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Abstract

An intense small-scale low pressure system that moved across portions of the midwest United States is examined. The system produced a continuous band of significant snowfall, typically only 50 km wide but extending over 1500 km in length. The system traveled across the Iowa Department of Transportation surface mesonet network, allowing high-resolution surface analyses that show a closed circulation and intense pressure gradients around the mesolow, comparable to those occurring in warm season MCS events. Radar and satellite images also revealed the small-scale low-level circulation, which apparently was confined below about 800 mb. Although the strong vorticity advection aloft and baroclinicity at lower levels present in this system are typical of baroclinic cyclones, the unusually small scale and short lifetime of the surface system are more reminiscent of polar lows. Mesoscale simulations of the system using the Pennsylvania State University-National Center for Atmospheric Research Mesoscale Model Version 5 with 20-km horizontal grid spacing and initialized with standard synoptic-scale data were unable to capture the closed circulation and significantly underestimated the strength of the mesolow. The inclusion of mesonet surface data in an initialization significantly improved the initial pressure field but did not significantly change the simulation. The simulation was also not strongly sensitive to variations in horizontal and vertical resolution, surface characteristics, convective parameterizations, and the use of nudging toward observations. However, an adjustment of upper-level fields to support the surface mesoscale low did result in a significantly improved simulation of the event, apparently due to better simulation of forcing from warm advection in low levels. A simulation neglecting latent heating produced a surface low that was at least 1 mb weaker than the full-physics run and had much weaker and disorganized upward vertical motion. The mesoscale low was apparently the result of upper-tropospheric forcing, which eliminated a small region, permitting precipitating convection and latent heat release.

Disciplines

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Comments

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An Intense Small-Scale Wintertime Vortex in the Midwest United States

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ABSTRACT

An intense small-scale low pressure system that moved across portions of the midwest United States is examined. The system produced a continuous band of significant snowfall, typically only 50 km wide but extending over 1500 km in length. The system traveled across the Iowa Department of Transportation surface mesonet network, allowing high-resolution surface analyses that show a closed circulation and intense pressure gradients around the mesowlow, comparable to those occurring in warm season MCS events. Radar and satellite images also revealed the small-scale low-level circulation, which apparently was confined below about 800 mb. Although the strong vorticity advection aloft and baroclinicity at lower levels present in this system are typical of baroclinic cyclones, the unusually small scale and short lifetime of the surface system are more reminiscent of polar lows.

Mesoscale simulations of the system using the Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model Version 5 with 20-km horizontal grid spacing and initialized with standard synoptic-scale data were unable to capture the closed circulation and significantly underestimated the strength of the mesowlow. The inclusion of mesonet surface data in an initialization significantly improved the initial pressure field but did not significantly change the simulation. The simulation was also not strongly sensitive to variations in horizontal and vertical resolution, surface characteristics, convective parameterizations, and the use of nudging toward observations. However, an adjustment of upper-level fields to support the surface mesoscale low did result in a significantly improved simulation of the event, apparently due to better simulation of forcing from warm advection in low levels.

A simulation neglecting latent heating produced a surface low that was at least 1 mb weaker than the full-physics run and had much weaker and disorganized upward vertical motion. The mesoscale low was apparently the result of upper-tropospheric forcing, which eliminated a capping inversion in a small region, permitting precipitating convection and latent heat release.

1. Introduction

Accurate prediction of mesoscale weather systems is known to be an important forecasting challenge during the warm season over the United States. Fritsch et al. (1986) have shown that over half of the precipitation in the agriculturally important Midwest is due to mesoscale convective systems (MCSs). These systems alter the mass and velocity fields over large regions in their vicinity, resulting in surface pressure perturbations such as mesohighs, presquall lows, and wake lows (e.g., Williams 1948; Pedgley 1962; Johnson and Hamilton 1988) along with midlevel vorticity centers (e.g., Bartels and Maddox 1991) and upper-level highs (e.g., Fritsch and Maddox 1981). Because the MCSs alter the larger-scale

environment, they can influence forecasts beyond 24 h and over large distances downstream. The accurate prediction of quantitative precipitation amounts by numerical models has therefore been strongly linked to accurate simulation of mesoscale features.

Mesoscale weather systems are not as widely distributed or as frequent during the cold season in the United States. Mesoscale variations do occur, but primarily as small-scale perturbations within a larger-scale weather system. Such phenomena include internal gravity waves (e.g., Bosart and Sanders 1986) and snow bands due to conditional symmetric instability (e.g., Wolfsberg et al. 1986). Mesoscale weather systems producing precipitation separate from larger-scale systems are much rarer in the midlatitudes.

Over polar oceanic regions, however, mesoscale systems with separate areas of precipitation are more common and are known as polar lows (e.g., Harold and Browning 1969). These systems have typical scales of roughly 500 km, making them difficult to resolve with

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the scarce data available at high latitudes. Special research projects have found that the systems may be linked to upper-level vorticity centers, and often occur along intense, but shallow, baroclinic zones that are present near the sea-ice boundary. In these systems, intense cumulus convection occurs with strong sensible heating from the ocean surface in a conditionally unstable environment. Polar lows may show a weak warm-core structure and have a relatively cloud-free eye within a comma-shaped cloud mass. Bresch et al. (1997) suggest that since polar lows have many physical characteristics in common with extratropical cyclones, they should not be considered as a separate phenomenon, but as part of a broad spectrum of cyclones that differ in such respects as baroclinicity, strength of upper-level forcing, tropospheric stability, amount of latent heat release, and the amount of surface energy fluxes.

Some evidence exists that similar features occasionally occur over land at middle latitudes (Mullen 1982; Mills and Walsh 1988). These systems propagate within the polar airstream and do not generally intensify rapidly, probably because of the lack of strong surface heat and moisture fluxes as well as the retarding effects of friction over land. However, a 9-mb deepening rate over 12 h did occur in the midwestern mesoscale low studied by Mills and Walsh. The significant intensification in that case may have been attributable to an intense tropopause fold and stratospheric intrusion, which have been linked to rapid intensification (Uccellini et al. 1985).

On 15–16 February 1996, one such small-scale system tracked from southern Canada across the American midwest into the southeastern United States where the upper-level forcing influenced the evolution of an intense coastal cyclone. Operational numerical guidance failed to capture the observed intensity of the central sea level pressure, low-level circulation, and precipitation amounts within the mesoscale low. Other mesoscale simulations of the event also failed to produce a system of comparable intensity to that observed. This forecasting difficulty raises several questions to be addressed in this work:

- Is increased horizontal resolution alone able to improve a forecast of a very small-scale system?
- What impact does the inclusion of surface mesonet data in initialization have on simulation of small-scale long-lived systems?
- How do the dynamics of these small-scale midlatitude systems compare with those driving larger-scale baroclinic cyclones and the visually similar polar lows of higher latitudes?

In this paper, the mesolow will be described in detail and its forcing compared with both typical larger-scale baroclinic cyclones and polar lows. The mesoscale surface data available through the Iowa Department of Transportation (IADOT) mesonet will be shown to be invaluable in resolving the scale and intensity of the low

pressure system. In addition, simulations with a mesoscale research model will be used to offer some insight into the above questions.

2. Observations

a. Synoptic background

During the middle of February 1996, a series of Alberta clipper-like disturbances propagated southeastward across the Midwest into a deep eastern North American trough that was exceptionally persistent during the 1995–96 winter season. Each system generally produced no more than a few millimeters of precipitation and the small amounts were adequately forecasted by operational guidance.

On 15 February another in a series of disturbances was predicted to move southeastward across the Midwest. Operational model quantitative precipitation forecasts looked similar to other recent cases, with even high-resolution guidance like that from the 29-km mesoscale Eta Model (Black 1994) (run at 0300 UTC 15 February) only generating peak accumulations of 2–3 mm during the short-lived event in a band across central Iowa and into northern Missouri.

The 1200 UTC Eta analysis on 15 February (Fig. 1), however, showed an exceptionally strong vorticity maximum at 500 mb (Fig. 1a), exceeding $30 \times 10^{-5} \text{ s}^{-1}$, moving into Iowa from the northwest. At 850 mb (Fig. 1b), a narrow and weak thermal ridge was present ahead of the vorticity maximum, with a small region of warm advection occurring in parts of eastern Nebraska and western Iowa. Strong upper-level forcing induced a 1010-mb surface low near Sioux Falls, South Dakota. The 0-h operational analysis from the National Centers for Environmental Prediction Nested Grid Model (NCEP NGM; Phillips 1979) valid at this time, however, showed sea level pressures at least 5 mb too high in this region without a distinct surface low in the area of upper-level forcing. A distinct low pressure system associated with this upper-level forcing was also absent in the mesoscale Eta Model. Without a mesoscale network of surface observing sites in the Dakotas, the central pressure of the low can be estimated only prior to 1200 UTC. Available data suggests that the low deepened by roughly 2 mb as it traveled from near Aberdeen, South Dakota (where 5 cm h^{-1} snowfall rates were observed), to Sioux Falls, South Dakota (see reference map, Fig. 2).

b. Mesoscale observations

Shortly after 1200 UTC, the mesolow moved into Iowa, where a network of roughly 40 Automated Weather Observing System (AWOS) stations has been established by the IADOT (D. Burkheimer 1996, personal communication). Surface observations at 1200 UTC (Fig. 3a) showed winds backing to the southeast ahead

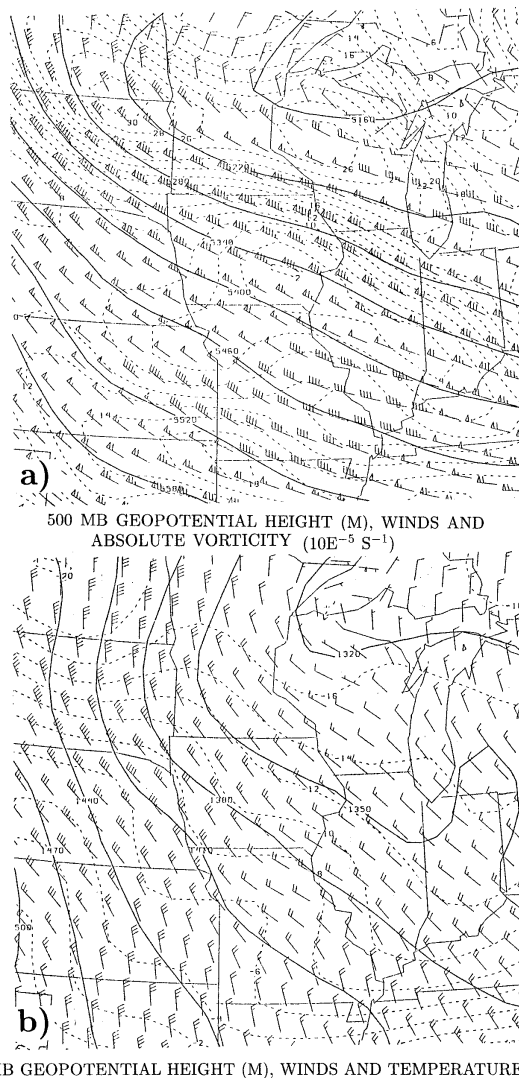


FIG. 1. Analyses of (a) 500-mb geopotential heights (solid) and absolute vorticity (dashed) and (b) 850-mb geopotential heights (solid) and temperatures (dashed) valid at 1200 UTC 15 February. Height information is contoured with an interval of 30 m at 850 mb and 60 m at 500 mb. Contour interval for temperature is $2^{\circ}C$ and for vorticity, $2 \times 10^{-5} s^{-1}$.

of the low in northwest Iowa. The altimeter setting has been subjectively analyzed and contoured with a 1-mb interval. The backing of the winds observed at 1200 UTC helped to transport relatively warmer, moist air from the southwest into the low circulation. At this time, composite radar imagery showed evidence of a circulation in the low-level reflectivity fields, and although the scale of the circulation was greater than that of a supercell thunderstorm, a mesocyclone was identified by a WSR-88D algorithm (figure not shown).

Over the next several hours, the mesolow continued moving southeastward at around $20 m s^{-1}$. The central pressure decreased to around 1008 mb by 1500 UTC (Fig. 3b) and remained between 1007 and 1008 mb

through the next 3 h (Figs. 3c–e). The deepening of the low was accompanied by a closing off of the surface circulation. This can be seen at 1600 UTC (Fig. 3c) when the low was located near Carroll (CIN). Winds were backing strongly and becoming southerly in a region to the southeast of the low, and winds had become almost easterly at Boone (BNW) where heavy snow was falling. The low passed just west of Des Moines at 1700 UTC (Fig. 3d) and just northeast of Chariton (CNC) by 1800 UTC (Fig. 3e), where the lowest pressure occurred, around 1007 mb. The closed surface circulation is readily apparent at both of these times with a mesolow pressure distinctly lower than that elsewhere in eastern Iowa and western Illinois. Pressure falls ahead of the system exceeded 4 mb in 2 h, with rises as large as 3 mb or more in just 30 min after its passage. A small-scale boundary labeled as a warm front in the surface analyses marked the northeastward edge of a zone of distinctly higher equivalent potential temperatures ahead of the mesolow. By 2000 UTC (Fig. 3f), the low had moved out of the mesonet into northeastern Missouri.

Radar images available from the Des Moines WSR-88D site strongly suggested a closed surface circulation (Fig. 4). At 1730 UTC, the highest reflectivities occurred in a band extending from just north of the low eastward and east-southeastward about 100–150 km. Although reflectivities greater than 28 dBZ are omitted in the figure (showing up as white regions within the precipitation shield), other radar data indicated a narrow swath of reflectivities exceeding 40 dBZ. These high reflectivities are supported by observations of snowfall rates exceeding $10 cm h^{-1}$ in parts of central Iowa. An echo-free region matches well with the location of the surface low at this time (Figs. 3d,e) and has tracked just east of Creston (CSQ). The actual lowest pressure at this time was about 30 km northeast of CSQ, or at the northeastern edge of the echo-free region. An additional narrow band of enhanced reflectivities, occasionally exceeding 28 dBZ, can be seen extending northeast–southwest ahead of the low and southward into Missouri. This band formed along the cold front, where winds abruptly shifted from southwesterly to northwesterly and speeds increased dramatically. As the afternoon progressed, the precipitation along the cold front became better organized, producing brief, near-blizzard conditions across much of Missouri.

Satellite data also showed strong evidence of the small-scale circulation. A visible image taken at 1900 UTC (Fig. 5) shows a curved small-scale band of deeper convective-like clouds at a time when the system was exiting southern Iowa. (Lake Michigan can be seen to the right of the comma-shaped cloud and provides a reference to the scale of the cloud features.) The scale of the comma cloud head, roughly 200 km, agrees almost exactly with the scale of the feature in the Mills and Walsh (1988) case. An eyelike feature is apparent at this time, in agreement with the radar observations. Eyelike features such as that found in Fig. 5 have been

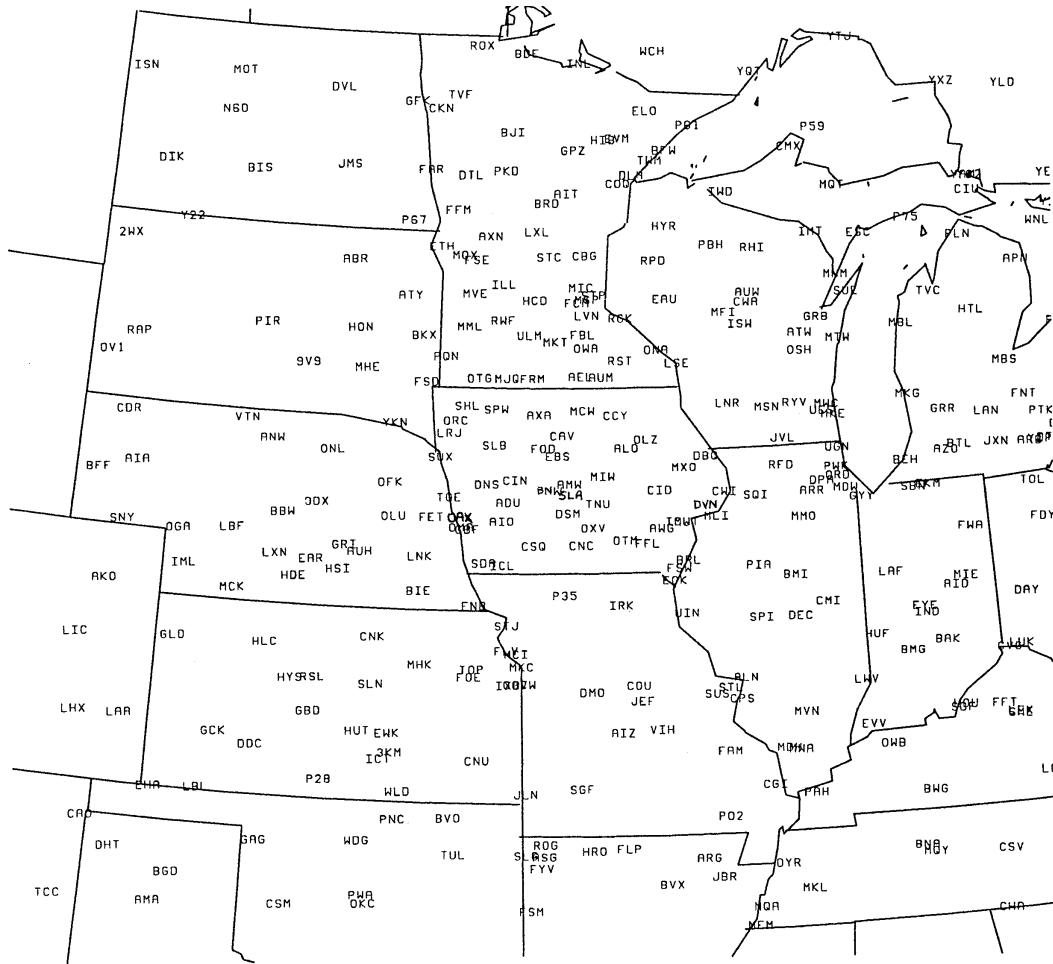


FIG. 2. Region through which the mesoscale low propagated. Station identifiers of observing sites are indicated.

observed in many polar lows (e.g., Bluestein 1993), and in some larger scale, intense baroclinic cyclones (e.g., Presidents' Day storm; Bosart 1981). In this case, the eyelike appearance may be due to the extreme narrowness of the dry slot entering the system from the southwest. To the northwest of the system, a narrow bright band can be seen extending in a north-northwest direction, marking the narrow swath of heavy snow produced earlier by the low.

Although no reports of thunder or lightning were received in Iowa during the event (K. Jungbluth 1996, personal communication), the unusually heavy snowfall rates imply that convective processes similar to those occurring in lake effect snow events (e.g., Braham 1983; Hjelmfelt 1990) were occurring. The sounding from Omaha (OAX) at 1200 UTC shows rather steep lapse rates in the lowest 2.5 km (Fig. 6) below an intense inversion. Omaha was south of the track of the low but was in the region from which the low-level heat and moisture fed the system. A sounding from Davenport, Iowa (DVN), at 0000 UTC 16 February (overlaid with dashed curves) reveals that the inversion at midlevels

was much weaker north of the track of the low. Observed surface temperatures and dewpoints in the vicinity of the low were around -1°C and -2°C , respectively, and these values when input into the OAX sounding yield a sounding with some positive area in the lowest layers. Some freezing rain was reported in an exceptionally narrow zone directly under the path of the low, and the warmer temperatures just above the surface implied by these reports suggests even greater low-level instability. Additionally, as implied by the DVN sounding, the temperature gradient aloft was directed from north-northeast to south-southwest so that temperatures at all levels from 850 to 500 mb were as much as 5°C lower along the path of the low in Iowa than in the 1200 UTC Omaha sounding. Again, these colder temperatures aloft suggest an increase in instability over that seen in the OAX sounding. The presence of shallow convection in this system is another similarity with polar lows. Conditional instability was found in the 800–850-mb layer in the similarly small-scaled Midwestern mesolow discussed by Mills and Walsh (1988).

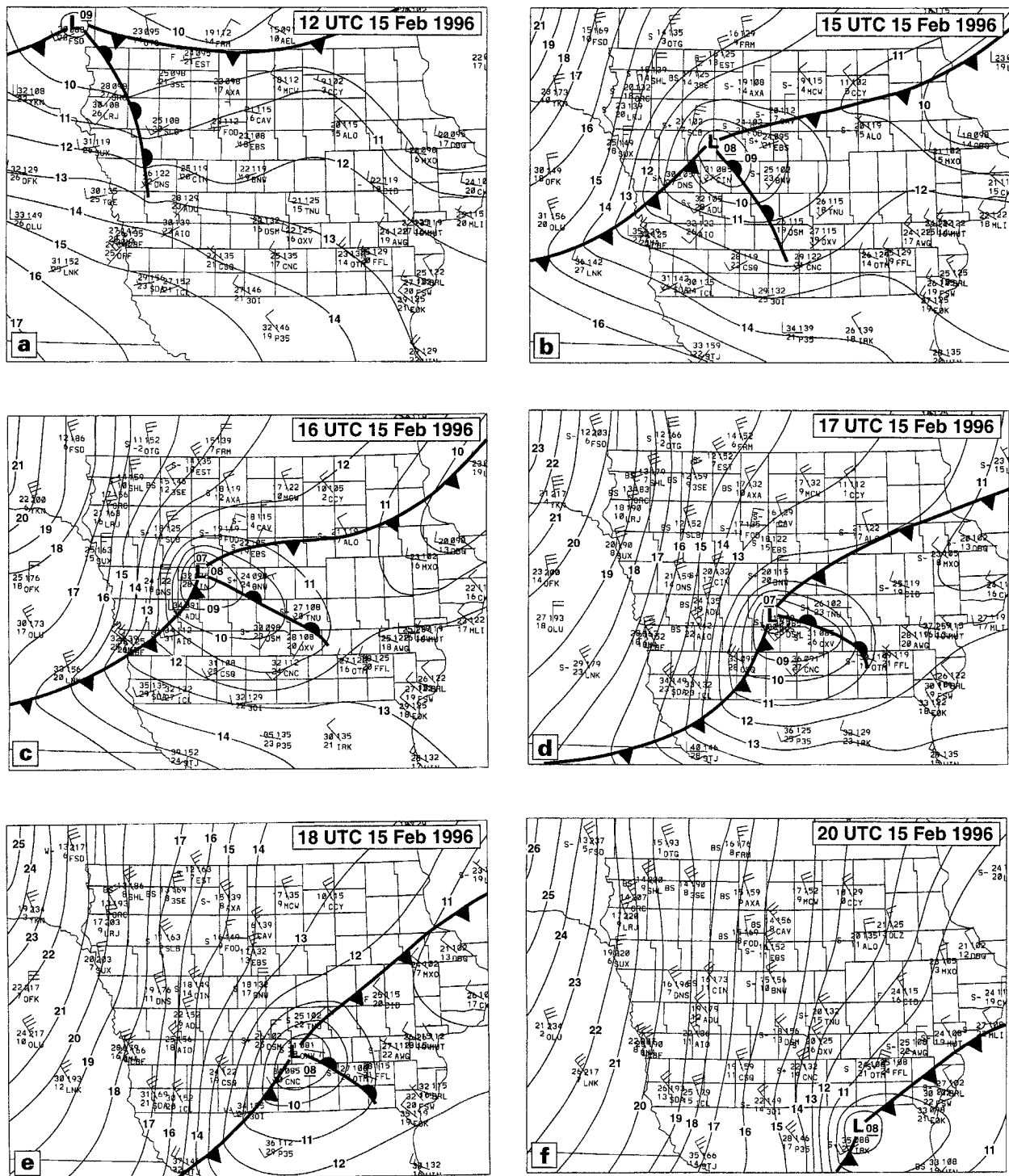


FIG. 3. Surface analyses at (a) 1200, (b) 1500, (c) 1600, (d) 1700, (e) 1800 UTC, and (f) 2000 UTC. Altimeter setting is contoured with an interval of 1 mb.

Because the low tracked very near both the Des Moines WSR-88D site and the Slater, Iowa, wind profiler, some data are available to determine the vertical structure of the circulation associated with the system.

The WSR-88D VAD (vertical-azimuth display) wind profile (Fig. 7) indicates an abrupt shift from southwest winds to northeast winds at around the 600-m level between 1610 and 1640 UTC. Substantial weakening of

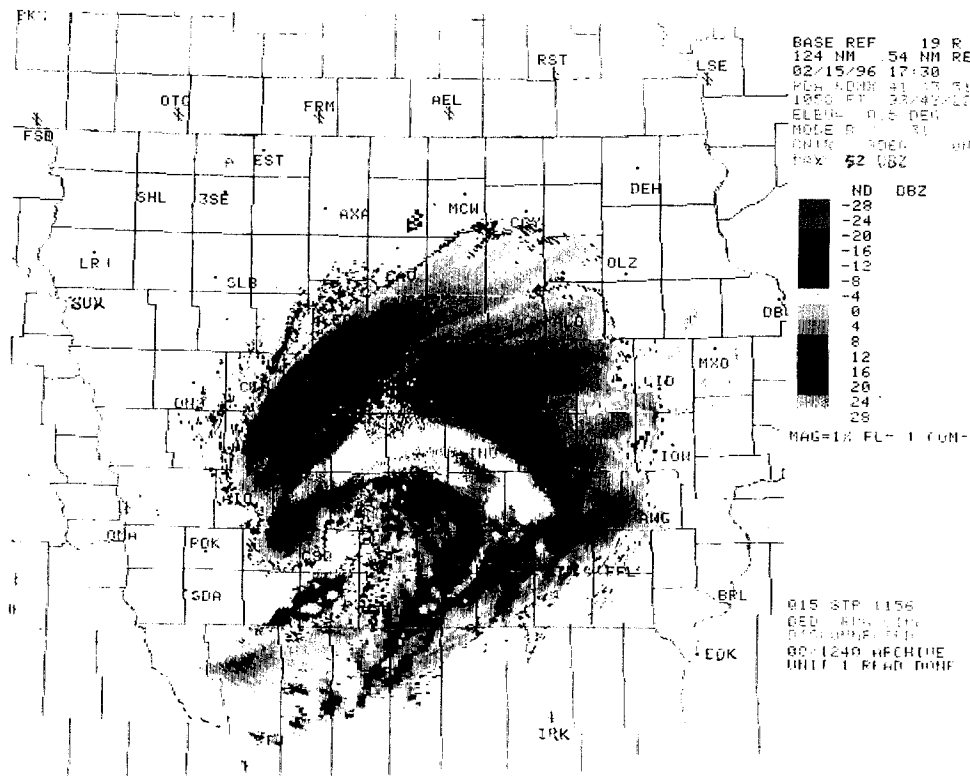


FIG. 4. NEXRAD base reflectivity information from Des Moines, Iowa (DMX), at 1730 UTC.

the flow at around the 5100-m level can also be seen during this time. The deepening layer of arctic air is implied by the increasing depth of northerly winds after 1640 UTC. Most radar data for this case (such as the VAD profile) suggest cloud tops at around the 6-km level. As shown earlier (Fig. 6), an intense inversion was present in the Omaha sounding, which would prevent cloud tops from exceeding 3–4 km. It is possible that ducting of the radar beam occurred above this level and the VAD winds may not be reliable above 3 or 4 km. However, the Davenport sounding data, along with model output to be discussed later, imply a rapid weakening of the inversion toward the northeast, so that the 6-km estimate of cloud tops from radar data may be reasonable. In addition, the winds in the 4–6-km layer are in good agreement with those from the Slater wind profiler (Fig. 8).

An abrupt wind shift can be seen between 1600 and 1700 UTC in the Slater profiler data, with deepening northerlies through 1900 UTC. The wind profiles strongly suggest that any low-level circulation was extremely shallow. The VAD wind profile implies that the closed circulation did not extend beyond about 850 mb (1200–1500 ft) and the Slater data support this. Des Moines NEXRAD velocity data (not shown) did suggest that a small-scale (50–100 km wide) circulation extended to around 2 km at 1800 UTC. A strong jet maximum (at around 2100 m) can be seen reaching Slater around 1500 UTC, just before the time when the heavi-

est snow began falling there. Rapid deceleration occurred after this time during the heavy snow event as the upward branch of the secondary circulation associated with the exit region of the jet moved into the region.

By 1900 UTC, the system moved out of the Iowa mesonet, and a central pressure of 1009 mb was reported at Kirksville, Missouri, around 2000 UTC (Fig. 3f). Even though mesoscale surface information is not available south of Iowa, the path of the system near the Mississippi River resulted in a reasonable amount of observations. Thus, although the central pressure of the mesolow may have been slightly deeper than that indicated by the standard surface data network, enough data exist to show that the system weakened after exiting Iowa. Pressures rose over the next 12 h; however, a pronounced circulation continued to be evident in radar imagery with narrow bands of very heavy snow as the system moved southeastward. A central pressure of 1010 mb occurred near St. Louis around 0000 UTC 16 February, with minimum pressures of around 1011 or 1012 mb common in southern Illinois and into Kentucky and Tennessee after 0600 UTC 16 February.

One of the more unusual aspects of the system was its precipitation field (Fig. 9). At least 1 mm of precipitation occurred in a continuous band from north-central North Dakota to central Tennessee, a path of over 1500 km. At least 2 mm occurred over nearly the entire length of this band, with 4 mm values extending from southeast



FIG. 5. NOAA-14 visible satellite image from 1914 UTC. Horizontal scale can be estimated by observing Lake Michigan to the east of the disturbance, which at this time was centered over southern Iowa.

North Dakota through western Kentucky. Isolated 8-mm amounts occurred across Iowa, Missouri, and Illinois. In the northern part of the band, snow to water equivalents were often 20 to 1 or greater, so that a narrow stripe, often only 30–50 km wide received 7–17 cm of snow. The maximum snowfall, 17.5 cm in Ames, Iowa (AMW), occurred primarily within a 2-h period. The band was broadest in eastern Missouri and southwestern Illinois where significant amounts occurred along the advancing cold front. The system propagated through this region near the time of maximum heating, which may have increased destabilization, resulting in the more pronounced precipitation band along the cold front.

3. Mesoscale model simulations

Because the horizontal scale of the system, as determined from the sea level pressure and wind fields, and radar and satellite imagery, was no more than 200 km, it is understandable that conventional operational guidance would fail to forecast this event. Mesoscale models run with rather standard horizontal resolutions of 25–30 km may also encounter problems since the heavy snow band was typically no more than 50 km wide. To investigate the ability of numerical models to simulate such an intense, small-scale cold-season event, the Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model Version 5 (MM5)

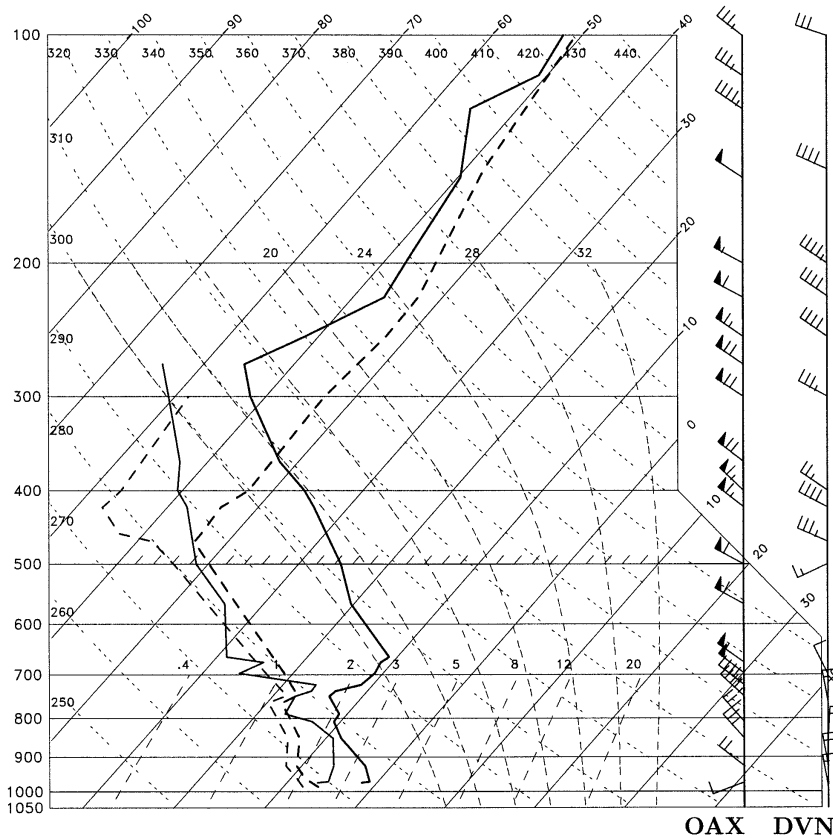


FIG. 6. Thermodynamic diagram at Omaha, Nebraska, at 1200 UTC with temperature and dewpoint curves solid. Thermodynamic diagram from Davenport, Iowa, at 0000 UTC 16 February is overlaid with dashed curves.

(Dudhia 1993) is run at several different horizontal and vertical resolutions at two different times, and with several variations in initial conditions. Results from the operational mesoscale Eta Model are also presented. The purpose of the simulations is to provide model output that may be used in lieu of an observational dataset (e.g., Keyser and Uccellini 1987) to determine the internal dynamics of the system, and to determine the importance of using mesoscale surface data in model initialization.

a. Mesoscale Eta results

The 29-km horizontal resolution used in the mesoscale Eta Model is designed to improve forecasting of smaller-scale events such as this one compared with 48-km guidance. The mesoscale Eta (with 50 vertical layers) initialized at 0300 UTC simulated a stronger surface low tracking across Iowa than the operational 48-km run; however, the Iowa low was never truly distinct in the simulation (Fig. 10), and the central pressure remained above 1011 mb. As might be expected with a weaker low, the system also did not dig as far to the west in the simulation as observations showed. The meso-Eta did generate a band of precipitation in roughly

the same region as it occurred (Fig. 11), but the peak amounts were significantly underestimated, with a maximum of around 3 mm.

b. MM5 simulations

A 27-km fine grid domain was used in a 24-h MM5 simulation of the event initialized at 0000 UTC. A coarse grid with 81-km spacing surrounded the two-way interactive fine grid so that the boundary conditions feeding the inner domain had a high temporal resolution. Twenty-seven vertical σ levels were employed along with the Blackadar planetary boundary layer scheme (Zhang and Anthes 1982), the Kain–Fritsch cumulus parameterization (Kain and Fritsch 1992), and the four-category grid-resolvable precipitation scheme (Grell et al. 1994) with prognostic equations for ice, snow, rain, and cloud water. Initial conditions were obtained by using the NCEP 2.5° analyses as a first-guess field with enhancement using standard surface and upper-air observations.

This simulation, like the meso-Eta, produced only a weak area of lower sea level pressure in Iowa that was not truly distinct from the stronger low to its northeast (Fig. 12). At 1800 UTC, when the actual low had a

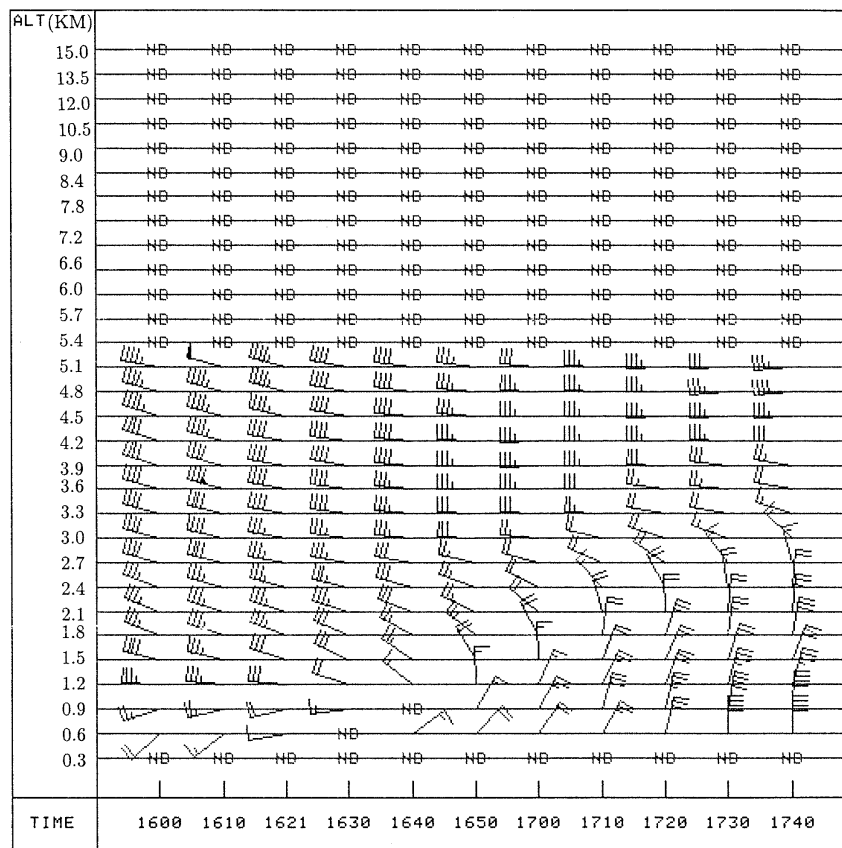


FIG. 7. Des Moines NEXRAD VAD wind time series (one full barb represents 5 m s^{-1}) for the period 1600–1740 UTC. (ND represents no data.)

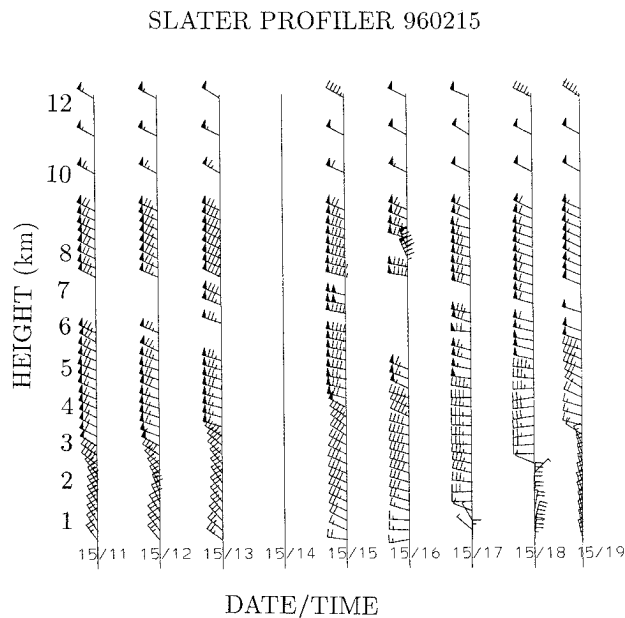


FIG. 8. Time series of wind measurements (one full barb represents 5 m s^{-1}) from Slater, Iowa, wind profiler valid for the period 1100–1900 UTC.

pressure of 1007 mb, the MM5 simulation showed only 1012–1013 mb. In addition, not only was a closed circulation not produced but a southerly wind component did not develop at any grid point near the low.

A band of precipitation along the track of the low was produced in the MM5 model with peak amounts reaching 5.6 mm in extreme northern Missouri (Fig. 13). The location of the band agreed reasonably well with observations, although it tended to be 50–100 km east of the observed band north of Iowa and a similar distance west of the observed band south of Iowa. Additionally, the heavier precipitation amounts were restricted to extreme southern Iowa and points south. The broader area of precipitation in Missouri agrees with observations, but in general, the simulation appeared to underestimate precipitation, especially in central Iowa and portions of South Dakota.

A sensitivity test was performed in which the horizontal resolution of the finest model grid was increased by a factor of 3, to 9 km. If insufficient resolution accounted for disagreement between the numerical results and observations, this change should produce a better simulation. Results were relatively unchanged from the

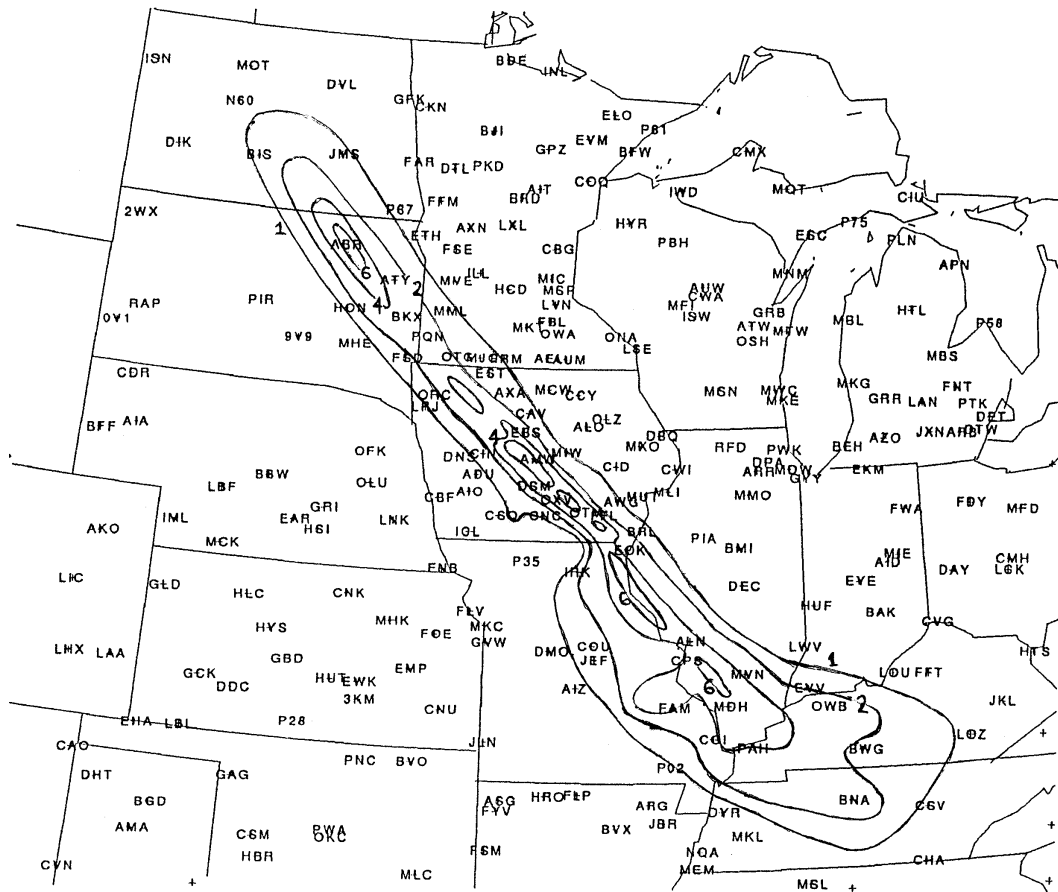


FIG. 9. Storm-total precipitation (mm). Contours at 1, 2, 4, and 6 mm.

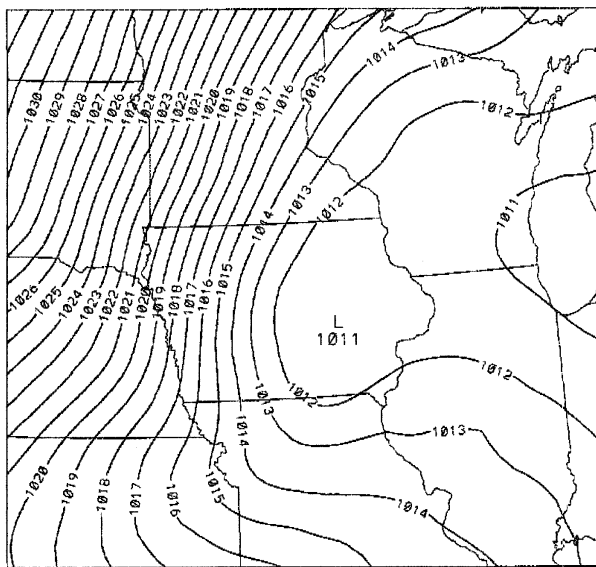


FIG. 10. Sea level pressure field valid at 1800 UTC from the 0300 UTC 29-km mesoscale Eta Model. Contour interval is 1 mb.

27-km simulation. The surface low was too weak and winds failed to back sufficiently at low levels (figure not shown). In addition, no substantial improvement occurred in the precipitation field (figure not shown). In both the 9- and 27-km fine grid simulations, all of the precipitation was resolved by the grid, with no contribution from the convective parameterization. An additional sensitivity test was performed using the 0000 UTC initialization but with nudging toward a 1200 UTC analysis. This “dynamic” initialization again failed to noticeably change the simulation.

A second set of sensitivity tests were performed using a 1200 UTC initialization on 15 February to investigate the role of incorporating mesoscale surface data in a numerical simulation. This set of tests used 23 vertical levels, an outer domain with 60-km grid spacing, a 20-km nested grid, and the Grell (1993) subgrid-scale convective parameterization scheme. First, a control run was performed in which mesonet data were not used in the 1200 UTC initialization. The results were generally in less agreement with observations than the simulation

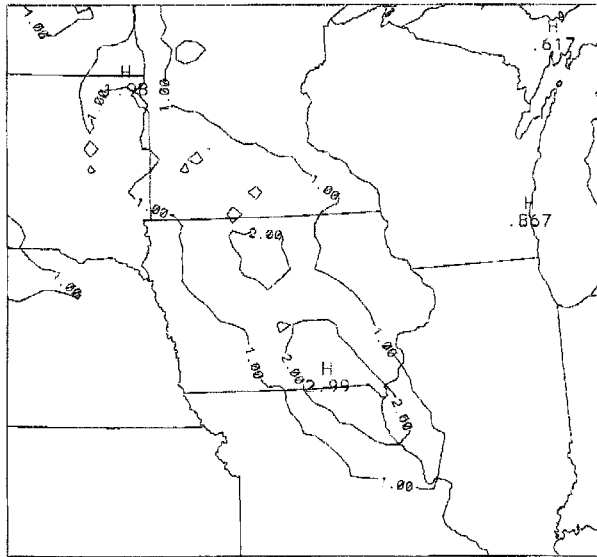


FIG. 11. Total accumulated precipitation for 12 h ending at 0000 UTC 16 February from the 29-km mesoscale Eta Model. Contour interval of 1 mm is used.

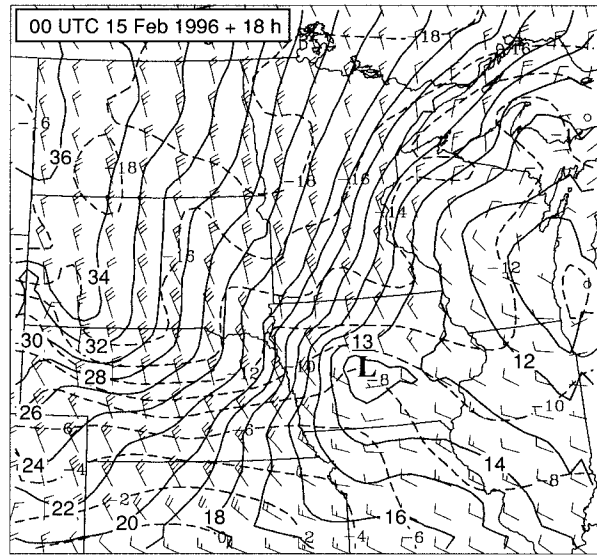


FIG. 12. Sea level pressure field valid at 1800 UTC 15 February with temperature (dashed) and winds overlaid for MM5 simulation initialized at 00 UTC with standard data. Pressure is contoured with an interval of 1 mb, temperature with a 2°C interval.

initialized at 0000 UTC, probably a result of spinup delay in the simulation. In Iowa, the initial 1011-mb surface low (Fig. 14a) disappeared by hour 3 of the forecast (Fig. 14b) and was only around 1013 mb at hour 6 (Fig. 14c), when the actual low was most intense. The 0000 UTC initialized run indicated a central pressure roughly 1 mb lower at this time. The low did deepen somewhat further by 2100 UTC (Fig. 14d) when its lowest pressure (1012 mb) occurred in northern Missouri. After that time, it began to weaken (Fig. 14e). In general, no real improvement occurred in the sea level pressure field in the 1200 UTC run compared with the earlier 0000 UTC run.

Predicted precipitation from the 1200 UTC simulation exhibited a typical spinup delay (e.g., Molinari and Dudek 1992), but by 12 h (Fig. 15) a narrow band was located over western Iowa. The band's size and orientation agreed well with observations, but the band was displaced substantially westward and amounts significantly exceeding 4 mm did not occur in Iowa. Peak amounts did reach 7 mm in this simulation in north-central Missouri, but this was not supported by observations. The maximum precipitation amount in the 1200 UTC simulation more closely matched the observed maximum than the 0000 UTC simulation, but had a larger position error.

Next, a sensitivity test was done in which only mesonet surface data were added to the standard observations used in the 1200 UTC initialization. This procedure resulted in an improved initial surface analysis (figure not shown) with a deeper surface low (1010 mb compared with 1011 mb) and more realistically backed surface winds, but the changes disappeared quickly (by

the 3-h forecast) and there was no improvement in the simulation at later times (not shown).

A modification of this sensitivity test was done in which one artificial sounding was also input into the initialization to support the observed mesoscale surface low. The artificial sounding was produced by using the observed surface pressure in extreme northwestern Iowa at 1200 UTC and adjusting temperatures aloft using the hypsometric equation. The large-scale 1200 UTC height analyses aloft were assumed to be representative of the

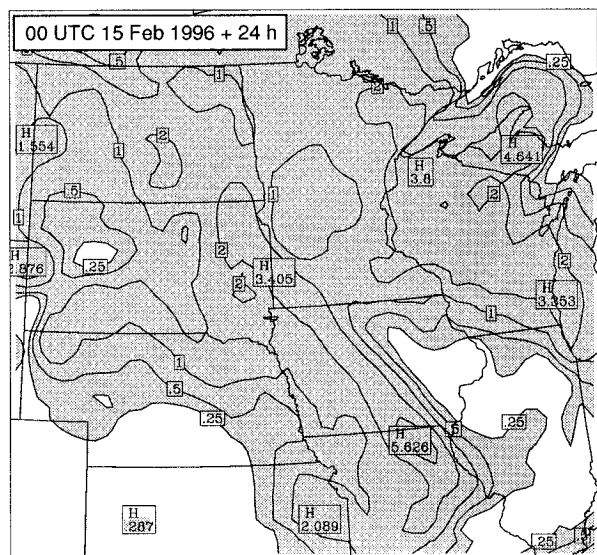


FIG. 13. Total accumulated precipitation for 24 h ending at 0000 UTC 16 February from the MM5 model with standard initial data. Contours for 0.25, 0.5, 1, 2, and 4 mm.

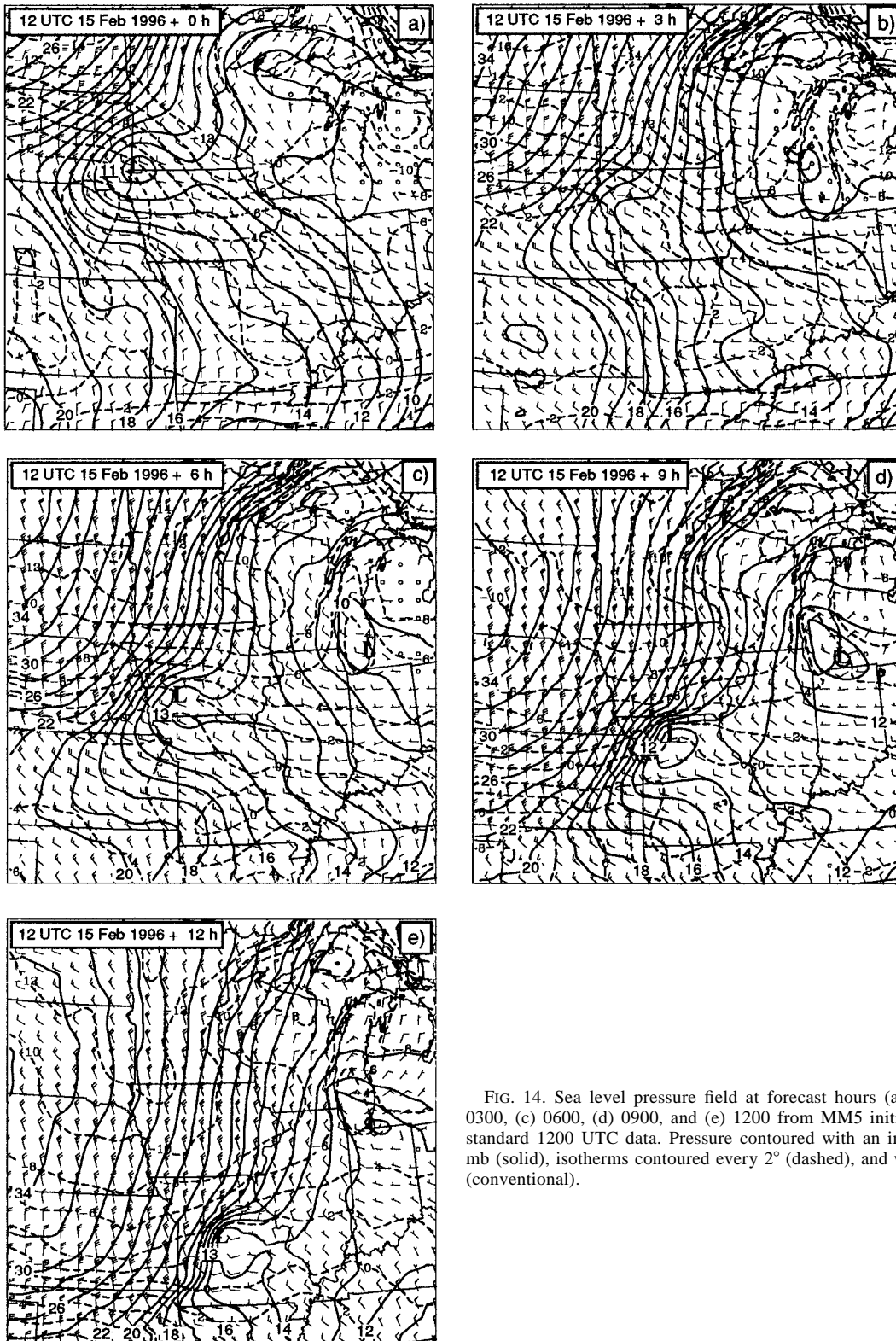


FIG. 14. Sea level pressure field at forecast hours (a) 0000, (b) 0300, (c) 0600, (d) 0900, and (e) 1200 from MM5 initialized with standard 1200 UTC data. Pressure contoured with an interval of 1 mb (solid), isotherms contoured every 2° (dashed), and winds barbs (conventional).

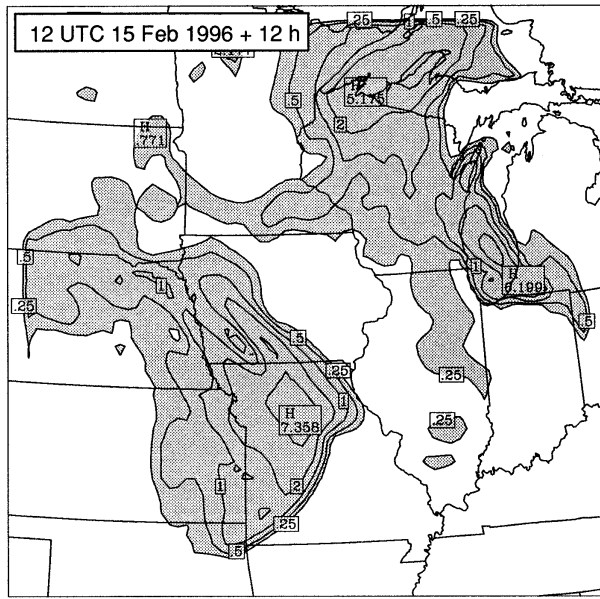


FIG. 15. Total accumulated precipitation for the 12 h ending at 0000 UTC February 16 from the MM5 model (1200 UTC initialization) with standard initial data. Contours of 0.25, 0.5, 1, 2, and 4 mm.

region, as it was assumed the mesoscale system was not significantly altering these fields at high levels. The temperatures and dewpoints that would justify a 1010-mb sea level pressure were then checked against nearby rawinsonde reports for consistency. The surface conditions at this point showed a nearly saturated environment, as heavy snow was falling. A nearly moist adiabatic profile was used as seen in the Omaha sounding (Fig. 6), with nearly saturated conditions up to around 850 mb. Winds were input into the sounding based on those observed by the Des Moines WSR-88D and the Slater profiler 4 h later when the center of the low passed by in a similar position relative to the site. The winds in the artificial sounding help to produce a deeper, though still shallow, layer of southwesterly flow.

Dramatic changes occur in the simulation using this artificial sounding to represent the mesoscale low environment. Figure 16 shows the sea level pressure pattern over the 1200 to 0000 UTC time period. The model does indicate a 1010-mb low in the initialization (Fig. 16a). Although model spinup again exerts a damping influence on the low in the first 3 h (Fig. 16b), the low is still distinct at 1500 UTC whereas it was difficult to discern in the simulation without mesoscale initial data (Fig. 14b). By 1800 UTC (Fig. 16c), an intense small-scale low with very tight pressure gradients is found in a location reasonably close to that observed. The central pressure of 1011 mb is 2 mb lower than that in the other 1200 UTC MM5 simulation. The 1011-mb low moves into Missouri by 2100 UTC (Fig. 16d) although the number of closed contours decreases. By 0000 UTC

(Fig. 16e), the low weakens slightly (to 1012 mb) as it moves southward.

Unlike all of the other simulations, a closed circulation develops in this simulation that is significant (Fig. 16). A rather substantial area of east winds develops ahead of the low in an area that takes on the appearance of a warm front (Figs. 16b,c). The closed circulation extends aloft a short distance, and some southerly component can be found through about 700 mb (figure not shown), as in observations from the Slater profiler.

The precipitation field is likewise dramatically improved (Fig. 17), with heavier precipitation farther north into Iowa. A surprisingly narrow stripe of enhanced precipitation matches rather well with observations. The peak value is still around 7 mm and it appears the most substantial changes occur in the first 9–12 h when improvement was most needed.

The marked changes in the simulation can best be seen in difference fields (Fig. 18), where values from the run without mesoscale data are subtracted from the run with mesoscale data and the bogus sounding. Sea level pressure in the mesolow was roughly 2 mb deeper in the run initialized with the added sounding (Fig. 18a). (A small eastward shift in low location also occurred but it was not large enough to significantly change this result.) The stronger low was associated with increased precipitation, with difference values exceeding 4 mm in one location (figure not shown). The most significant change occurred in the surface wind field where a much stronger circulation develops, with wind differences as large as 8 m s^{-1} . The low-level cyclonic circulation was absent in the original simulation without mesoscale data. This circulation increased warm advection at low levels, which would also help sustain a more intense cyclone.

The results from these numerical simulations suggest that both improved resolution within the model and initialization of higher-resolution surface data may fail to improve a model forecast of some mesoscale phenomena. The inclusion of mesoscale surface data in an initialization may improve the representation of the initial surface fields, but the model dynamics apparently adjust to the unaltered model atmosphere above the surface so that any initial improvement is quickly lost. However, with a small amount of effort, it appears the mesoscale surface data can be “linked” to the upper-level fields, and the resulting improvements in the forecast are substantial. The importance of adding mesoscale data aloft was further revealed in a test where the bogus sounding was used in initialization without the surface mesonet data. Results were almost unchanged from the run with the surface mesonet data, implying the greatest improvements are due to the mesoscale data aloft and not at the surface. It can be argued, however, that the surface mesonet data is critical for defining the location of the mesolow and placement of the bogus sounding.

To further investigate the significance of adding the bogus sounding in the initialization, other sensitivity tests were performed. In one set of simulations, the ver-

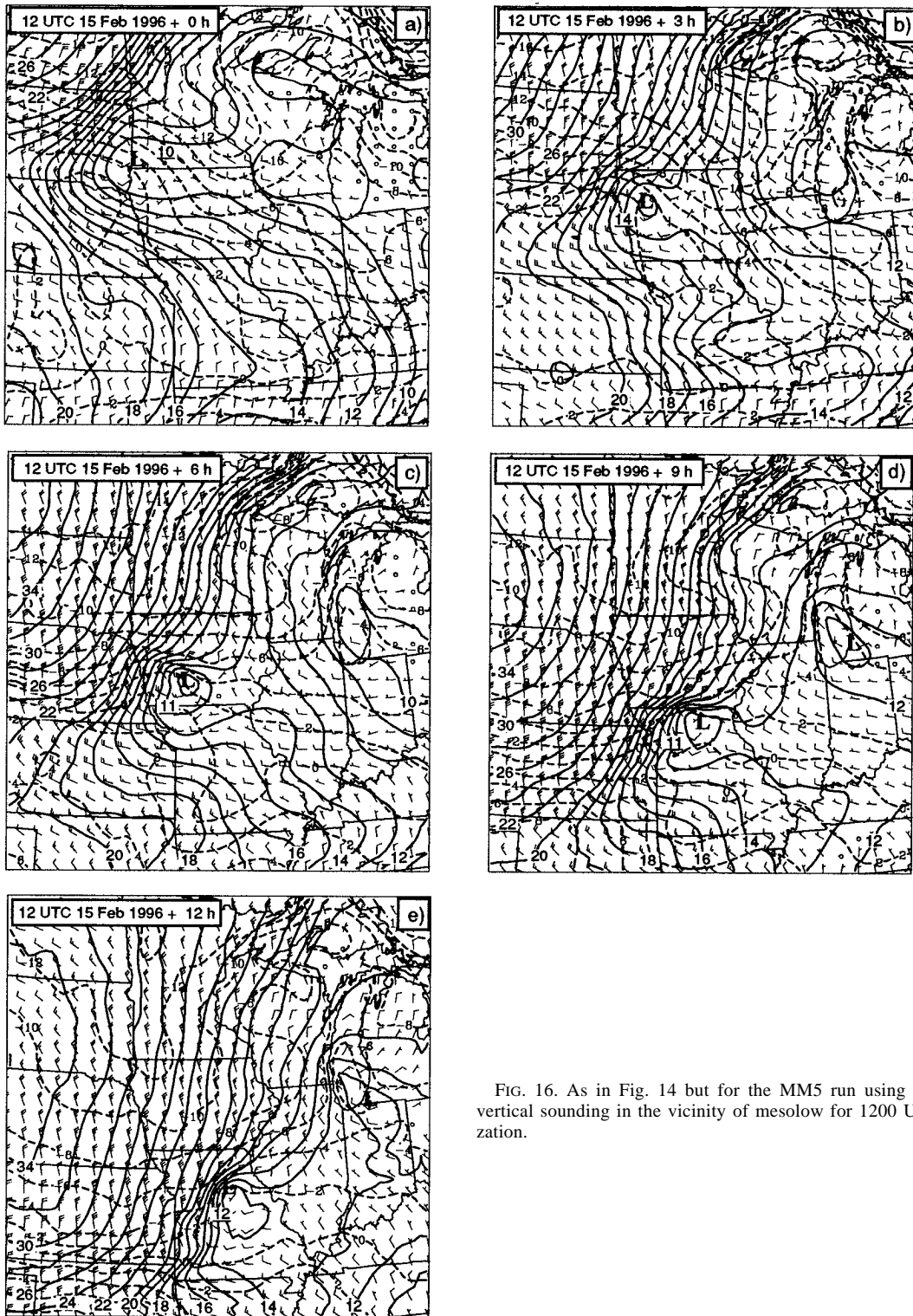


FIG. 16. As in Fig. 14 but for the MM5 run using an artificial vertical sounding in the vicinity of mesolow for 1200 UTC initialization.

tical resolution was improved by a factor of 2 to investigate whether the shallow nature of the disturbance was responsible for poor model performance. All three of the initial datasets described above were repeated

with the 1200 UTC initialization of the 45-layer model. Changes in the simulations were insignificant, in agreement with other studies showing that sensitivity to vertical resolution is relatively small compared with other

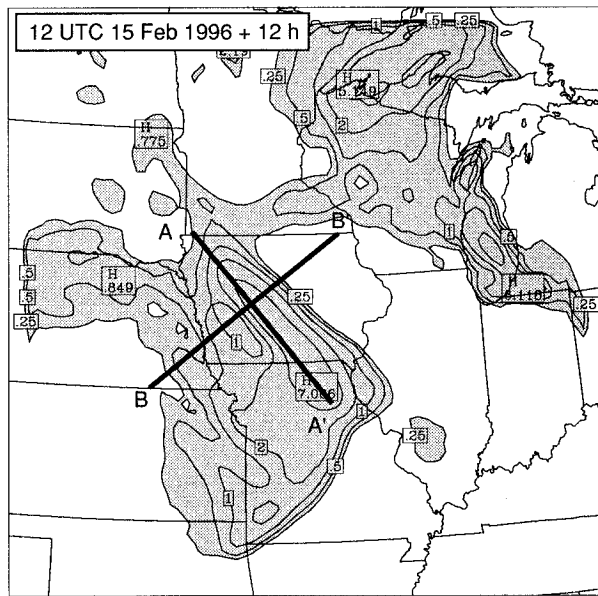


FIG. 17. Total accumulated precipitation for 12 h ending at 0000 UTC 16 February for the MM5 run initialized with mesonet surface data and an artificial sounding in the vicinity of the mesolow. Lines labeled AA' and BB' refer to cross sections shown in Figs. 19 and 23, respectively.

factors (Gyakum et al. 1996; Kuo and Low-Nam 1990; Wang and Seaman 1997).

Because fluxes of heat and moisture are important in oceanic polar lows, another sensitivity test was run in which all land south of 45°N was replaced by open water having temperatures similar to those off the western coast of the United States. This run used the same model configuration and initialization as the 0000 UTC runs discussed earlier. Despite the significant change in surface characteristics, changes in the simulation were minor.

Another test was performed by increasing horizontal resolution to 3.3 km to better resolve the system and the precipitation areas in particular. With this cloud-scale resolution, the weakening of the system due to spinup delays (evidenced in Fig. 16b) is significantly lessened, and the surface low is 2 mb deeper at 1500 UTC (figure not shown) than in the 20-km resolution simulation. Likewise, the band of heavier precipitation does extend farther northwest into northwestern Iowa. However, by 1800 UTC and at all later times, the simulations are not significantly different. Difference fields of sea level pressure (not shown) at 1800 UTC (model output minus observations) indicate that the addition of the extra sounding improves positive errors near the low by at least 1–2 mb. The increase in horizontal resolution from 20 to 3.3 km results in an improvement of 1 mb or less. All of the sensitivity tests demonstrate that the most significant improvement in the simulation of the system, by a substantial degree, occurs from the addition

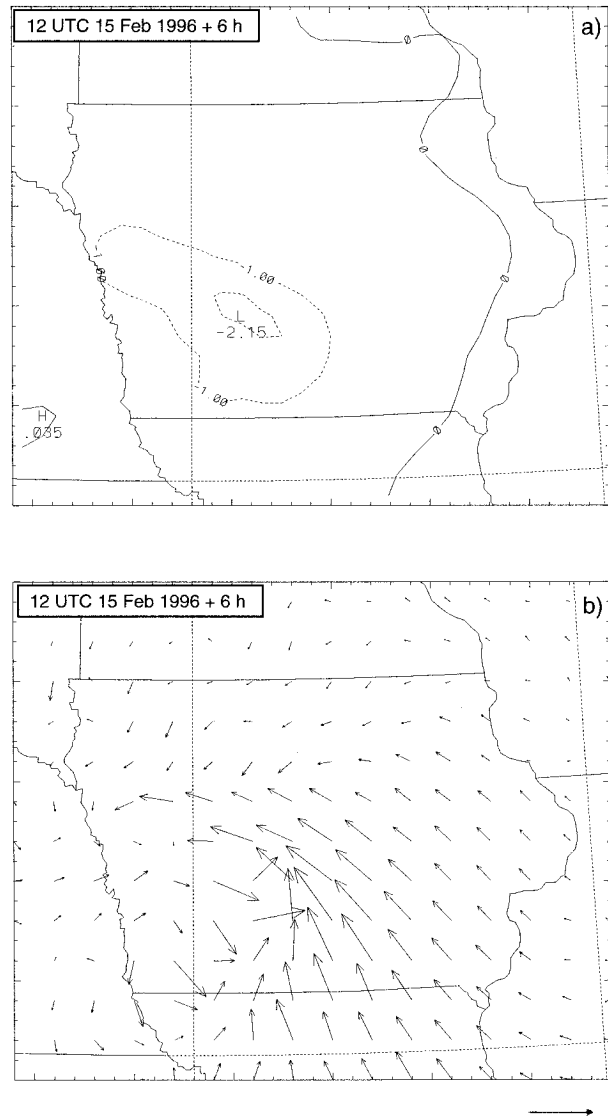


FIG. 18. Difference fields (mesonet and bogus sounding initialization minus standard initialization) of (a) sea level pressure and (b) lowest layer (40 m) winds from MM5 output valid at 1800 UTC 15 February. Pressure contours of 1 mb with reference wind vector ($m s^{-1}$) shown at lower right.

of upper-air data representative of conditions above the mesolow center during initialization.

The importance of proper initialization of mesoscale features for a warm-season case has been demonstrated by Stensrud and Fritsch (1994a; 1994b). Although some differences remain between the simulation and observations, and might be explained by parameterization deficiencies in cases of shallow cold-season convection, the results are encouraging and suggest that the inclusion of surface mesoscale data, in conjunction with upper-level modifications to physically account for the surface features, or the addition of actual upper-level observations on the mesoscale can significantly improve short-range mesoscale forecasting.

4. Discussion of forcing mechanisms

The observational data available from this case implied some similarities with both more common larger-scale baroclinic cyclones and smaller-scaled polar lows. The surface data, satellite and radar imagery all suggest a system with a roughly 200-km scale, possessing a tight low-level circulation and shallow convection. The system's spatial and temporal scales were truly mesoscale and unusual for a midlatitude wintertime system over land. However, the strong vorticity maximum aloft and pronounced baroclinicity at lower levels are common with most synoptic-scale cyclones. What explanation can be given for the small-scale, polar-low-like appearance of this system?

Thorough study of upper-level forcing mechanisms is complicated in this case because the small scale of the system and its timing and track between rawinsonde and wind profiler sites prevents a detailed analysis of upper-air data, which could allow a more substantial quantitative comparison of this system with polar lows. Fortunately, the 1200 UTC MM5 simulation making use of the mesonet data and the artificial sounding presents an evolution and movement of the system that agrees well with available observations, at least during its trek across Iowa. Therefore, it is reasonable to use the MM5 results, in lieu of a synoptic dataset (e.g., Keyser and Uccellini 1987). From the MM5 data, the driving mech-

anisms for this mesoscale low appear to be somewhat similar to those associated both with larger-scale baroclinic systems and with polar lows.

At high levels in this case, a pronounced potential vorticity anomaly could be found with values exceeding 2 PVU ($1 \text{ PVU} = 10^{-6} \text{ K kg}^{-1} \text{ m s}^{-1}$) extending downward nearly to 600 mb (Fig. 19). Grønås and Kvamstø (1995) have shown that as the depth between the tropopause (considered by them to be the 2-PVU surface) and the top of the convective boundary layer decreases, the potential for polar low development increases. The conceptual model of polar-low development put forth by Montgomery and Farrell (1992) in which a mobile upper trough induces surface cyclogenesis and is followed by a second stage of deepening due to diabatic processes may also be valid in the present case. While surface fluxes in this case were significantly smaller than for a typical oceanic polar-low case, the upper-level trough was very intense. Thus, development of a meso- β -scale cyclone was able to proceed. The mesolow followed a track just ahead of a pronounced tropopause fold (Fig. 20) with lowest surface pressure in the region of greatest change in tropopause height (cf. Fig. 20a with Fig. 3b and Fig. 20b with Fig. 3e).

The vorticity maximum aloft continued to track southeastward during the event (Fig. 21a) with strong cyclonic vorticity advection present over Iowa. Low-

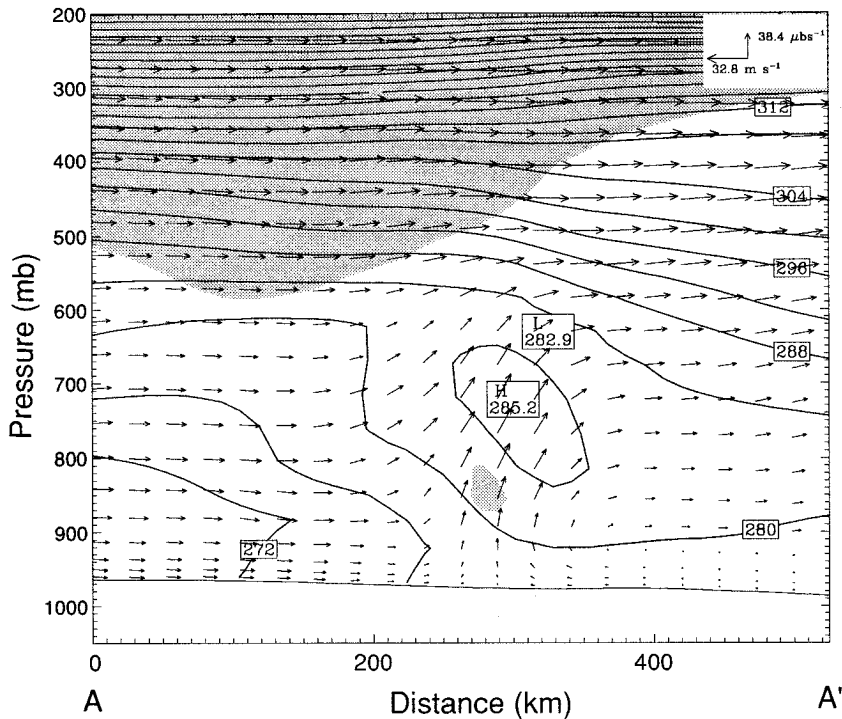


FIG. 19. Vertical cross section (AA' shown on Fig. 17) valid at 1800 UTC from MM5 output showing equivalent potential temperature (solid lines) and circulation vectors. Potential vorticity exceeding 2 PV units is shaded. Contours of potential temperature use an interval of 4 K, with scaling of vectors shown at upper right.

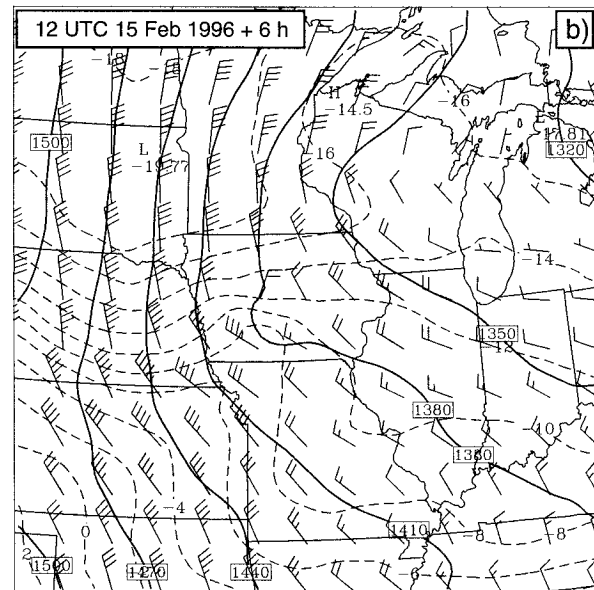
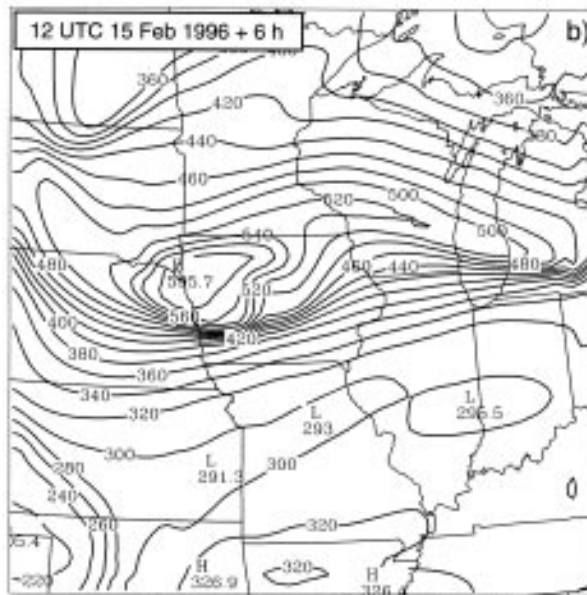
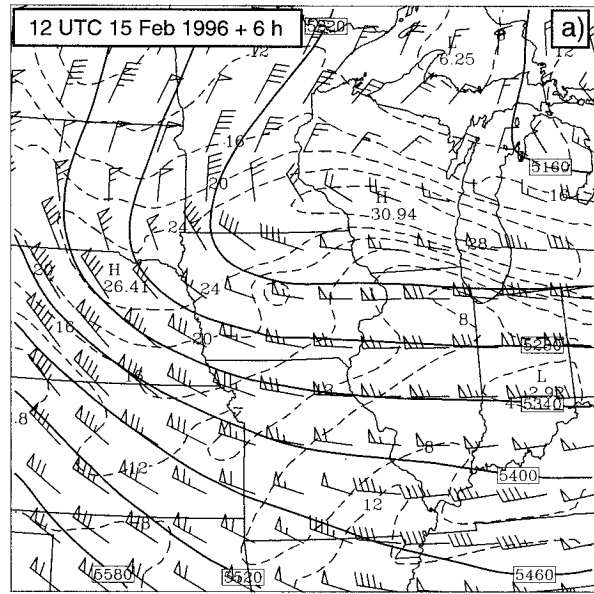
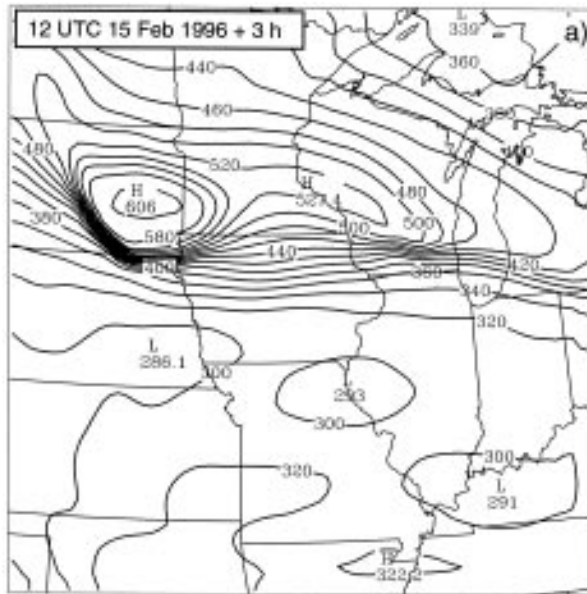


FIG. 20. Tropopause height (mb) at (a) 1500 UTC and (b) 1800 UTC.

FIG. 21. Simulated (a) 500-mb geopotential heights (solid), winds (barbs), and absolute vorticity (dashed); and (b) 850-mb geopotential heights (solid), winds (barbs), and temperatures (dashed) at 1800 UTC 15 February. Heights contoured every 30 m for 850-mb data and 60 m for 500-mb data. One full wind barb is 5 m s⁻¹. Temperature contoured every 2°C, and vorticity every 2 × 10⁻⁵ s⁻¹.

level warm advection did increase through 1800 UTC (Fig. 21b) with a narrow tongue of relatively warm air present near or just ahead of the surface mesolow. The warm advection weakened after this time.

The significant backing of winds that occurred in the lowest layers greatly increased the frontogenetical forcing near and just ahead of the low. The pronounced warm advection present in a small region contributed to the initial intensification of the low and its later maintenance. This is again implied by the fact that the MM5 simulations without mesoscale initialization failed to back the low-level winds, and the low pressure system

never became a distinct entity. Without substantial backing of the winds, positive temperature advection is lacking. As the forcing from the low-level warm advection resulted in upward motion, increased precipitation and a drop in surface pressures, a closed circulation was able to be maintained throughout the system's path across Iowa. The vertical motion field from MM5 valid at 1800 UTC (Fig. 22a) displays the comma shape that

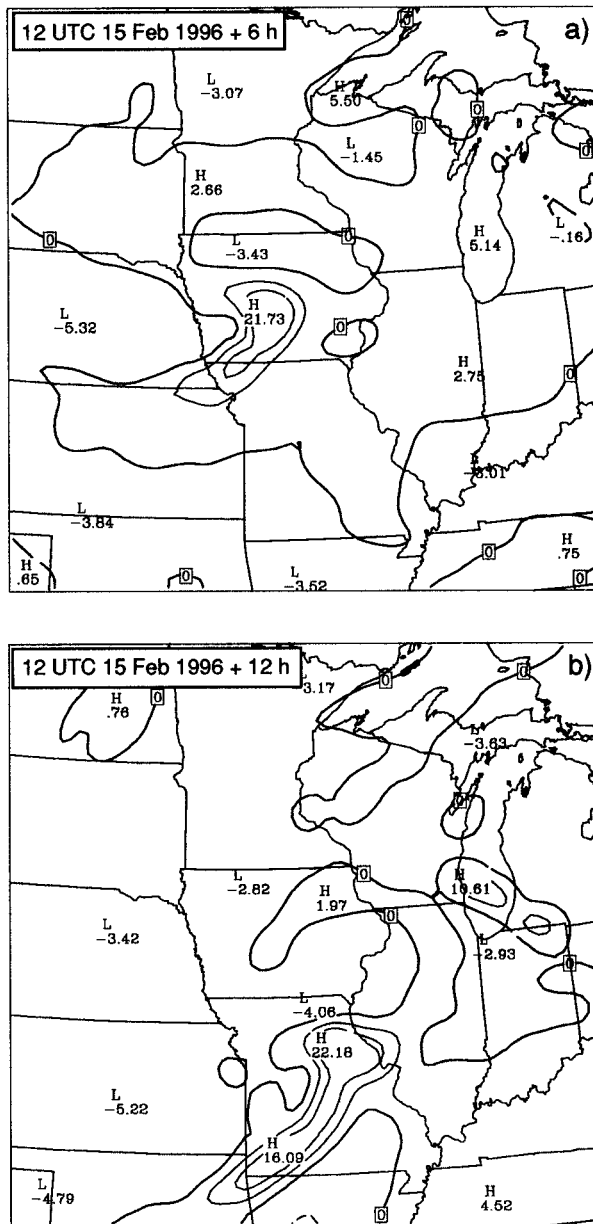


FIG. 22. Vertical velocity from MM5 data valid at (a) 1800 and (b) 0000 UTC. Contour interval is 7 cm s^{-1} .

was seen on both radar and satellite images at this time. Model soundings from this region near the mesolow at 1800 UTC show that the strong upward motion led to rapid cooling of the inversion layer, completely eliminating the inversion in a small region (figure not shown).

Also of note in the vertical motion field is the intensification of upward motion along the cold front as it moved through Missouri at 0000 UTC (Fig. 22b). As stated earlier, the precipitation band was broadest in Missouri due to the formation of a more organized band of precipitation along the front at that time. The strengthening of the frontal forcing and increase in pre-

cipitation ahead of it are well simulated by MM5. The low's small-scale structure, with warm advection east of the low center and a precipitation band north of an apparent warm front bears some similarity to the Bering Sea polar low described by Bresch et al. (1997) as well as a typical midlatitude cyclone. The strongest surface pressure gradient (and surface winds) was located to the west of the low center as is found in many polar lows (e.g., Shapiro et al. 1987; Bresch et al. 1997).

One of the forcing mechanisms believed to be important for polar lows that was obviously absent in this case is the strong flux of heat and moisture at low levels from the ocean surface. These fluxes help to sustain the instability that allows the convection found in polar lows. As shown in the Omaha sounding earlier (Fig. 6), some conditional instability was present in this case at low levels due to the relatively warm, moist air advecting from the southwest, and the cold temperatures at midlevels.

An analysis of moist potential vorticity also suggests that conditional symmetric instability (CSI) could occur in Iowa during this case (Fig. 23). CSI is possible when saturated conditions exist in the presence of negative moist potential vorticity. Such conditions are present over central Iowa at 1800 UTC.

Because shallow precipitating convection occurred during this case, an additional simulation was run in which latent heating was neglected in order to investigate the role that moist processes played in evolution of the system. Latent heat release has been shown to play an important role in the evolution of extratropical cyclones, particularly if it occurs near the center of lowest pressure (e.g., Danard 1964; Tracton 1973; Bosart 1981), although the scale involved is normally larger than that with this system. In this "dry" run, the mesolow intensity at 1800 UTC and 2100 UTC, as measured by the sea level pressure, was at least 1 mb weaker than in the run with full physics (adjusting for a small positive tendency in pressure over the whole domain). More importantly, a closed circulation at low levels was lacking, and winds were noticeably weaker. Warm advection was much weaker. The greatest impact of excluding latent heating can be seen in the vertical motion field where w at 1800 UTC (Fig. 24) is no longer organized near the mesolow and peak ascent is less than 7 cm s^{-1} compared with over 20 cm s^{-1} in the standard run. (Fig. 22a). By 0000 UTC, differences in the simulations are less significant, as it appears the larger-scale forcing mechanisms dominated over any influence of convection. As stated earlier, the cold front became more active by this time, accounting for a broader region of precipitation with a less concentrated core of heavier snow and rain.

Thus, the mesoscale cyclone on 15 February formed as an intense upper-level vorticity maximum, associated with a jet streak, propagated into a region of somewhat lower static stability. The strong inversion present across portions of the Midwest at around the 700-mb level on

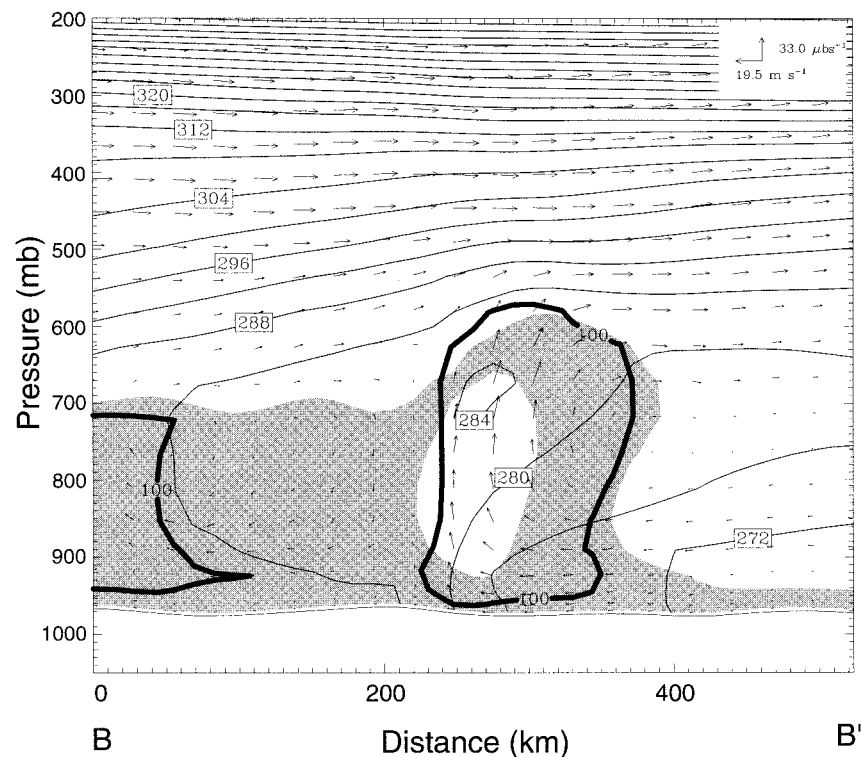


FIG. 23. Vertical cross section (BB' shown in Fig. 17) of equivalent potential temperature (solid lines) and circulation vectors, with negative moist potential vorticity shaded. Relative humidity values with respect to ice exceeding 100% are also outlined.

this day may have prevented the formation of a larger-scale system, in spite of unusually strong positive vorticity advection. Instead, only in the region of strongest forcing was upward motion able to significantly eliminate the inversion and allow the formation of deeper clouds, precipitation, and some convection. The release of latent heat in a concentrated region of relatively heavy precipitation apparently deepened the small-scale system enough to allow enhanced backing of low-level winds. This backing in the presence of a tight thermal gradient resulted in additional forcing from low-level warm advection in an unusually small area.

The forcing was able to maintain low enough surface pressures to produce a closed circulation during the track of the low across Iowa. The tight pressure gradient and intense cold advection behind the system allowed strong winds to occur at the surface, creating near-blizzard conditions in some areas. Unlike polar-low situations, surface fluxes of heat and moisture were not needed in this case since low-level static stability was already small. The lack of low-level fluxes of heat and moisture present in oceanic polar lows did, however, prevent the Iowa system from intensifying significantly, and convection therefore remained more shallow than that in the oceanic cases. Nonetheless, the development of the low in this case is quite similar to the potential vorticity paradigms put forth by Nordeng and Rasmussen (1992) and Rasmussen et al. (1992) for polar-low cases. As

with some polar-low cases, the larger-scale environment was not favorable for the formation of a longer-lived synoptic-scale cyclone, and a mesoscale system ensued.

5. Summary

A mesobeta-scale wintertime vortex moved across Iowa on 15 February 1996, producing extremely heavy short-duration snowfalls and near-blizzard conditions. Such an intense small-scale cyclone is unusual in mid-latitudes during the cold season, and the system exhibited some characteristics similar to a polar low. A potential vorticity maximum aloft was present, with PV exceeding 2 PVU extending down to about 600 mb. An eyelike feature was present in both satellite and radar imagery within the roughly 20-km-wide comma head of the system.

The mesolow was poorly forecasted by standard operational models, most likely due to its small size. In addition, some mesoscale simulations with the MM5 model were also unable to accurately depict the intensity and evolution of the system. Mesoscale surface data alone, added to the initialization, did not appreciably change the simulation. However, when the mesoscale feature at the surface was supplemented by one artificial sounding using the hypsometric equation and nearby observations, the simulation was dramatically improved. This suggests that even with likely limitations

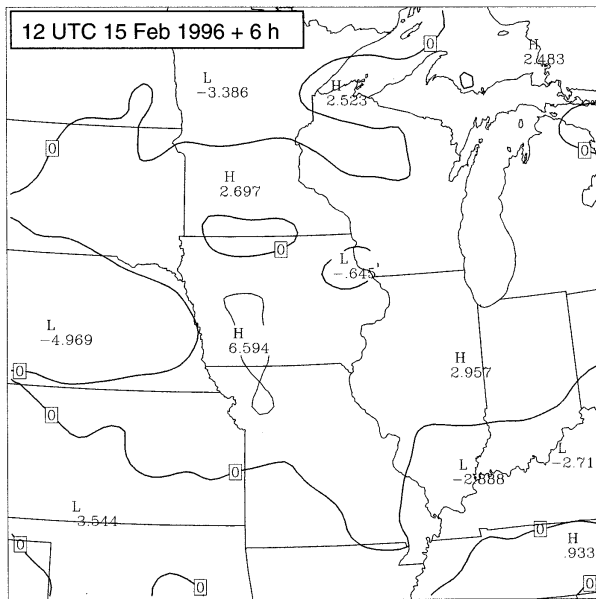


FIG. 24. Vertical velocity at 1800 UTC from MM5 data for the "dry" run where latent heating is neglected. Contour interval is 7 cm s^{-1} .

on the skill of convective parameterizations at accurately resolving shallow cold-season convection, substantial improvements are possible in mesoscale forecasting, simply by initializing with mesoscale data. It also suggests that increased horizontal resolution in numerical models may not result in improved short-range forecasts without a corresponding increase in the resolution of initial data or better use of available data within a variational assimilation system.

The Iowa AWOS mesonet was not only critical in obtaining necessary mesoscale observations for model initialization but was also invaluable in resolving the system's intensity and closed low-level circulation as it tracked across Iowa. Surface analyses done without the mesonet data showed a low pressure system 2 mb weaker and displaced 100 km to the east of the actual track. Interestingly, the analyses without mesonet data resemble some of the incorrect numerical guidance for the case. The addition of mesonet networks from various states whose data can be accessed by model users should be strongly encouraged. Also, the improved results obtained from the inclusion of one artificial sounding demonstrate the potential benefits of a mesoscale sounding network (Douglas and Stensrud 1996) and the potential benefits of using targeted observations (Snyder 1996).

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