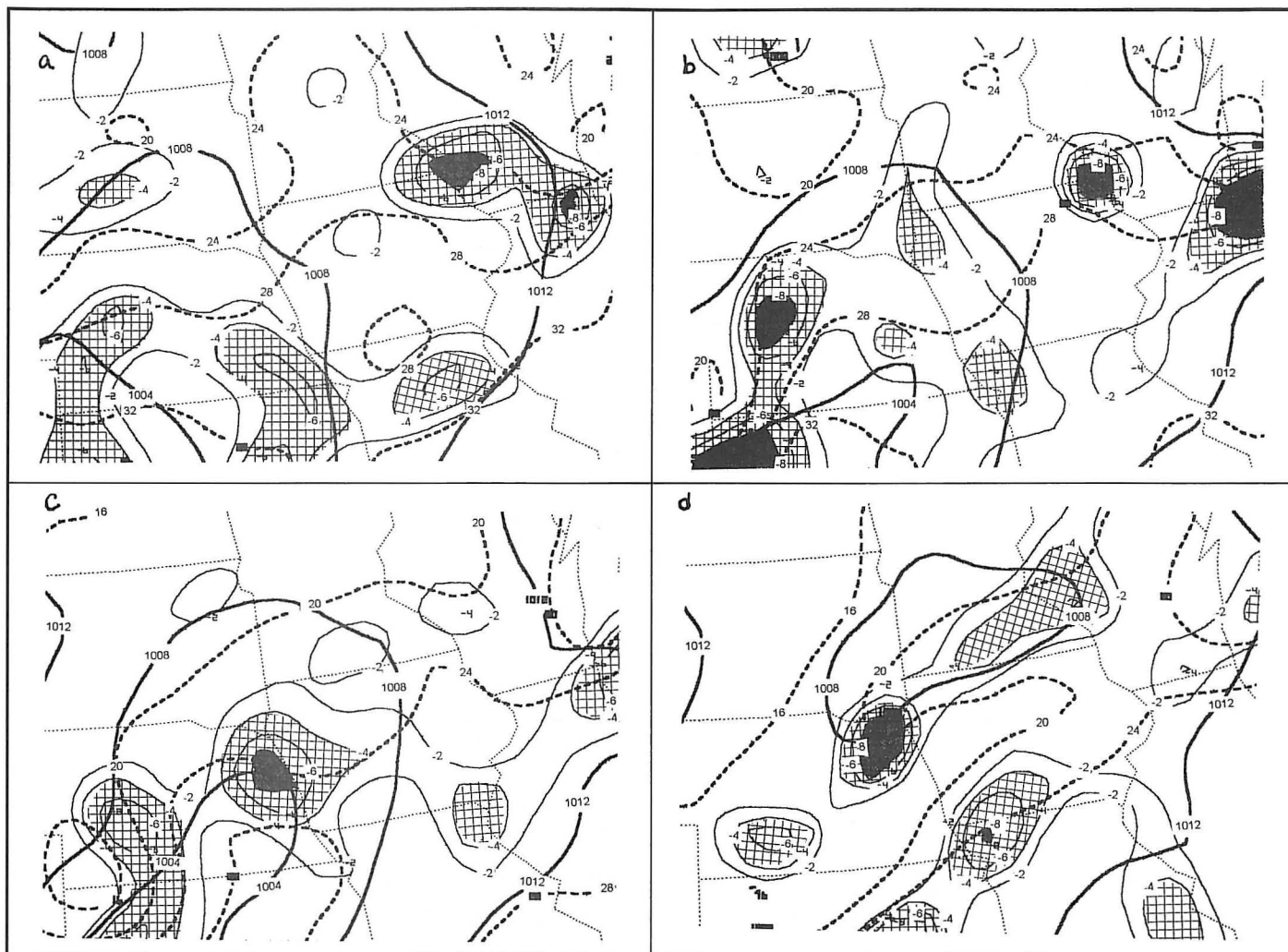
Fig. 9. RUCS mean sea level pressure (thick solid, interval = 4 mb) and surface moisture flux divergence (convergence) (thin lines, only negative values of −2 or less are depicted with interval = −2 × 10^{-7}s^{-1}, values less than −4 × 10^{-7}s^{-1} are hatched while values less than −8 × 10^{-7}s^{-1} have dark shading, valid at a) 2100 UTC 8 July 1993, b) 0000 UTC 9 July 1993, c) 0300 UTC 9 July 1993 and d) 0600 UTC 9 July 1993.

have allowed a forecaster to anticipate that the MCS over Iowa would be slow moving, and that one MCS would eventually track into eastern Iowa while another redeveloped or propagated southward and westward into Missouri and Kansas. The method, however, indicated the period of slow movement would continue after 0600 UTC, a period when the MCS accelerated to the east. In summary, the CMF method appeared to provide useful information that might have allowed a forecaster to anticipate that the MCS over Iowa would be slow moving, and that one MCS would eventually track into eastern Iowa while another redeveloped or propagated southward and westward into Missouri and Kansas.

4. The Quasi-Stationary Convection Near Kansas City, Missouri, 10 July 1993

a. Overview

The front that had helped contribute to the flooding rains over Iowa stalled across Missouri and Kansas setting the stage for the development of the next quasi-stationary MCS. Compos-

ite radar charts (Figs. 12a-d) and satellite imagery (Figs. 13a-d) indicated that cell formation along the western flank of an east-west band of convection led to an extended period of quasi-stationary convection that produced almost 10 inches of rain just south of Kansas City, Missouri. Significant flooding and flash flooding resulted from the heavy rains since the ground was already saturated from heavy rains earlier in the week.

The first cells began to form at around 2235 UTC 9 July 1993 (not shown), but the convection along the western end of the frontal band remained rather scattered through 0231 UTC 10 July 1993 (Fig. 13a) when convection began to organize into an MCS west of Kansas City. The convection continued to move very slowly eastward during the next few hours, but by 0631 UTC (Fig. 13b) the western flank of the convection had become stationary just south of Kansas City as new cells constantly formed on the west side of the system (Fig. 13c). The western end of the convection remained nearly stationary through 1031 UTC (Fig. 13d) before the MCS weakened. For most of the night, new cell formation led to westward propagation that appeared to offset the motion of the individual convective cells.
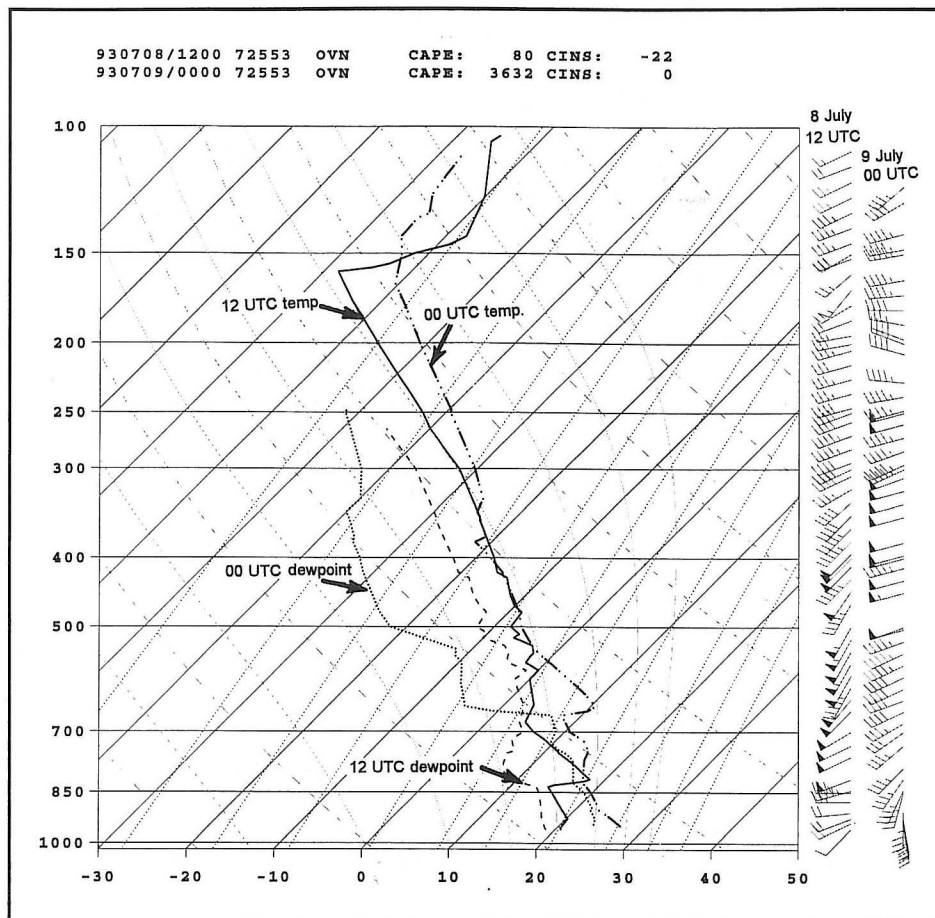
Fig. 10. Skew-T plot for Omaha, Nebraska (OVN) at 1200 UTC 8 July 1993 with temperature as solid line and dew point as dashed one; and 0000 UTC 9 July 1993 plot with temperature profile represented by dash/dotted line and dew point as dotted line. Wind profiles on right side of diagram have 1200 UTC 8 July winds on the left side of the two columns and 0000 UTC 9 July winds on the right.
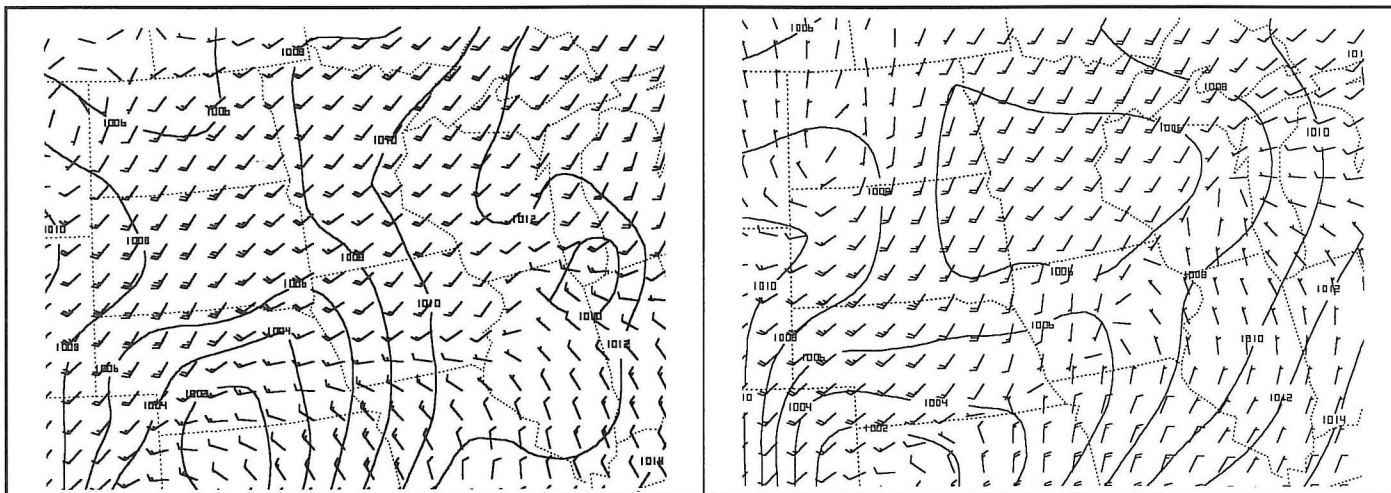

Fig. 11. Mean sea-level pressure (every 2 mb) and MBE movement vectors (full barb = 10 kt and half barb = 5 kt) a) from RDAS analysis valid 0000 UTC 9 July 1993, and b) from 18-h ETA model forecast valid 0600 UTC 9 July 1993.
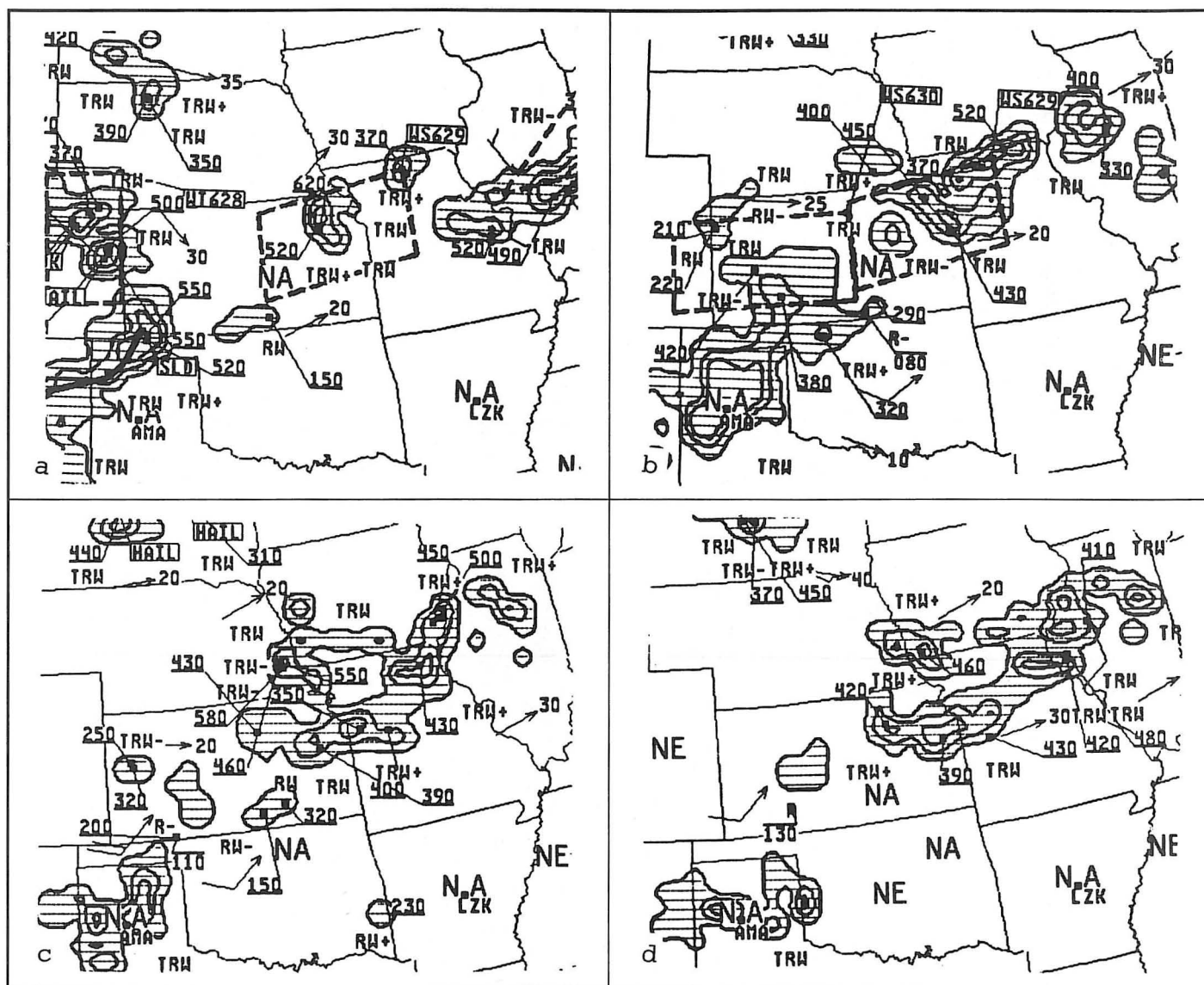
Fig. 12. Composite radar charts for a) 0235 UTC, b) 0635 UTC, c) 0835 UTC and d) 1035 UTC 10 July 1993.

In most respects, the 10 July case also fits the Maddox et al. (1979) composite for a frontal type event. An east-west oriented front was located over Missouri and Kansas with very deep moisture pooling along it. Precipitable water (Fig. 14) along the front was well above the average (1.62 in.) for frontal type, heavy rainfall events (Maddox et al. 1979). Not surprisingly, warm advection was also located across the area (not shown). Winds veered with height across northern Kansas and northwestern Missouri with easterly flow at the surface north of the front giving way to southerly 850-mb winds and westerly 500-mb winds. However, the vertical speed shear was light with winds gradually increasing from 20 to 25 kt at 850 mb (Fig. 15) to 40 to 50 kt at 250 mb (not shown). Maddox et al. (1979) identified a similar vertical wind profile for frontal type heavy rainfall events.

The development of new cells on the western flank of the MCS in the region of the strongest instability and moisture convergence is again consistent with Chappell (1986). The thermodynamic environment across eastern Kansas and western Missouri was again favorable for the formation of convection. The 1200 UTC 9 July sounding (not shown) again exhibited a considerable capping inversion with a fairly steep lapse rate above it. This cap may have prevented convection from developing earlier in the day which might have acted to dissipate the atmosphere's buoyant energy. Again, the cap increased to the west across Kansas. By 0000 UTC the CAPE at TOP was 3804 J kg^{-1} indicating the potential for strong updrafts across eastern Kansas. Analyses of the 850-mb equivalent potential temperature and lifted indices indicated that the most unstable air was found over Kansas and western Missouri (Fig. 15). The strongest instability, moisture transport and moisture convergence (Fig. 16) were located near but slightly to the west of where the MCS became quasi-stationary.

b. Application of the CMF method

The CMF method was first applied to the 0000 and 1200 UTC RDAS data to determine if the technique would correctly signal a period of quasi-stationary convection. At both times
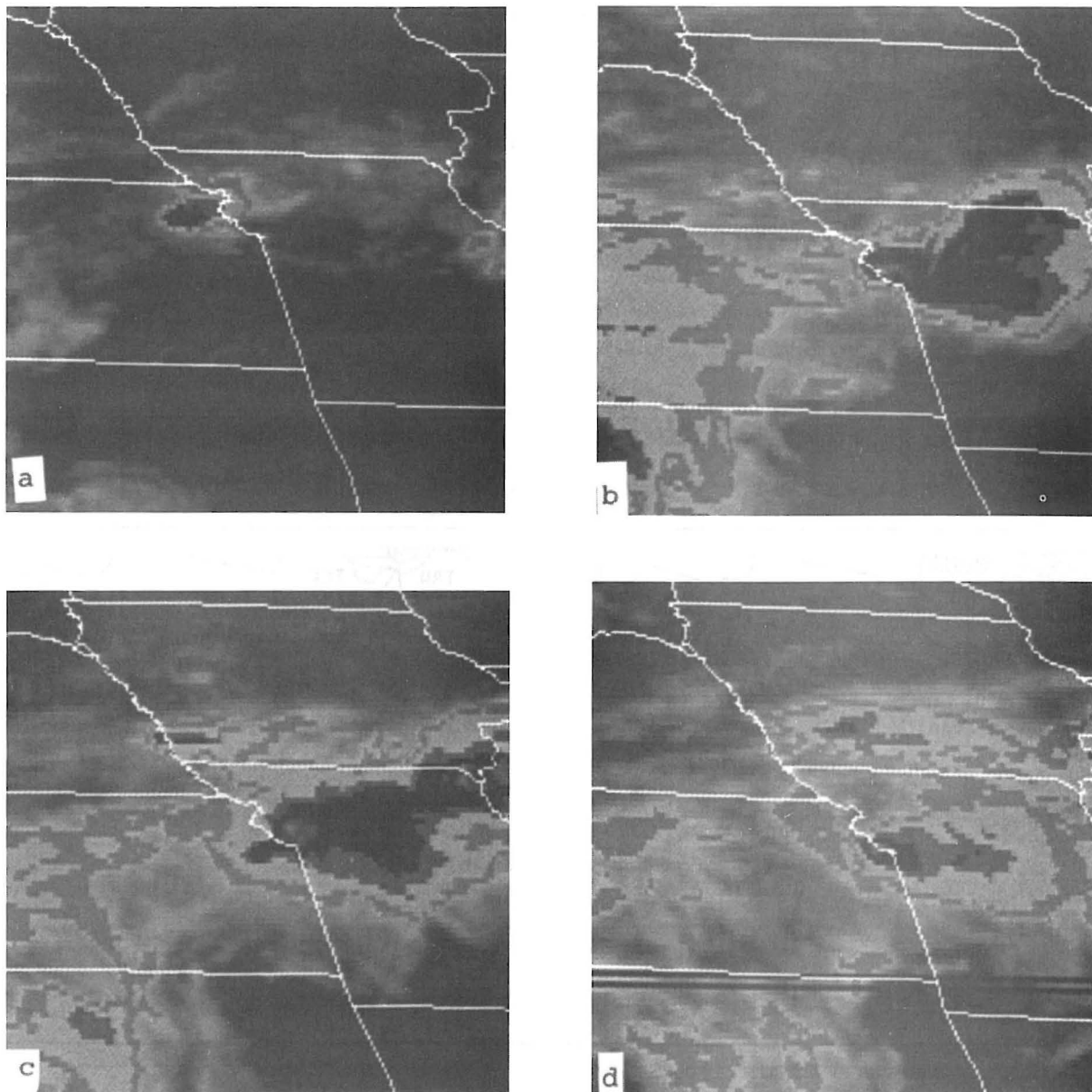
Fig. 13. Enhanced infrared satellite imagery valid 10 July 1993 at a) 0231 UTC, b) 0631 UTC, c) 0831 UTC and d) 1031 UTC.

the CMF method indicated that any MCS that formed would be very slow moving (Figs. 17a and b). The MBE vectors over Kansas change from showing a MBE movement of about 10 kt at 0000 UTC 10 July (Fig. 17a) to estimating very slow westerly motion at 1200 UTC (Fig. 17b). The period of quasi-stationary convection observed on the satellite imagery began around 0600 UTC, about the same time that linear interpolation of the 0000 UTC and 1200 UTC vectors would have signaled that the system might become stationary.

The 1200 UTC 10 July RDAS data, however, would not have been available to the forecasters. Therefore, an 18-h ETA model forecast valid at 0600 UTC 10 July 1993 was examined to see if model forecasts of MBE motion would be similar. The forecast CMF vector of less than 5 kt along the border between Kansas and Missouri correctly predicted than an MCS would hold almost stationary (Fig. 17c). The CMF method was able to provide guidance that a period of quasi-stationary

convection was likely suggesting the method has the potential to improve forecasts of quasi-stationary convective events.

5. Conclusion

Two quasi-stationary convective events that produced heavy rains during July 1993 were studied. Both cases supported Chappell's (1986) ideas about quasi-stationary convective events. During each case, the strongest potential buoyant energy (instability) and low-level moisture convergence were located on the western side of the initial convection that eventually developed into the quasi-stationary mesoscale convective system (MCS). The strongest low-level winds and moisture transport were also found west of the initial convection. The rate at which new cells formed on the western flank of the storm appeared to offset the movement of the individual cells within the MCS leading to a period of quasi-stationary convection.
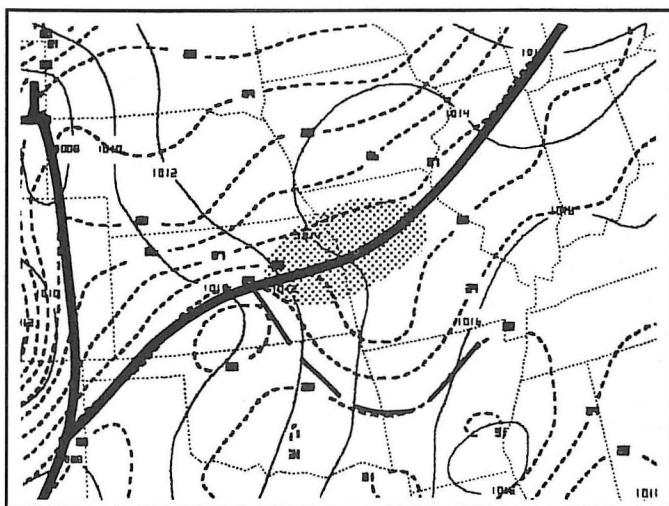
Fig. 14. Same as in Fig. 4 except that thicker dashed line represents possible thermal boundary due to convection earlier in the day and valid 0000 UTC 10 July 1993.

Fig. 16. Same as in Fig. 6 except valid 0000 UTC 10 July 1993.
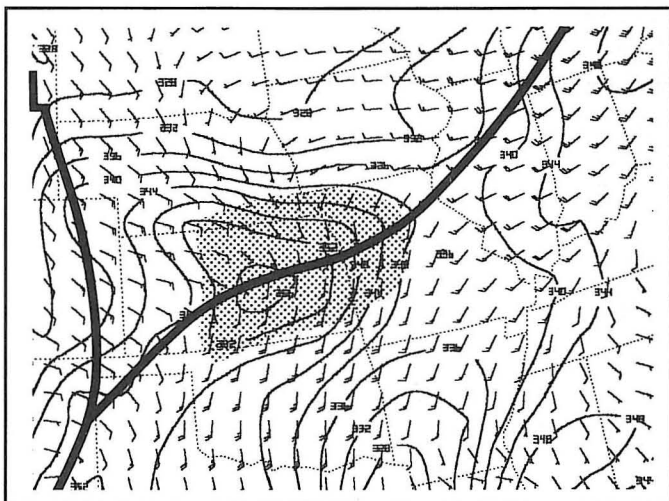

Fig. 15. Same as in Fig. 5 except valid 0000 UTC 10 July 1993.

A close examination of the period of quasi-stationary convection that evolved between 2100 UTC 8 July 1993 and 0600 UTC 9 July suggests that high temporal resolution gridded surface data that are now available operationally, such as the RUCS analyses, can provide valuable information on the evolution of the pressure, wind and moisture convergence fields that appear to play important roles in determining where new convection will form. Rapid increases in moisture convergence over eastern Nebraska during the Des Moines flash flood event preceded the period of new cell growth west of the initial convection. Using new high temporal frequency data sets along with the ideas developed by Chappell (1986) should help forecasters to more easily recognize cases when quasi-stationary convection will occur.

The CMF method for predicting the motion of mesoscale convective complexes (MCCs) described by Corfidi et al. (1996) was adapted and tested for use with gridded model output data. The two cases indicate the technique can be successfully
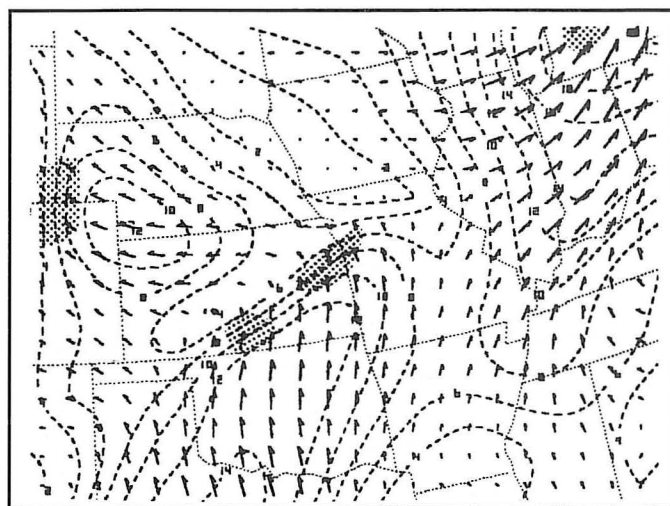
modified for use with gridded output data in an operational setting. However, results from the Des Moines case suggest that rapid changes to the mass and wind fields may limit the technique's usefulness if only 12-hour temporal resolution analyzed data were used. The CMF method was tested using ETA model forecasts of the wind fields every 6 hours to evaluate the methods forecast utility and to see if the increased temporal resolution might improve the MCS motion estimates. The resulting vectors correctly indicated that an MCS would be almost stationary (move at less than 5 knots) during each event. The two cases investigated suggest the technique has the potential to help forecasters anticipate which MCCs have the most potential to become quasi-stationary. The CMF method is currently displayed on the operational N-AWIPs prototype workstations at the Hydrometeorological Prediction Center of NCEP and will continue to be tested in an operational setting.

Acknowledgments

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Dr. Schneider was the Science and Operations Officer at HPC when this manuscript was written. He is now the Chief of the Science Support Branch at the Storm Prediction Center in Norman, Oklahoma. Dr. Schneider received his undergraduate, Master's and Ph.D. in Meteorology from the University of Wisconsin at Madison. His thesis research focused on the
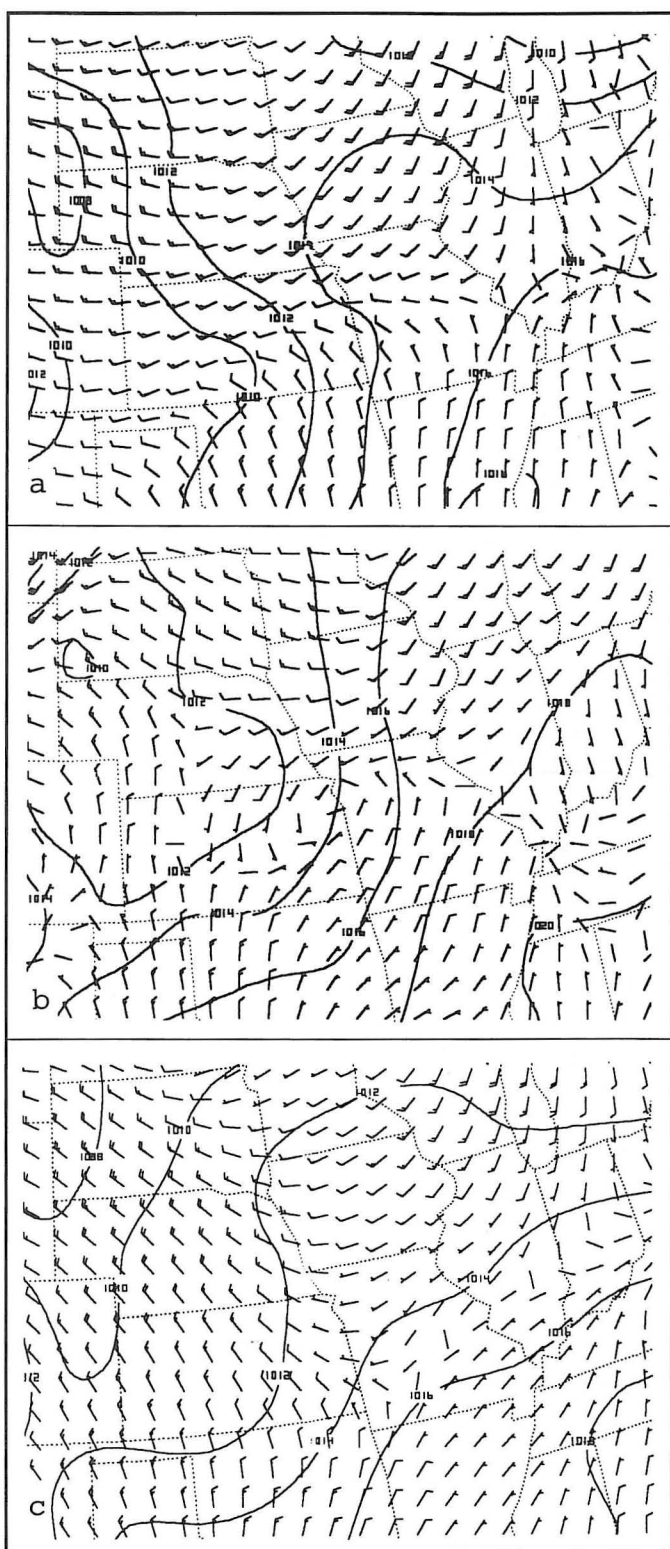
Fig. 17. Mean sea-level pressure (every 2 mb) and MBE movement vectors (full barb = 10 kt and half barb = 5 kt) from RDAS analysis valid a) 0000 UTC 10 July 1993, b) 1200 UTC 10 July 1993 and c) from 18-h ETA model forecast valid 0600 UTC 10 July 1993.

dynamics of extratropical cyclone lifecycles from diverse geographical locations. He formerly worked in the NCEP Environmental Modeling Center before he joined the HPC. Dr. Schneider is interested in a wide range of mesoscale meteorological problems.

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