SEVERE WEATHER

MESOANALYSIS OF SURFACE VARIABLES ASSOCIATED WITH THE SEVERE WEATHER OF 9-10 JULY 1980

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ABSTRACT

Meso-α scale regional analyses of selected surface variables are used to discuss the initiation and development of severe weather in Illinois and Indiana during the evening of 9/10 July 1980. This case illustrates the time evolution typical of severe weather produced in weakly baroclinic situations, and shows the utility of hourly regional objective surface analyses based on Service A teletype data as a diagnostic and (potential) forecast aid. Points of particular interest include the interaction of a lake breeze off Lake Michigan with a weak stationary frontal zone, and the development of what appears to be a strong isallobaric inflow wind vector into the advancing storm system.

1. INTRODUCTION

Miller (5) presents a summary of semi-empirical techniques developed during the period 1950-1960 for forecasting severe weather. The techniques emphasize use of analyses of the 3-hourly synoptic surface observations, and particularly the 12-hourly upper air data. They focus on subjective identification of critical patterns in the synoptic-scale fields of meteorological variables, and on the use of easily computed stability indices. Experience has shown (6) that the types of techniques described by Miller allow the forecaster to accurately predict many outbreaks of severe weather.

Recently, Maddox and Doswell (7) have noted that these traditional forecast methods are most effective in predicting the occurrence of severe convection in the strongly baroclinic situations encountered in the spring and early summer. The mid-tropospheric, synoptic scale forcing that occurs in such situations often results in the convection being organized into large squall lines. Considering the spatial and temporal scales characteristic of the forcing processes, the synoptic surface and upper air data are sufficient to allow resolution of the forcing phenomena. Hence it is not surprising that careful analysis and monitoring of macro-β and meso-α scale features (for definitions, see Table I) can provide valuable guidance for identifying the likelihood and the most favorable regions for the occurrence of severe weather.

However, as also discussed by Maddox and Doswell, the traditional techniques are not particularly effective in weakly baroclinic situations. Such situations are common in the upper Midwest in late summer and fall. Because the mid-tropospheric synoptic scale forcing is weak, the convection that occurs in such situations tends to be much more loosely organized on an area basis, often in the form of convective clusters. It appears to be triggered by meso-β scale phenomena not readily apparent in standard synoptic analyses. These triggering phenomena are typically confined to the lower troposphere, and may include highly localized forcing tied to regional topography and/or small, rapidly propagating waves on frontal boundaries.

To adequately treat the onset of convection and its subsequent development in these weakly baroclinic situations requires analysis and forecast techniques different from those discussed by Miller. The forecaster must focus on indentifying and then predicting the evolution of meso-β scale events which control the initiation and growth of the convective elements. While the synoptic scale analyses of surface and upper air data are still valuable, additional regional analyses with much greater spatial and temporal resolution are required. At present, the only routinely available data source which even begins to approach the required resolution is the hourly aviation reports provided over the Service A teletype network. Considering the amount of data and the time frame within which it is to be analyzed, an automated objective analysis scheme is highly desirable.

Here we describe a particularly interesting outbreak of severe weather that occurred over northern Illinois and Indiana on 9/10 July 1980. The synoptic setting was a weakly baroclinic type frequently encountered in the upper Midwest during the June to September period. This case was chosen for detailed analysis both to illustrate the time evolution of severe weather produced in such situations, and to show the utility of hourly regional objective surface analyses based on Service A teletype data as a diagnostic and (potential) forecast aid. Interest is further heightened by the fact that one of only five F4 intensity tornadoes that occurred during 1980 was produced in this outbreak (8).

Similar case studies have been presented by Ruthi and Kimpel (9) and others for the lower Great Plains region. The resolution of meso-β phenomena in such studies has been limited by the relatively large distances between observing stations. Further, the Great Plains work has tended to focus on phenomena peculiar to that region (e.g., the dry line of western and central Texas and Oklahoma). In the present study, the relatively greater density of stations in the upper Midwest improves the quality of regional surface analyses, and may allow the identification of meso-β scale forcing processes peculiar to this region.

In the present paper, objectively analyzed surface fields of equivalent potential temperature, velocity convergence, and temperature and moisture advection are used to identify areas conducive to strong convective development. Using the 9/10 July 1980 case as an example, the relevance of these and other parameters to the initiation and development of severe weather in the Upper Midwest is discussed. The conclusions of this study re-emphasize the points made by Maddox and Doswell concerning the importance of considering the surface advection of temperature and moisture in short time frames. The interaction of the lake breeze circulation over Lake Michigan (a meso-β scale phenomenon) with a frontal boundary (meso-α scale) is clearly shown to play an important role in the development of severe convection in the Upper Midwest. Furthermore, the onset of an isallobaric wind component into the region of convection initially triggered by a frontal wave appears to play an important role in the intensification of this convection, which ultimately produces an F4 intensity tornado.

Table I

Spatial and Temporal Scales after Orlanski (10)

Name	Space Scale	Time Scale	Example
macro-β	2000 to 10000 km	5 to 30 days	baroclinic waves
meso-α	200 to 2000 km	1 to 5 days	frontal zone
meso-β	20 to 200 km	1 hr to 1 day	squall line
meso-γ	2 to 20 km	30 min. to 5 hrs.	thunder-storms

Table II

Summary of Data Available for the Period 1500-0200Z 9/10 July 1980

Date	Time	T	T_d	P	Wind S/D (Calm)	Total
		Number of Individual Reports				
9 July	15Z	112	106	123	123 (10)	123
	18Z	110	106	123	123 (5)	123
	21Z	108	105	119	119 (8)	119
10 July	00Z	107	103	120	120 (7)	120
	01Z	110	104	124	124 (15)	124
	02Z	106	101	117	117 (21)	117

2. OBJECTIVE ANALYSIS SCHEME

PROAM (the Purdue Regional Objective Analysis of the Mesoscale) is an objective analysis scheme which follows in outline several similar schemes developed at the National Severe Storms Laboratory and Oklahoma University by Barnes (11 and 12); Inman (13); and Ruthi (14). The algorithm chosen is somewhat simplistic so as to reduce the computation time and allow PROAM to be run in an operational mode.

Typically, objectively analyzed and derived contour fields are available 10 to 15 minutes after data input.

Shown in Fig. 1 are the PROAM analysis region for the current study and the stations from which surface meteorological data are obtained. The inner box represents the grid area (i.e., the region over which the objective analysis is performed). The area between the inner box and the outer boundary contains the border stations. Data from these stations are necessary for a smooth, complete analysis.

From Fig. 1 it can be seen that the density of possible reporting stations is quite good. For a typical data set, average minimum station spacing is approximately 70 km. A few data sparse regions do exist. These areas include southwest Indiana, central Kentucky and southern Missouri. Nearly 100 data stations are located within the analysis region, and approximately 90 border stations surround this area. In actual analyses, practical limitations allow data from approximately one-half to three-quarters of the stations to be utilized. (For the actual number of observations used at a given analysis time for this study, see Table II.)

Analyses are performed on a polar stereographic map projection true at 60°N, having a scale factor of 1:10,000,000. On the map a 21 x 21 square grid is centered at 40.48° N, 88.93° W, just northwest of Decatur, IL. The axes of the grid are oriented north-south and east-west. The grid spacing is equivalent to 44.45 km on the image plane or 39.28 km on the earth at the center of the grid.

Input data consist of the surface reports of temperature, dewpoint temperature, wind speed/direction, and altimeter settings as determined from the hourly teletype reports. These data are visually scanned to check for erroneous values. Use is also made of incomplete observations from stations which do not report all four of the above quantities.

The weighting scheme used to interpolate grid point values from station values was developed by Barnes (11, 12) and modified by Inman's anisotropic weighting function (13). Despite its simplicity, this scheme has the ability to resolve features well after just one pass through the data (9).

The interpolation of a value at a grid point from values of surrounding stations was determined by the following expression:

$$G_{ij} = \frac{\sum_{k=1}^{n} W_{ijk} Z_k}{\sum_{k=1}^{n} W_{ijk}} \qquad (1)$$

where G_{ij} is the interpolated value at the grid point (i, j), W_{ijk} is the weight assigned by the grid point to the value at station k, Z_k is the value of the variable at station k, and n is the number of stations influencing the value G_{ij}. After searching the area within a defined radius, a check is made to insure that at least two data values from surrounding stations influence the interpolated grid point value. Otherwise, the radius of influence is increased and the above equation re-evaluated. This procedure provides for a smooth analysis, free from zero or first order discontinuities which would otherwise be a consequence of the interpolation scheme.

Stations outside of the grid point radius of influence have no effect upon the grid value. Inside this radius the weight function is defined as

$$W_{ijk} = \exp\left[\frac{-D^2_{ijk}}{\alpha\,(1 + \beta_k \cos^2 \phi_{ijk})}\right] \qquad (2)$$

where D_{ijk} is the distance between station k and the (i,j) grid point, α is an arbitrary filter parameter, β_k is the anisotropic wind weighting parameter, and ϕ_{ijk} is the angle between the vector from the (i,j) grid point and the reported wind velocity vector at the station k.

The parameter β_k represents a normalized wind and is defined as

$$\beta_k = \frac{V_k}{0.5\, V_{max}} \qquad (3)$$

where V_k is the wind speed reported at station k and V_{max} is the maximum reported wind speed. Obviously β_k is maximized where wind speeds are large, with the largest value that β_k can attain being two.

It is apparent from Eq. (2) that the influence a reporting station has upon the interpolated value at a grid point decreases rapidly as the distance between the two points increases. The anisotropic factor ($\beta_k \cos^2 \phi_{ijk}$) gives greater weight to stations directly upwind or downwind from the grid point than to those positioned in a crosswind direction. This term attempts to simulate the advective nature of the atmosphere.

The value of the filter parameter, α, determines the amount of smoothing produced by the interpolation process. Determination of an appropriate value of α is dependent upon the wavelength of the smallest resolvable feature obtainable from the data, which in turn is dependent upon the grid and station spacing. The response function R_f (which determines what percentage of the amplitude of a disturbance with a given wavelength is retained by the filter, with β set equal to zero, has been shown by Barnes (11) to be

$$R_f = \exp\left(-\frac{\alpha\pi^2}{\lambda^2}\right) \qquad (4)$$

where λ is the wavelength of interest.

Barnes (11) has also shown that erroneous data can create disturbances with wavelengths less than twice the grid spacing. Since the grid cannot resolve these waves, they are aliased to longer wavelengths. The grid spacing for the studies presented here is 44.45 km. Therefore, disturbances with wavelengths less than 88.9 km should be suppressed. The value of α used in this study was 0.4 cm^2. This value effectively damps wavelengths less than 100 km. From this it can be inferred that some useful information may have been filtered out. However, this value of α is deemed appropriate since there is good continuity between analysis times for most features and also the objectively analyzed fields closely match the subjectively analyzed fields.

In addition to analyzing the raw data, PROAM also computes derived quantities such as vorticity and divergence using center-differencing. Equivalent potential temperature θ_e was computed using a standard subroutine (15).

3. SYNOPTIC SETTING

During the week of 7-11 July 1980, a stationary front extended from central Iowa, through northern Illinois and central Indiana, into southern Ohio. On 9 July 1980, the synoptic surface analyses showed strong gradients of temperature and moisture across this frontal zone, with these gradients being particularly strong in the section stretching from north-central Illinois into central Ohio. The flow aloft at 00Z 10 July 1980 was characterized by anticyclonic curvature. A weak jet was present from central Illinois into Ohio; otherwise wind speeds were rather light. The 850 mb synoptic analysis also indicated the presence of abundant low level moisture along and to the south of the frontal zone. Stability analyses at 00Z revealed a large area of potentially unstable air across much of the region. In summary, the upper air environment would have been considered only moderately favorable for convective development according to Miller's criteria.

The surface frontal zone was continually perturbed by a series of meso-β scale waves that sequentially traveled eastward along the frontal boundary. As each of these waves moved eastward, one or more areas of thunderstorms were produced. As shown in Fig. 2 at 1500Z (0900 CST) on 9 July 1980, two such waves were present in the analysis region. The leading wave, shown centered on the Indiana-Ohio border, was relatively weak (central pressure = 1014 mb), but was sufficient to trigger an extensive area of strong thunderstorms over central and western Ohio shortly after 1500Z. These moved rapidly southeastward into West Virginia.

The second, slightly deeper wave (central pressure = 1009 mb) was moving over south central Iowa into the analysis region. This small wave apparent mainly in the surface wind field, moved into central Illinois during the period of primary interest here, 1500Z 9 July 1980 to 0300Z 10 July 1980. Two areas of convection were associated with this wave. The first consisted of a large area of showers and thunderstorms stretching from eastern Iowa to southwest lower Michigan (see Fig. 3). This convective area was the remains of a complex of thunderstorms that had been active during the previous day, and which had weakened and moved from the west into the analysis region during the night. This first area of convection continued to move eastward at 11 ms^{-1}, decreasing in intensity. South of the front, surface reports indicated broken to overcast high and middle level cloudiness - therefore, early in the analysis period differential heating was acting to increase the temperature contrast across the frontal zone.

By 2035Z (Fig. 4) only portions of central and northern Indiana were still experiencing precipitation from this first area; during the following three hours, it continued to move eastward into Ohio and to further dissipate. By 2335Z (Fig 5), there were no echoes reported over northern Illinois and northwestern Indiana. The western sub-synoptic (meso-β) wave had moved eastward and was now centered over northwest Illinois.

Shortly after 2335Z, new cells in a second area of convection associated with this wave began to develop rapidly in northeast Illinois. By 0103Z, it covered a large portion of central Indiana. The F4

Rushville, Indiana tornado occurred approximately one hour later at 0235Z (16).

4. INITIATION AND DEVELOPMENT OF INTENSE CONVECTION

This section presents an investigation of the initiation and development of intense convection during the period 1500Z (9 July 80) to 0300Z (10 July) over northern Illinois and central Indiana. While there was convective activity somewhere within this area of interest throughout the period, the focus here will be on the convective system which eventually produced the F4 intensity tornado over Rushville, IN. The period under investigation can be conveniently subdivided into an initiation stage (15-00Z) and an intensification stage (00-03Z). The following discussion will examine the important meso-ß scale features associated with these stages in the life cycle of this particular system.

a. Initiation Stage

The initiation of convection is generally associated with low level convergence of warm, moist air. Consequently, it was anticipated that analyzed fields of equivalent potential temperature (θ_e) should provide important clues for locating areas of potential convective activity. Ruthi and Kimpel (9) have shown that an area with a strong gradient in the (θ_e) field is conducive to convective development. Fig. 6 shows the development of the field from 1500 to 0000Z. At 1500Z a strong gradient in (θ_e) existed over central Ohio and Indiana. This strong gradient corresponds well with the position of the stationary front (Fig. 2). During the afternoon (θ_e) values increased due to daytime surface heating. Furthermore, advection of warm, moist air east of the meso-ß scale low over Iowa produced a maximum in the (θ_e) field over central Illinois by 2100Z. A trough in the (θ_e) field had developed over Lake Michigan, reflecting the effect of the cooler surface temperatures over the water body relative to those of the surrounding land. These effects resulted in the intensification of the (θ_e) gradient over northeast Illinois. The (θ_e) isopleths were also reoriented from west-east at 1500Z to northwest-southeast at 2100Z due to the circulations about the meso-ß scale lows over Iowa and Ohio. The intensification of the (θ_e) gradient over Illinois continued through 0000Z, as the maximum over central Illinois and the minimum over Lake Michigan both strengthened.

Strong gradients in (θ_e) alone generally are not sufficient to initiate convection; however low level convergence can greatly assist this process. Convergence acts to concentrate the gradient as well as force vertical motions which lift warm, moist air upward. At 1500Z (Fig. 7) strong divergence (negative isopleths) over northern Illinois and Indiana is associated with outflow from thunderstorms (Fig. 3). The area of convergence (positive isopleths) corresponds with the frontal zone that extends from southern Iowa to central Ohio. During the afternoon low level convergence increased, and by 2100Z there was convergence throughout most of Illinois. This area of convergence is associated with the advancement of the meso-ß scale wave from central Iowa. Divergence is evident over Lake Michigan.

It becomes apparent that Lake Michigan plays a significant role in altering the thermal and circulation patterns in this region, which in this case, was instrumental in the development of convection. Recall the development of the trough in the θ_e field during the early afternoon hours (Fig. 6). Due to differential heating the water body is cooler than the surrounding land mass; consequently a lake breeze is induced. The advection of the cooler and moister air from the lake intensifies the θ_e gradient in northeastern Illinois. Furthermore, the combination of the northeasterly flow diverging from the lake and the southwesterly flow advancing from central Illinois acts to produce a meso-ß scale vortex by 2100Z over northeastern Illinois (Fig. 8) along the stationary front.

There was evidence of convection along the stationary front at several times throughout this period. The composite Radar Summary Chart at 1435Z (Fig. 3) indicates showers and thundershowers over central Ohio extending southeastward into West Virginia. More intense convection was observed ahead of the wave in Iowa, with maximum tops of 13740 m (45,000 ft), located over northwest Illinois and northeast Indiana. This activity moved to the east and weakened during the afternoon. By 2335Z (Fig. 5), however, no echoes were being reported by the Marseilles', IL radar over northern Illinois or northwest Indiana. A severe thunderstorm watch had been issued at 1930Z for an area extending from eastern Iowa to central Indiana (valid until 0300Z). Another watch was issued at 2105Z which included central and southeast Indiana. Both of these watch areas lie along the stationary front and their issuance appears to have been motivated by the movement of the meso-ß scale wave into an area of a potentially unstable surface layer. Shortly after 2335Z, Marseilles, IL radar noted the first convective echoes (denoted by the X in Fig. 5) near

Danville, IL. It should not be surprising that this region in east-central Illinois would be the area of initial convection. An examination of the surface flow field (Fig. 9) shows a line of confluence extending from a closed circulation near Marseilles southeastward to Danville, then curving to the southwest. Furthermore, this is also the area of maximum gradient in θ_e.

b. Intensification

The period between 0000Z and 0300Z was marked by the intensification of the convective activity that began in east-central Illinois. This convective development culminated in an F4 intensity tornado which occurred at approximately 0235Z at Rushville, IN. There appears to be several subsynoptic features which occurred just prior to the development of the single, intense tornadic event. (It should be noted that the data available do not allow one to resolve features on the order of the thunderstorm on meso γ-scale (2-20 km); however, a detailed analysis of the region within which the severe weather occurred is possible).

An indicator for delineating regions of potentially vigorous convective development is the level of the lifting condensation level. One generally expects vigorous convection in areas of warm, moist air where dew point temperatures are high and temperature - dew point depressions are low. Pettersen (17) has shown that the lifting condensation level (LCL) for a convectively mixed layer can be approximated using surface data by $K (T - T_D)$, where K is a constant. Livingston and Darkow (17) have suggested a modification to this expression, $T_{-D} (T - T_D)$, called the modified lifting condensation level (MLCL), to better incorporate the effect of low level moisture as reflected by high dew point temperatures. Higher values of MLCL indicate both a low lifting condensation level and high moisture content, both features being conducive to convective intensification. Livingston and Darkow (18) have shown this parameter to be quite distinctive in areas a few hours prior to tornado activity.

In this particular case values of MLCL were very useful in denoting the area of convective intensification. MLCL values during the morning (Fig. 10a) range from 8.2° on the Indiana-Illniois border to 19.7°C over the Iowa-Wisconsin border to a maximum of 21.7°C on the Indiana-Ohio boundary. By 0000Z a closed center of MLCL values (Fig. 10b) exceeding 18°C had developed over western Indiana. The storm which originated over east-central Illinois rapidly intensified as it moved eastward into Indiana. (It should be noted that the highest values of MLCL located over the Iowa-Illinois-Wisconsin borders did not produce convective activity, probably due to the lack of sufficient forcing. Convergence values are small and positive (and in some cases, even negative) in this region.

Another feature of interest is found in the u-component of the wind field. The surface flow pattern (Fig. 9) at 0000Z indicates southwesterly flow throughout the southern portion of the domain, consequently the u-component was positive (Fig. 11). By 0200Z an area of easterly flow ($u < 0$) had developed over southwest Ohio, which intensified and moved westward into Indiana. This component of the subsynoptic flow resulted in the advection of warm, moist air into the storm complex advancing southeastward across central Indiana. An examination of surface wind reports from Dayton, OH (Table III) further exemplified this change in the low level winds. Wind speeds at Dayton increased over the 0000Z to 0200Z periods, and there was a sharp backing in the wind direction from southeasterly to easterly. Such a shift in the wind field resulted in the formation of a strong wind vector into the region of convective development.

Time (Z)	Direction (°)	Speed (ms^{-1})
0000	140	2.1
0100	90	3.6
0200	90	4.1
0300	190	3.6

Table III
Hourly Surface Wind Reports from Dayton, OH for the Period 0000Z - 0300Z 10 July 1980

What was the mechanism responsible for the formation of the inflow wind vector and what role did it play in the development of the intense convection? Recall that at 0000Z the wind was primarily from the south in east-central Indiana. The period from 2100-0000Z was characterized by falling pressure tendencies throughout central Indiana (Fig. 12). One source of change in the wind field could be an isallobaric acceleration. Saucier (19) has suggested that the isallobaric wind can be a major contributor to ageostrophic (hence convergent) flow, noting that the isallobaric wind is directed along the gradient of the isallobars. Such an acceleration in this situation would tend to back the southerly winds to a more easterly direction, thereby producing an inflow toward the developing storm. Frictional effects would also contribute to the ageostrophic component of the wind, thereby producing a similar backing in the wind direction.

As the wind switches from southerly to easterly, there is increasing convergence into eastern Indiana, resulting in the advection of warm, moist air into the area. This can be seen by comparing the field of equivalent potential temperature convergence at 0000Z to 0200Z (Fig. 13). The increase in the values of $-\nabla \cdot \vec{V}\theta_e$ reflects the effects of both advection and convergence on the thermal and moisture fields. The enhancement of both fields results in increased buoyancy in this area, which, in turn, intensifies the convective process. This intensification is evidenced by an examination of the radar summary chart for 0235Z (Fig. 14), where maximum tops reach 18,320 m (60,000 ft) over central Indiana. Futhermore, an F4 intensity tornado was reported in Rush County, IN at 0235Z (20).

Tegtmeier (21) has reported similar developments of intense convective activity over Oklahoma. He noted the development of an inflow vector in regions east of meso-ß scale low pressure systems generally induced the most intense convection, and often it was associated with tornado formation. Consequently, this development of the inflow wind vector in the meso-ß scale flow field may offer a significant feature in identifying regions where intense convection will occur.

5. CONCLUSIONS

A simple objective scheme, PROAM, has been implemented for the analysis of hourly surface data from the Service A teletype data, producing gridded fields of both measured and computed variables. This scheme has been used as an aid in identifying meso-ß scale areas of potential convective development in weakly baroclinic systems in the Upper Midwest.

This application has been illustrated through presentation of a case study of the development of intense convection over the Midwest on 9/10 July 1980. The analysis of equivalent potential temperature and of the convergence of the wind, thermal, and moisture fields are shown to provide important clues for identifying areas of potential convective development within this weakly baroclinic system 2-4 hours in advance of the occurrence of severe weather. Furthermore, the circulations produced by the lake breeze off Lake Michigan have been shown to play an important role in adjusting the regional circulation and thermal patterns. This adjustment and accompanying interaction with a weak stationary frontal system resulted in the development of locally sharp gradients in the thermal and moisture fields that effected the formation of strong convection activity.

Later the loosely organized convective system underwent significant intensification as the result of the formation of an inflow wind vector into the advancing system. This inflow wind appears to be the result of an isallobaric wind component and perhaps frictional effects. The inflowing air further enhanced the buoyancy in the area due to the advection of warm, moist air. The convection ultimately produced an F4 intensity tornado over Rush County, IN.

In summary, it appears that carefully interpreted objective analysis of surface data on a meso-α scale can be important diagnostic and short-term forecasting tools for detecting areas of potential convective development, especially in weakly baroclinic situations.

6. ACKNOWLEDGMENTS

Ms. Tanya L. Care provided good service in typing and assembling the manuscript. The cooperation of personnel at the NCC EDS, Asheville, NC, in obtaining data from several stations is also recognized. A part of this work was supported by the National Science Foundation under Grant No. ATM 80-03403.

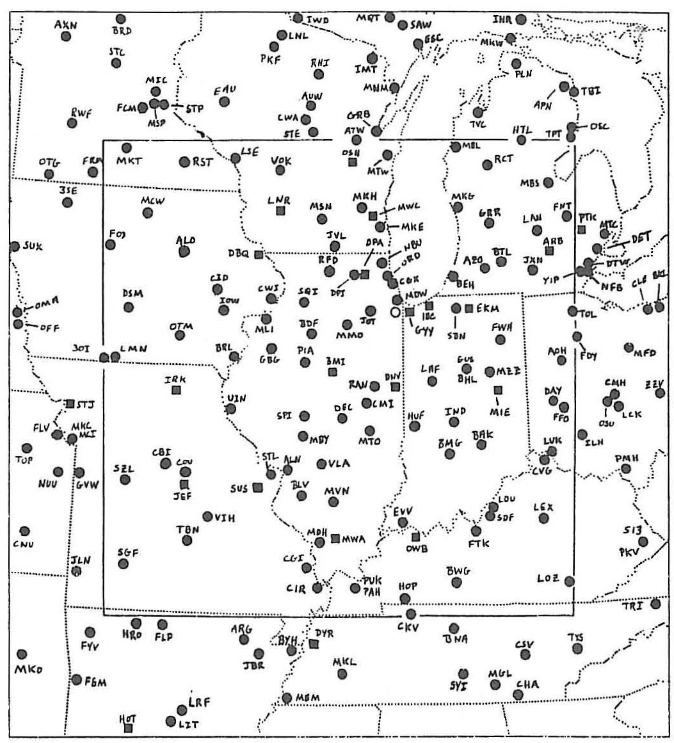


Figure 1. PROAM analysis region and reporting surface observation stations. The analysis region is outlined by the inner box. Stations denoted by a circle routinely report every hour; those denoted by a square report on a less frequent basis. (Note: since July 1980, some of these stations have been closed.)

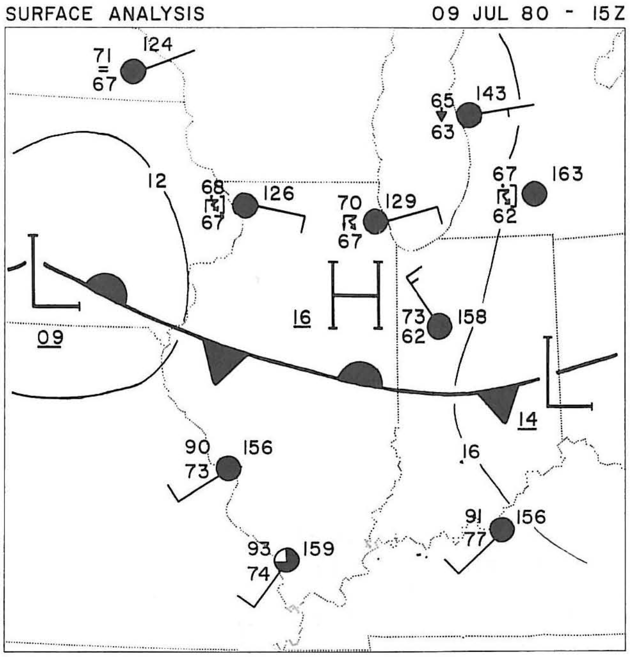


Figure 2. Regional surface analysis for 1500Z 9 July 1980 as extracted from the NMC synoptic analysis for this time. (Station models and pressure analysis follow standard NMC convections.)

Figure 3. Reproduction of NMC composite radar summary chart for 1435Z 9 July 1980 (For explanation of symbols see NWS, 1980).

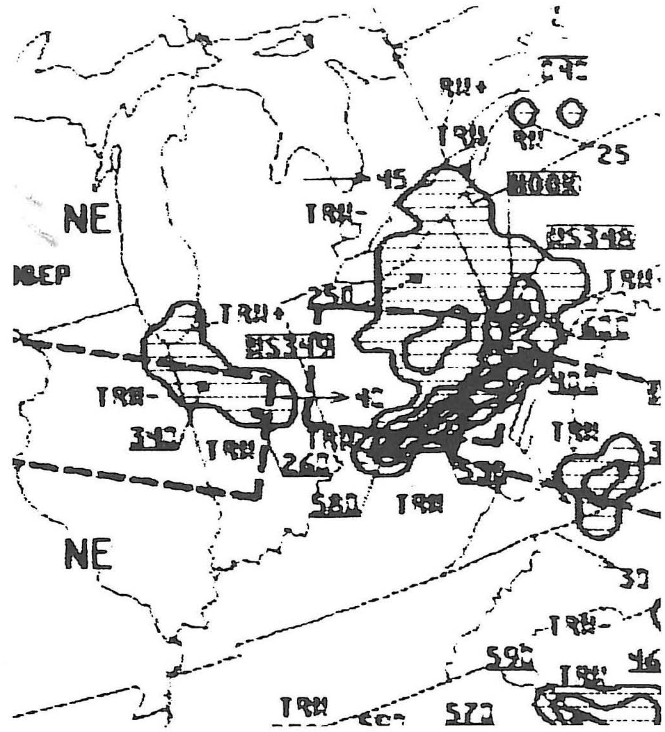
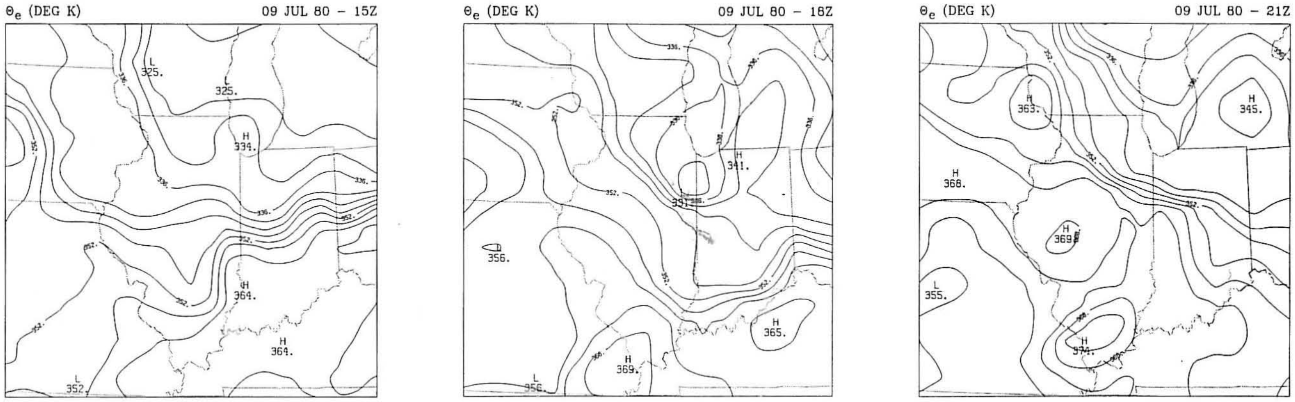


Figure 4. Same as Figure 3 except for 2035Z 9 July 1980.

Figure 5. Same as Figure 3 except for 2335Z 9 July 1980.



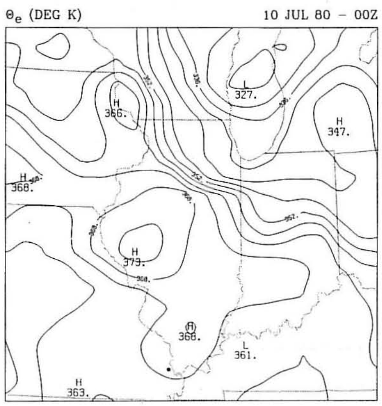
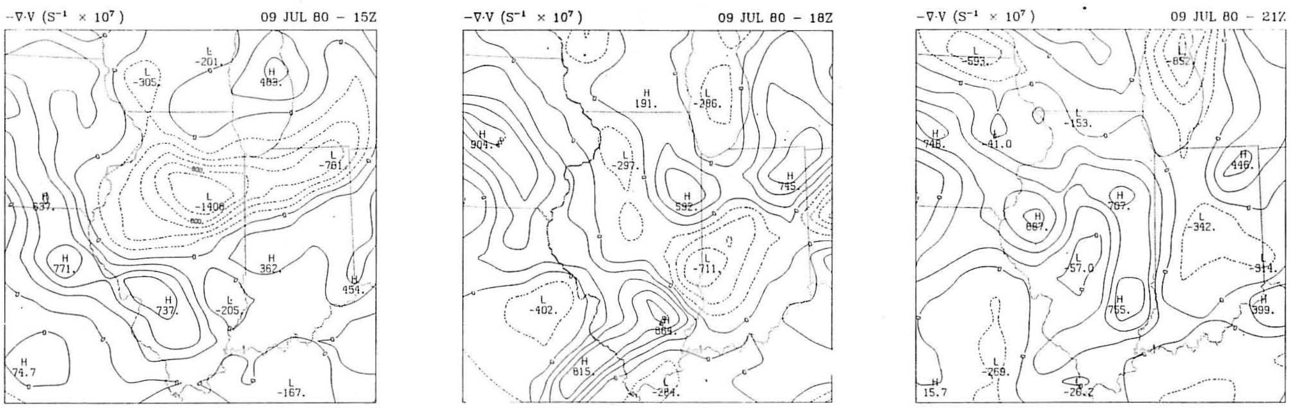


Figure 6. Objective analyses of equivalent potential temperature (θ_e) shown in units of °K. Contours at intervals of 4K from a base value of 324K. (a) 1500Z 9 July 1980, (b) 1800Z 9 July 1980, (c) 2100 9 July 1980, (d) 0000Z 10 July 1980.



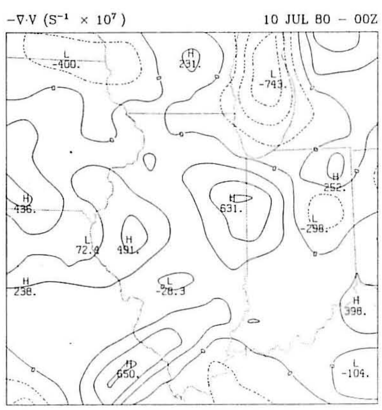


Figure 7. Objective analyses of wind convergence ($-\nabla \cdot V$) shown in units of s^{-1}. (Values scaled by a factor of 10^7.) Contours at intervals of 2.0 x 10^{-5} s^{-1} with a base value of -12.0 x 10^{-5} s^{-1}. (a) 1500Z 9 July 1980, (b) 1800Z 9 July 1980, (c) 2100Z 9 July 1980, (d) 0000Z 10 July 1980.

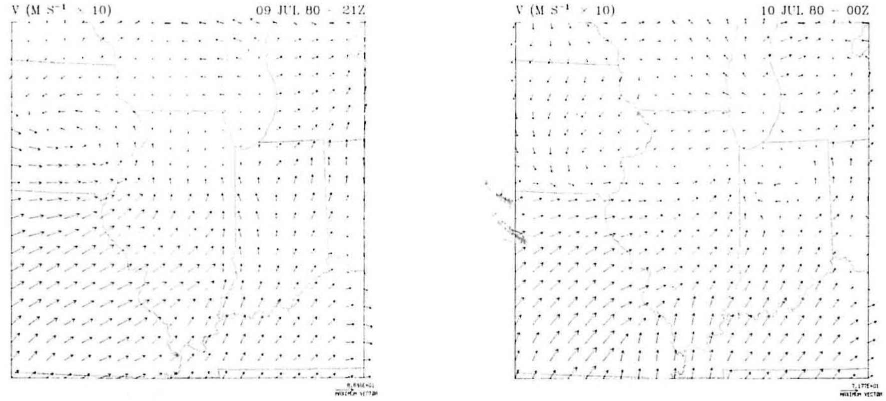


Figure 8. Objective analyses of surface wind fields shown in terms of velocity vectors at the grid points. Speeds are given in units of 10 ms^{-1}, with magnitude of maximum vector shown in the lower right hand corner of each diagram. (a) 2100Z 9 July 1980, (b) 0000Z 10 July 1980.

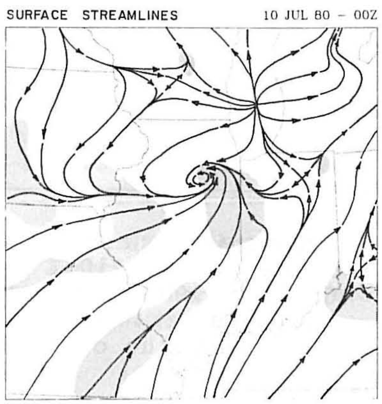
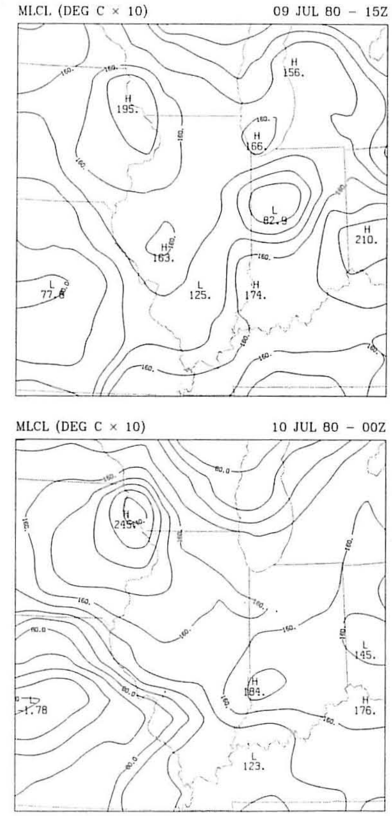


Figure 9. Hand drawn surface streamline pattern at 0000Z 10 July 1980. (Corresponds to Fig. 8b.) Stipling denotes areas with convergence exceeding 2.0 x 10^{-5} s^{-1}.

Figure 10. Objective analyses of modified lifting condensation level shown in units of °C. (Values scaled by a factor of 10.) Contours at intervals of 2°C with a base value of 0°C. (a) 1500Z 9 July 1980, (b) 0000Z 10 July 1980.



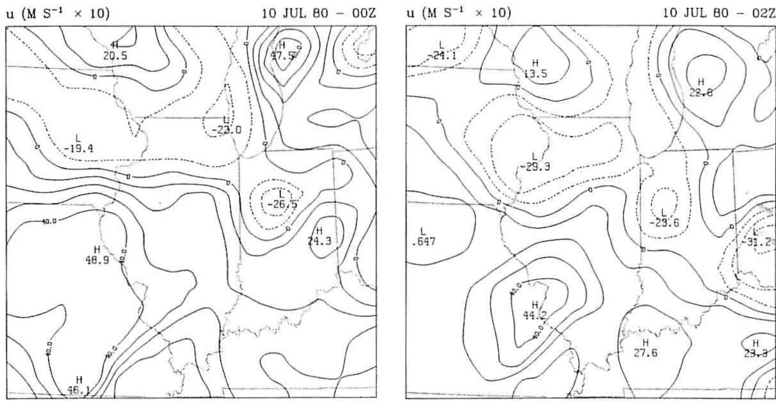


Figure 11. Objective analyses of u-component of wind shown in units of m s^{-1}. (Values scaled by a factor of 10.) Contours at intervals of 1 m s^{-1} with a base of value of -10 m s^{-1}. (a) 0000Z 10 July 1980, (b) 0200Z 10 July 1980.

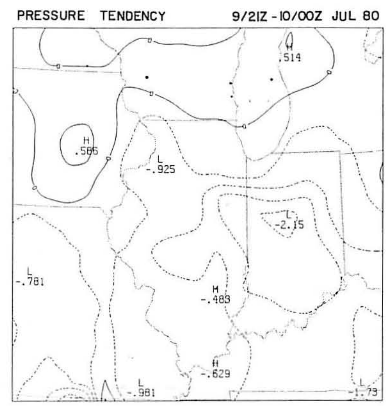


Figure 12. Objective analysis of pressure tendency for the period 2100Z 9 July 1980 to 0000Z 10 July 1980. Shown in units mb/3 hr. Contours at intervals of 0.5 mb/3 hr with a base value of -2.0 mb/3 hr.

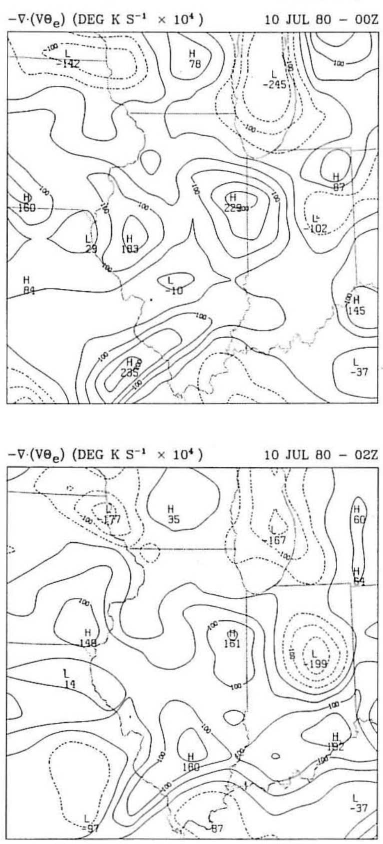


Figure 13. Objective analyses of convergence of equivalent potential temperature ($-\nabla \cdot V\theta_e$) shown in units of °K s^{-1}. (Values scaled by a factor of 10^4.) Contours at intervals of .005 °K s^{-1} with a base value of -0.0200 °K s^{-1}. (a) 0000Z 10 July 1980, (b) 0200Z 10 July 1980.

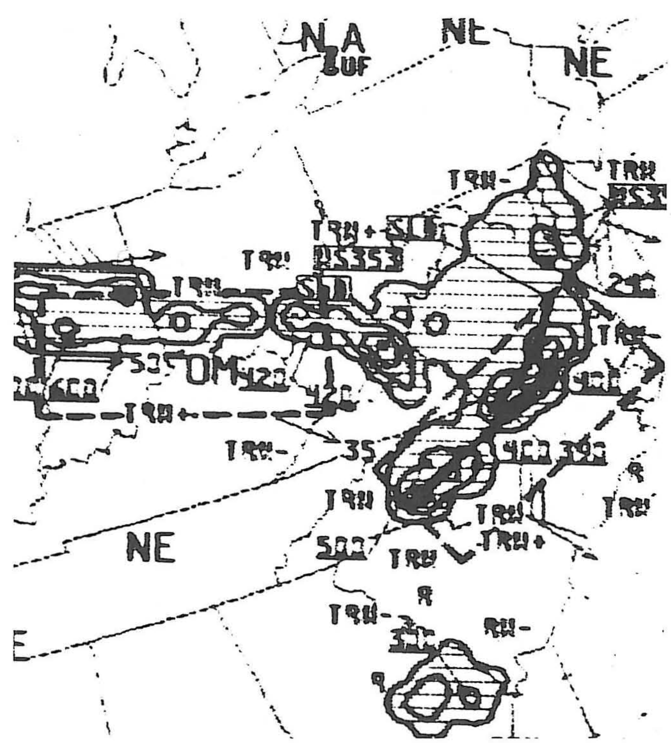


Figure 14. Same as Figure 3 except for 0235Z 10 July 1980.

FOOTNOTES AND REFERENCES

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