NOAA TECHNICAL MEMORANDUM NWS CR-105

FORECASTING SNOWFALL USING MIXING RATIOS ON AN ISENTROPIC SURFACE

AN EMPIRICAL STUDY

Crispin Garcia, Jr.
National Weather Service Forecast Office
Milwaukee, Wisconsin

May 1994

U.S DEPARTMENT OF Commerce / National Oceanic and Atmospheric Administration / National Weather Service

NOAA TECHNICAL MEMORANDA
National Weather Service, Central Region Subseries

... Central Region (CR) subseries provides an informal medium for the documentation and quick dissemina-
...ate, or not yet ready, for formal publication. The series is used to report on work in progress, to
...s and practices, or to relate progress to a limited audience. These Technical Memoranda report on
...rily to regional and local problems of interest mainly to regional personnel, and hence will not be

...e former series, ESSA Technical Memoranda, Central Region Technical Memoranda (CRTM); Papers 16
...series, ESSA Technical Memoranda, Weather Bureau Technical Memoranda (WBTM). Beginning with Paper 37,
...ries, NOAA Technical Memoranda NWS.

Papers that have a PB or COM number are available from the National Technical Information Service, U. S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22151. Order by accession number shown in parenthesis at the end of each entry. Prices vary for all paper copies. Microfiche are $4.50. All other papers are available from the National Weather Service Central Region, Scientific Services, Room 1836, 601 East 12th Street, Kansas City, MO 64106.

ESSA Technical Memoranda

CRTM 1 Precipitation Probability Forecast Verification Summary Nov. 1965 - Mar. 1966, SSD Staff, WBCRH, May 1966.
CRTM 2 A Study of Summer Showers Over the Colorado Mountains. William G. Sullivan, Jr., and James O. Severson, June 1966.
CRTM 3 Areal Shower Distribution - Mountain Versus Valley Coverage. William G. Sullivan, Jr., and James O. Severson, June 1966.
CRTM 4 Heavy Rains in Colorado June 16 and 17, 1965. SSD Staff, WBCRH, July 1966.
CRTM 5 The Plum Fire. William G. Sullivan, Jr., August 1966.
CRTM 6 Precipitation Probability Forecast Verification Summary Nov. 1965 - July 1966. SSD Staff, WBCRH, September 1966.
CRTM 7 Effect of Diurnal Weather Variations on Soybean Harvest Efficiency. Leonard F. Hand, October 1966.
CRTM 8 Climatic Frequency of Precipitation at Central Region Stations. SSD Staff, WBCRH, November 1966.
CRTM 9 Heavy Snow or Glazing. Harry W. Waldheuser, December 1966.
CRTM 10 Detection of a Weak Front by WSR-57 Radar. G. W. Polensky, December 1966.
CRTM 11 Public Probability Forecasts. SSD Staff, WBCRH, January 1967.
CRTM 12 Heavy Snow Forecasting in the Central United States (an Interim Report). SSD Staff, January 1967.
CRTM 13 Diurnal Surface Geostrophic Wind Variations Over the Great Plains. Wayne E. Sangster, March 1967.
CRTM 14 Forecasting Probability of Summertime Precipitation at Denver. Wm. G. Sullivan, Jr., and James O. Severson, March 1967.
CRTM 15 Improving Precipitation Probability Forecasts Using the Central Region Verification Printout. Lawrence A. Hughes, May 1967.
WBTM CR 16 Small-Scale Circulations Associated with Radiational Cooling. Jack R. Cooley, June 1967.
WBTM CR 17 Probability Verification Results (6-month and 18-month). Lawrence A. Hughes, June 1967.
WBTM CR 18 On the Use and Misuse of the Brier Verification Score. Lawrence A. Hughes, August 1967 (PB 175 771).
WBTM CR 19 Probability Verification Results (24 months). Lawrence A. Hughes, February 1968.
WBTM CR 20 Radar Prediction of the Topeka Tornado. Norman E. Prosser, April 1968.
WBTM CR 21 Wind Waves on the Great Lakes. Lawrence A. Hughes, May 1968.
WBTM CR 22 Seasonal Aspects of Probability Forecasts: 1. Summer. Lawrence A. Hughes, June 1968 (PB 185 733).
WBTM CR 23 Seasonal Aspects of Probability Forecasts: 2. Fall. Lawrence A. Hughes, September 1968 (PB 185 734).
WBTM CR 24 The Importance of Areal Coverage in Precipitation Probability Forecasting. John T. Curran and Lawrence A. Hughes, September 1968.
WBTM CR 25 Meteorological Conditions as Related to Air Pollution, Chicago, Illinois, April 12-13, 1963. Charles H. Swan, October 1968.
WBTM CR 26 Seasonal Aspects of Probability Forecasts: 3. Winter. Lawrence A. Hughes, December 1968 (PB 185 735).
WBTM CR 27 Seasonal Aspects of Probability Forecasts: 4. Spring. Lawrence A. Hughes, February 1969 (PB 185 736).
WBTM CR 28 Minimum Temperature Forecasting During Possible Frost Periods at Agricultural Weather Stations in Western Michigan. Marshall E. Soderberg, March 1969.
WBTM CR 29 An Aid for Tornado Warnings. Harry W. Waldheuser and Lawrence A. Hughes, April 1969.
WBTM CR 30 An Aid in Forecasting Significant Lake Snows. H. J. Rothrock, November 1969.
WBTM CR 31 A Forecast Aid for Boulder Winds. Wayne E. Sangster, February 1970.
WBTM CR 32 An Objective Method for Estimating the Probability of Severe Thunderstorms. Clarence L. David, February 1970.
WBTM CR 33 Kentucky Air-Soil Temperature Climatology. Clyde B. Lee, February 1970.
WBTM CR 34 Effective Use of Non-Structural Methods in Water Management. Verne Alexander, March 1970.
WBTM CR 35 A Note on the Categorical Verification of Probability Forecasts. Lawrence A. Hughes and Wayne E. Sangster, August 1970.
WBTM CR 36 A Comparison of Observed and Calculated Urban Mixing Depths. Donald E. Wuerch, August 1970.

NOAA Technical Memoranda NWS

NWS CR 37 Forecasting Maximum and Minimum Surface Temperatures at Topeka, Kansas, Using Guidance from the PE Numerical Prediction Model (FOUS). Morris S. Webb, Jr., November 1970 (COM 71 00118).
NWS CR 38 Snow Forecasting for Southeastern Wisconsin. Rheinhart W. Harms, November 1970 (COM 71-00019).
NWS CR 39 A Synoptic Climatology of Blizzards on the North-Central Plains of the United States. Robert E. Black, February 1971 (COM 71-00369).
NWS CR 40 Forecasting the Spring 1969 Midwest Snowmelt Floods. Herman F. Mondschein, February 1971 (COM 71-00489).
NWS CR 41 The Temperature Cycle of Lake Michigan 1. (Spring and Summer). Lawrence A. Hughes, April 1971 (COM 71-00545).
NWS CR 42 Dust Devil Meteorology. Jack R. Cooley, May 1971 (COM 71-00628).
NWS CR 43 Summer Shower Probability in Colorado as Related to Altitude. Alois G. Topil, May 1971 (COM 71-00712).
NWS CR 44 An Investigation of the Resultant Transport Wind Within the Urban Complex. Donald E. Wuerch, June 1971 (COM 71- 00766).
NWS CR 45 The Relationship of Some Cirrus Formations to Severe Local Storms. William E. Williams, July 1971 (COM 71- 00844).
NWS CR 46 The Temperature Cycle of Lake Michigan 2. (Fall and Winter). Lawrence A. Hughes, September 1971 (COM 71-01039).

(Continued on Back Cover)

NOAA TECHNICAL MEMORANDUM NWS CR-105

FORECASTING SNOWFALL USING MIXING RATIOS ON AN ISENTROPIC SURFACE

AN EMPIRICAL STUDY

Crispin Garcia, Jr.
National Weather Service Forecast Office
Milwaukee, Wisconsin

May 1994

UNITED STATES DEPARTMENT OF COMMERCE
Ronald H. Brown
Secretary

National Oceanic and Atmospheric Administration
D. James Baker
Under Secretary

National Weather Service
Elbert W. Friday, Jr.
Assistant Administrator

Table of Contents

FORECASTING SNOWFALL USING MIXING RATIOS ON AN ISENTROPIC SURFACE

AN EMPIRICAL STUDY

Crispin Garcia Jr
National Weather Service Forecast Office
Milwaukee, Wisconsin

ABSTRACT

This study attempts to correlate isentropic mixing ratios and the amount of snowfall produced by different snow events. During the course of the study, a forecast technique was developed that utilized real-time quantitative moisture values (mixing ratios) to predict maximum snowfall during the ensuing 12-hour period.

The forecast technique lists seven steps for analyzing isentropic plots and associated cross sections. These steps are necessary in order to isolate the mixing ratios which will be most pertinent to a forecasted or ongoing snow event. From empirical evidence gathered during the six years of the study, a scale was developed that directly related mixing ratios on an isentropic surface to maximum snowfall using an approximate 2 to 1 ratio.

Included are three case studies detailing snow events ranging from light to heavy snowfall. The studies concentrate primarily on isentropic analyses with only a minimal amount of standard pressure level or prognostic information. The case studies point out the value of isentropic analyses and how isentropic mixing ratio information can be applied to expected snowfall in a 12-hour (nowcast) period.

1. INTRODUCTION

The lack of a forecast scheme that could incorporate real-time quantitative moisture values and snowfall amounts has always been a hinderance to forecasters. Past forecast approaches have used 850 mb dew points or precipitable water to predict snowfall amounts. However, these methods have not always been successful since their use cannot consider the moisture advection process within a three dimensional framework. Often times, the QPF (Quanitative Precipitation Forecast) from the Eta[1] and NGM computer models are used for 12-48 hour snowfall forecasts by utilizing a liquid to snow ratio.

[1]The Eta model QPF replaced the LFM model in 1993.

Isentropic analysis is ideally suited for fall and winter systems since synoptic scale air masses tend to move along isentropic surfaces and are less convective in nature. Convection will make air parcels jump off isentropic surfaces so little or no continuity is possible. Diurnal heating and cooling as well diabatic heating associated with thunderstorms in the summer can often cause large changes in the isentropic surfaces. The cooling and warming of isentropic surfaces (causing a change in the elevation of the isentropic surfaces) in winter storms can also provide some continuity problems, but much less than in the summer. The rise and fall of isentropic surfaces during winter storms and snow events are generally due to warm and cold advection , but these factors are much easier to take into account.

In late 1986, the NWS Forecast Office in Milwaukee, Wisconsin (MKX) installed an AFOS (Automated Field Operations and Services) isentropic plotting program written by Little (1985). The forecast staff began using the isentropic plots generated by this program on an as-needed basis in January 1987. AFOS was eventually set up to run one plot automatically every 12 hours with the receipt of the new upper air data. The isentropic plot level was changed according to the season and any additional levels were run manually. A study was initiated in January 1987 that sought to correlate snowfall amounts with the amount of moisture available to the snow producing system.

2. APPROACH

Historically, many meteorological studies in the 1930s and early 1940s recognized the importance of the 10,000 foot level for forecasting weather. When the U.S. Weather Bureau converted to constant pressure surfaces many of these early studies were considered applicable to the nearest standard pressure level - 700 mb.

The 700 mb level is used by the NGM and Eta progs to depict vertical velocities and mean (SFC-500 mb) relative humidities (RH). Forecasters eventually developed a rule-of-thumb that linked 70% + RH with general cloudiness and 90% + RH with precipitation depending on the strength of the associated upward vertical velocities (UVV) and adjusted somewhat from season-to-season. In addition, the 700 mb net vertical displacement (NVD) prognostic chart depicting synoptic scale lift became the foundation for the "Magic Chart" technique (developed using the LFM model) of heavy snowfall forecasting (Chaston, 1989).

At the onset of this study, it was realized that a standard reference level in the atmosphere would be needed to focus forecaster attention on a particular layer where the most significant parameters were ocurring or expected to occur. After evaluation of two early January 1987 snowfall case studies, the 700-750mb layer was chosen. One of the reasons that this level was selected was that it closely coincided with the aforementioned 700 mb products. Secondly, if one considers the large volumetric flow into a winter cyclone, it is easy to imagine a "conveyor belt" of moisture ascending isentropically into the middle levels of the atmosphere. Based on observations over the past several years, moisture arriving at the 700-750 mb layer finds itself at the optimum elevation for use by the engine of a winter storm.

3. DATA

The AFOS isentropic program used at the Milwaukee/Sullivan office produces a tailored plot for the central portion of the U.S. The isentropic station model at each rawinsonde location contains an analysis of pressure, condensation pressure, mixing ratio (specific humidity), and an actual or interpolated wind direction and speed. In addition, if the temperature and dew point depression is within 5 degrees, the station circle is shaded. Should the plotted isentropic surface intersect the ground at a certain station, a missing symbol is plotted. If the mixing ratio at a certain station is less than one tenth g/kg then the mixing ratio and the condensation pressure both are plotted as 999. A diagram of the isentropic station model plot and a brief definition of potential temperature is located in Appendix A.

4. PROCESS

A technique was developed at MKX that provided a "quick look" at new upper air data at the beginning of a 12-hour period. The technique lists a series of steps that should be used to view the data in a three dimensional isentropic aspect that complements the analyses of standard pressure levels. Often, the time element can be crucial in a fast developing weather situation. It is realized that a system of analysis that proves too cumbersome to use will not be utilized. A streamlining of the technique will likely emerge after familiarity with this method of isentropic analysis.

In many cases of light and moderate snowfall, steps 6 and 7 are more simplified since the mixing ratios that will be available to a snow system are already within or near the *"area of concern"*. A more detailed example of steps 6 and 7 is provided later in this paper (Heavy Snowfall Event) while describing the isentropic processes of an intense winter storm.

If time allows, an additional isentropic surface plot should be considered, approximately 3 to 6 degrees Kelvin cooler than the original isentrope. This second plot will help depict the moisture field at a lower level in the atmosphere. The Surface Mixing Ratio (SMR) graphic from AFOS Data Analysis Programs (Bothwell, 1985) can also be referenced when isentropes dip beneath 900 mb. In this situation, the mixing ratios at the lower isentropic level will tend to reflect or compliment the mixing ratios seen at the surface. It is important to keep a continuity of the same isentropic surface plot(s) to see if the surface decreases or increases in elevation or remains the same. This tends to affect the mixing ratios seen on that surface (i.e., an increase in elevation will generally produce lower mixing ratios and correspondingly a decrease in elevation will have higher mixing ratios). However, it is even more important to keep track of the location of the 700-750 mb layer used in step 3 of this technique.

The Technique

1. Determine the geographical location of the *"area of concern"*. This *"area of concern"* is defined as that area where potential snowfall would create travel or safety problems. The location of this area can generally be deduced by using one or more of the forecast placement techniques located in Appendix B.

2. Run an isentropic cross section through this area, preferably parallel to the prevailing flow in the immediate region. (There are 18 different cross sections set up in the AFOS computer in the Milwaukee/Sullivan office). A cross section plot run parallel to the flow will provide a better depiction of the isentropic sloping in the air mass under investigation..

3. Through interpolation on the cross section determine which isentropic surface (degrees Kelvin) best intersects the 700 mb to 750 mb layer over the *"area of concern"*. An example cross section is provided (Heavy Snowfall Event).

4. Run the selected isentropic surface, the 295K surface plot, for example. Then analyze the pressure surfaces every 50 mb and the mixing ratios every 1 g/kg. This detailed analysis will also serve to point out any bad upper air data or an erroneously plotted element. The isentropic program will occasionally plot a station wind with the wrong direction. If the station mixing ratio appears too dry or too moist when compared to surrounding stations, investigate for accuracy by looking at that station's sounding.

5. A quick sketching of streamlines over these two fields is optional but recommended. This will help in visualizing the flow and assessing whether the air is moving up or down the isentropic slope (across the pressure contours). If the flow is parallel to the analyzed pressure surfaces, then little ascent or descent of the air parcels is implied. This determination can often be aided by referring back to the original cross section.

6. An effective mixing ratio value for the 12-hour period can be calculated by averaging the mixing ratio over the *"area of concern"* and the highest mixing ratio that could be advected into this area. This average mixing ratio value will provide the basis for the maximum snowfall forecast. One way of approximating where the highest mixing ratio may lie upstream is to use the wind field on the isentropic plot. The direction of origin can be derived from the streamlines in Step 5 or by visually assessing the prevailing flow on the plot. A simple estimate of the distance from the *"area of concern"* to the location of the highest (maximum) mixing ratio can be obtained by multiplying the average wind speed by the time period (12 hours). For example, 30 knots times 12 hours yields a distance of 360 nm. Remember that this is just an approximation of the distance since the air parcels are moving along a slope and not horizontally.

> Examples: The 2.5 g/kg mixing ratio in the *"area of conern"* will be reinforced by a 3.5 g/kg mixing ration (360 nm. away). In this case, the effective mixing ratio for the 12-hour period is 3 g/kg, not a significant difference in moisture. However, the advection of a mixing ratio value of 6.5 g/kg would raise the averaged value to 4.5 g/kg.

7. The strong dynamic forcing (lift) necessary for maximum snowfall will be caused by an extra-tropical cyclone, vorticity maximum, jet streak and so forth. Determine if the dynamic forcing will exist for most or just part of the 12-hour period. Frequently, the assumption can be made that the forcing will be sustained for much of the period. This will be a subjective opinion based on analyses and observations, or an opinion based partially or wholly on model input. However it is made, this determination will have an impact on whether the "potential" snowfall is actually realized.

Empirical observation has shown that an approximate 2 to 1 correlation exists between the average mixing ratio (determined in step 6) and the maximum snowfall amount. This relationship has been confirmed many times in case studies and in actual forecast situations over the past six winter seasons. The snowfall scale (below) was originally developed for Wisconsin and neighboring states. However, case studies done at this office, have shown that the scale is applicable to much of the central portion of the U.S. from the Northern to the Southern Plains and the Ohio Valley region. This technique is not suited for the localized phenomena of "lake effect" snowfall common around the Great Lakes region. Whether this snowfall forecasting scheme can be used successfully on the East or West Coast is unknown at this time. Their proximity to the copious moisture of the Atlantic and Pacific Ocean plus the orographic lifting provided by the mountains introduce important factors not accounted for in this study.

SNOWFALL SCALE
(12 HOUR PERIOD)

1 - 2 g/kg	=	2 - 4" snow
2 - 3 g/kg	=	4 - 6" snow
3 - 4 g/kg	=	6 - 8" snow
4 - 5 g/kg	=	8 - 10" snow
5 - 6 g/kg	=	10 - 12" snow
6 - 7 g/kg	=	12 - 14" snow

Note: The mixing ratios shown on this scale should be considered to be average mixing ratios. The snowfall amounts should be considered maximum snowfalls for a 12 hour period.

5. CASE STUDIES

Three case studies dealing with differing snowfall situations are examined and the isentropic information provided at the beginning of each 12 hour period is analyzed. Since the emphasis is on isentropic analyses and mixing ratios, there is only a minimal amount of standard pressure level or prognostic information.

A. Light snowfall event - January 2, 1991
B. Moderate snowfall event - January 19, 1987
C. Heavy snowfall event - October 31 - November 2, 1991

A. Light Snowfall Event - January 2, 1991

Surface Synoptic Pattern

Arctic high pressure building into the Northern Plains was centered over South Dakota by 2100 UTC (Figure 1.0). The high was ridging east into the western Great Lakes. The cold and dry air mass was producing single digit temperatures and sub-zero dew points. A light snow event that began in South Dakota at 0600 UTC had spread into southern Wisconsin by this time. The following weather depiction charts (Figures A through E) show ceiling heights, visibilities, and precipitation type from 0600 to 2100 UTC.

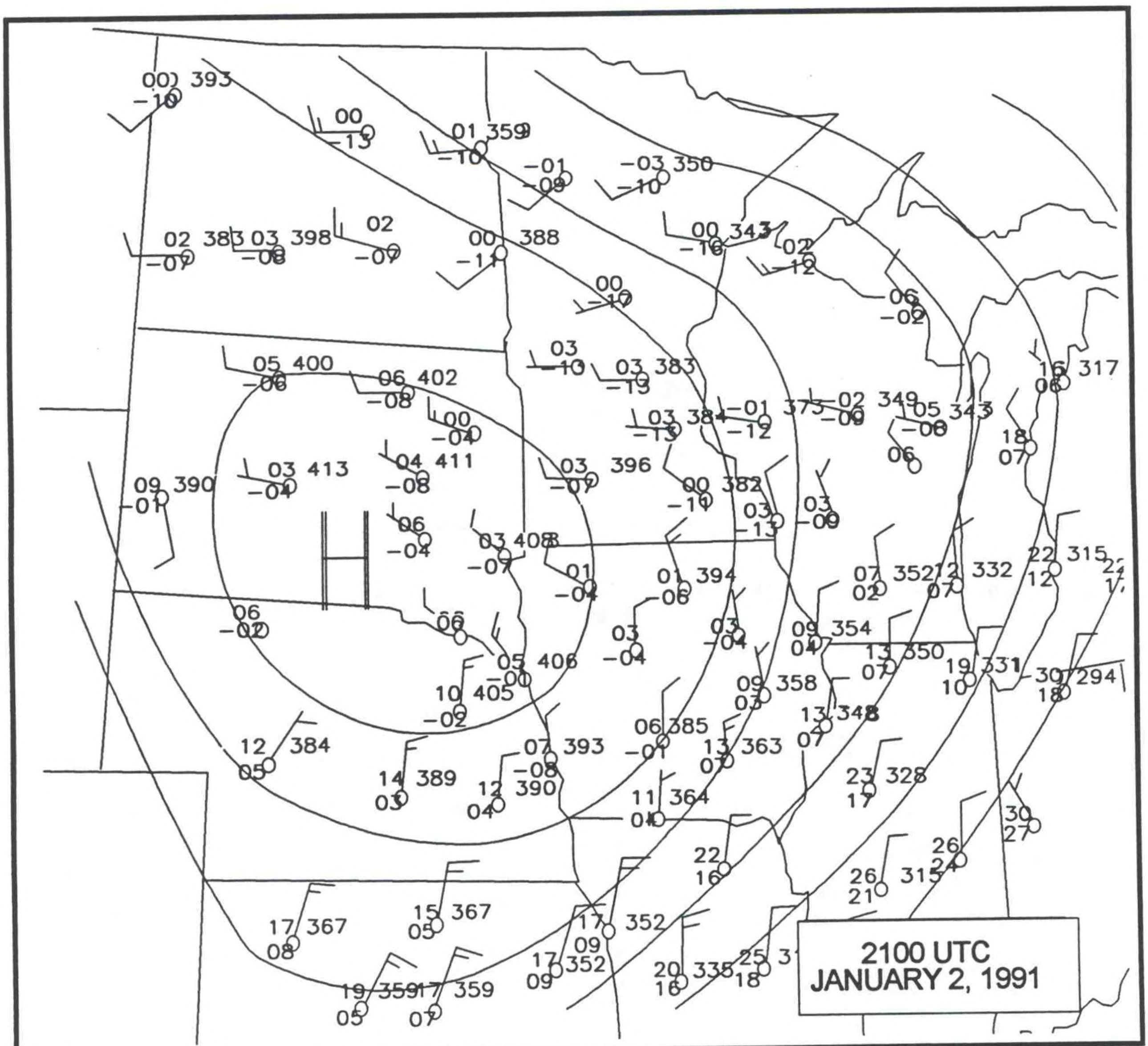


Figure 1.0 Sea-level pressure analyzed every 2 millibars. Winds (knots), temperatures and dew points in °F.

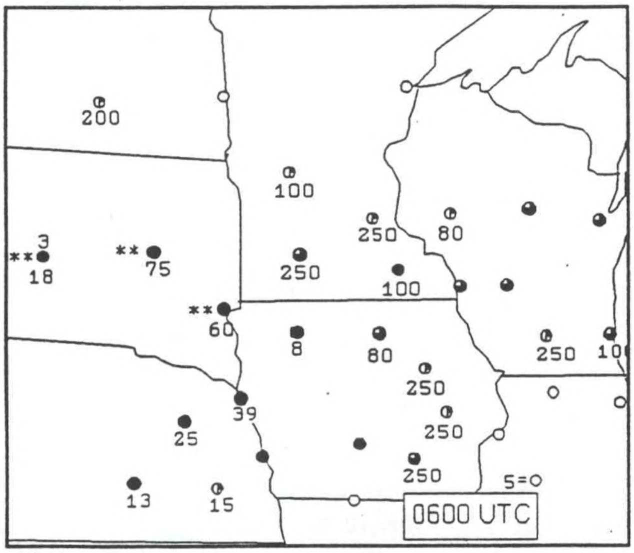


Figure A

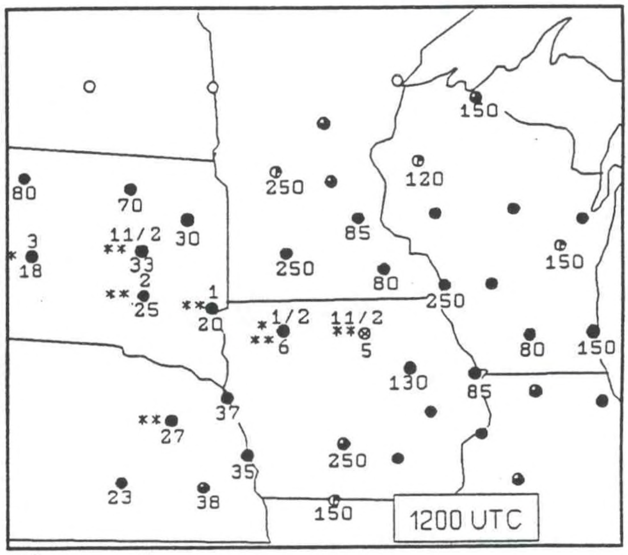


Figure B

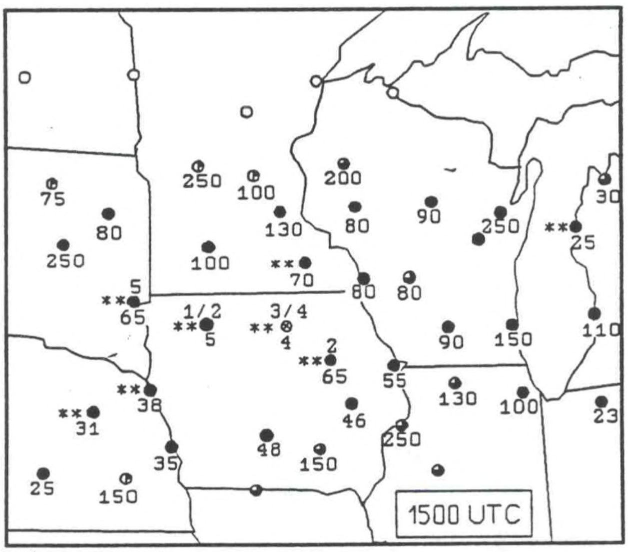


Figure C

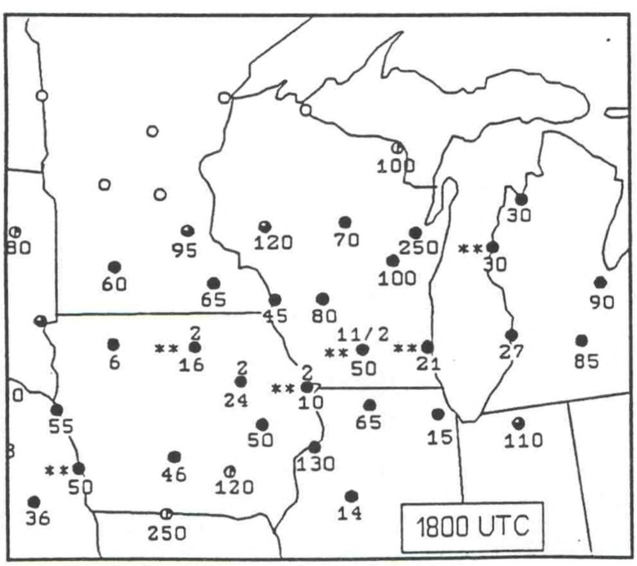


Figure D

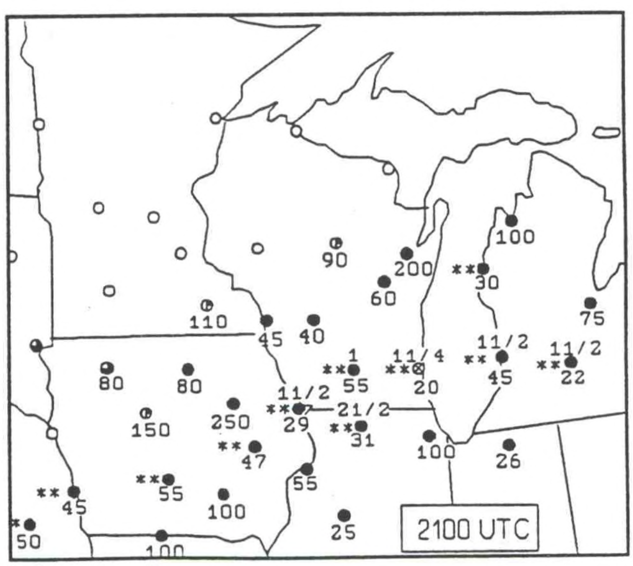


Figure E

A band of light to moderate snow developed from South Dakota into northern Iowa between 0600 and 1200 UTC. Satellite imagery (not shown) showed a compact but vigorous vorticity maximum (vort max) and minor trough moving east over the affected area. The vort max was projected to track to southern Wisconsin (which was now the *"area of concern"*) during the day.

After running an isentropic cross section from Rapid City, South Dakota to Flint, Michigan (not depicted), it was determined that an isentropic plot at the 290K level would intersect the 700 and 750 mb layer (about 9,000 to 10,000 feet in altitude) over southern Wisconsin (Figure 1.1). In this particular case, the *"area of concern"* would be directly beneath the path of the vort max. Since a persistent and fast westerly flow had been noted at this level during the past 24 hours, it was concluded that the meager moisture available over this region was likely of Pacific origin. The mixing ratio analysis over the *"area of concern"* at the 290K level showed values just over 1 g/kg to just under 2 g/kg. With the lack of upper air data over Iowa, it was decided that a minor range of 1 to 1.5 g/kg would be used as the average mixing ratio. Using the "2 to 1" rule, it was determined that a maximum snowfall of 2 to 3 inches would be possible during the next 12 hours. This calculation was simplified by a high confidence that no other moisture would be available to this weather feature.

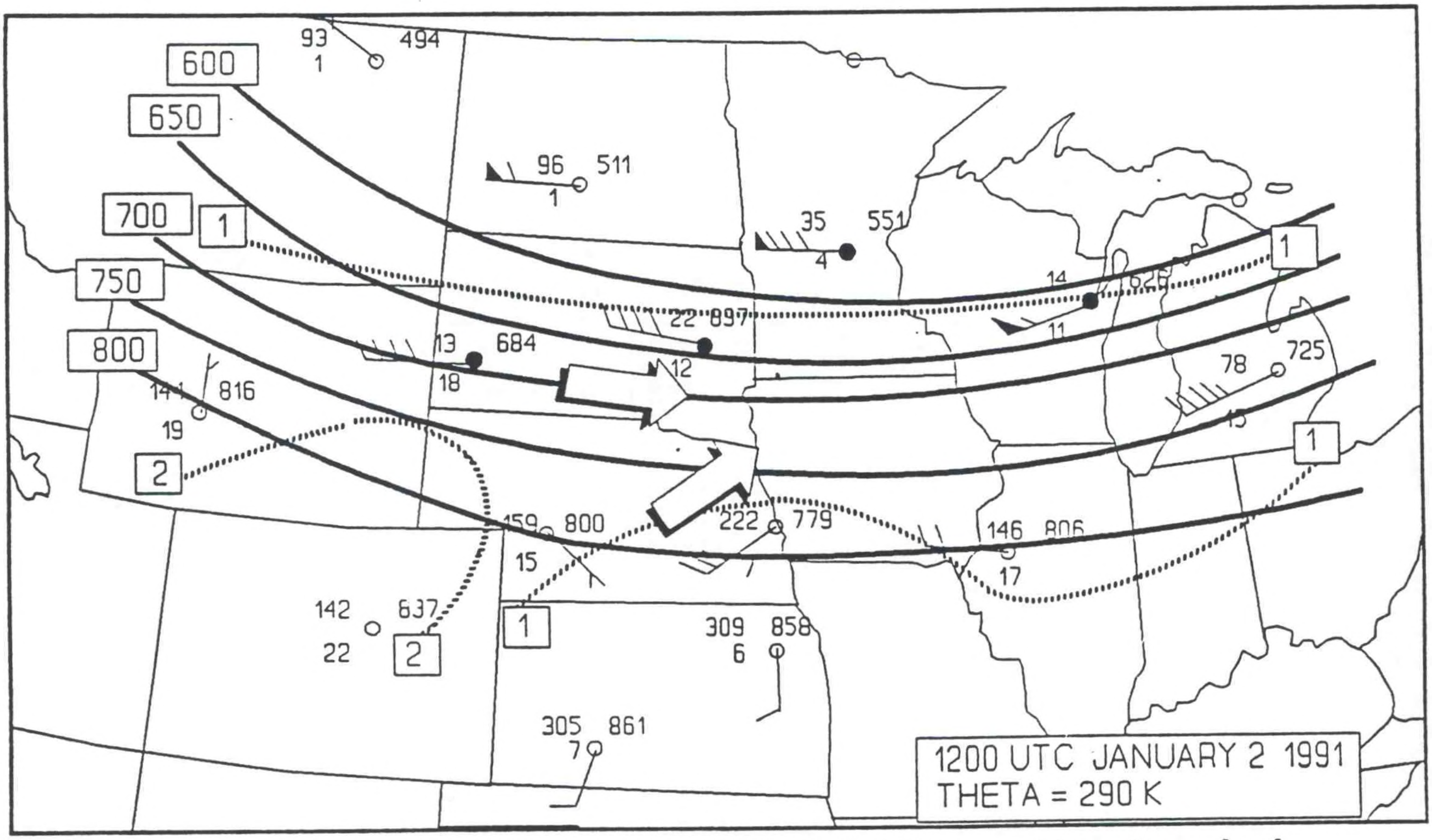


Figure 1.1 Solid lines indicate pressure levels (mb). Dashed lines are mixing ratios analyzed every gram per kilogram. Arrows denote weak middle level convergence. Winds in knots.

The snowfall map for January 2, 1991 (Figure 1.2) shows the narrow swath of snow that fell over the affected area. The snow averaged 1 to 2 inches with amounts falling off sharply on either side of this band.

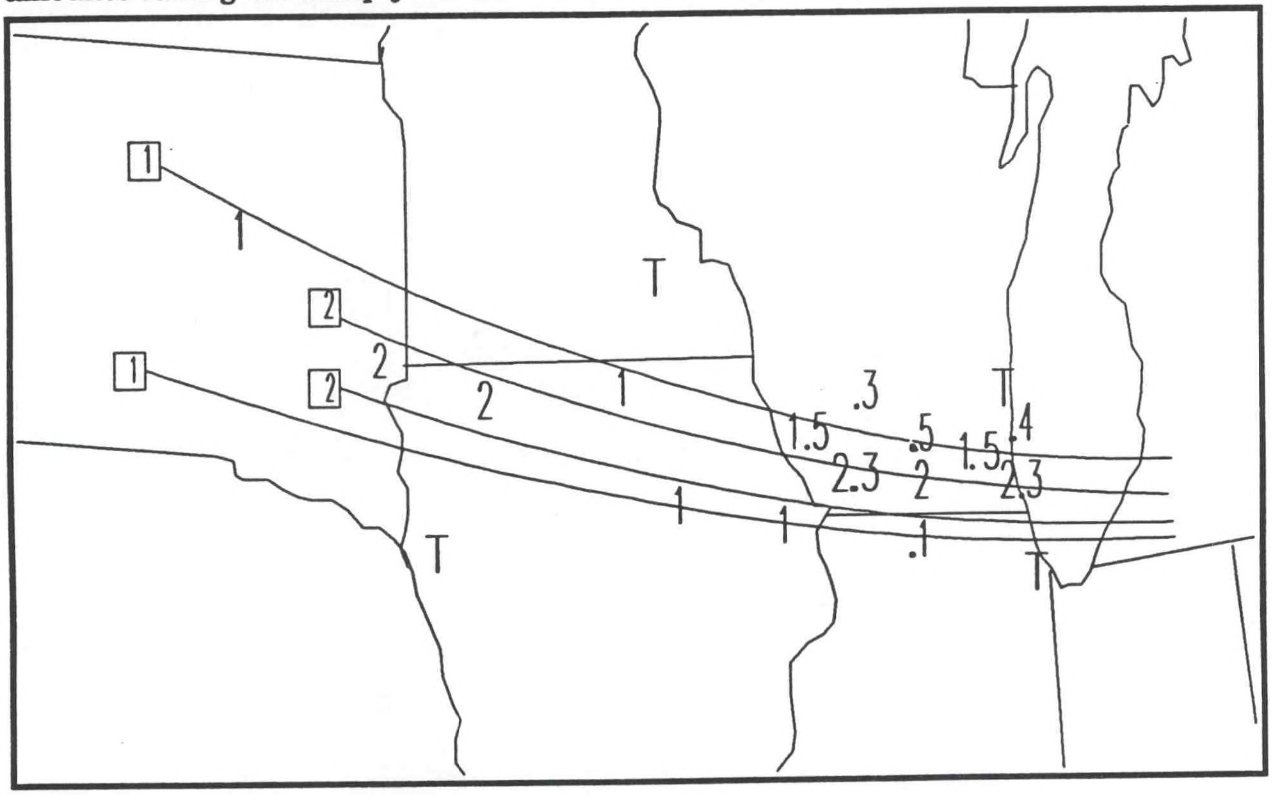


Figure 1.2 Total snowfall (inches) January 2, 1991.

SPECIFIC SNOWFALL AMOUNTS FOR THE EVENT

HURON, SD	1"	SIOUX FALLS, SD	2"	SPENCER, IA	2"
MASON CITY, IA	1"	WATERLOO, IA	1"	DUBUQUE, IA	1"

IN SOUTHERN WISCONSIN

PLATTEVILLE (20 MI. NORTHEAST OF DBQ)	2.3"
KENOSHA (32 MI. SOUTH OF MKE)	2.3"
AFTON (37 MI. SOUTHEAST OF MSN)	2.0"
LAFAYETTE CO. (SOUTHWEST WI)	2.0"
GREEN CO. (SOUTH CENTRAL WI)	1.8"

OUTSIDE OF THE MAIN SNOW BAND

WSFO SULLIVAN	0.5"	MILWAUKEE	0.4"	MADISON	0.4"
ROCKFORD, IL	0.1"	CHICAGO, IL	TRACE		

B. Moderate Snowfall Event - January 19,1987

Synoptic Pattern (500 Millibar)

On January 18, a weak surface low pressure area in the Gulf of Mexico had moved into southern Louisiana at 1200 UTC (Figure 2.0) At the same time, a closed 500 mb low over southeast New Mexico was preparing to move northeast as a 250 mb wind speed maximum (120 knot, not depicted) swung around the base of the upper trough.

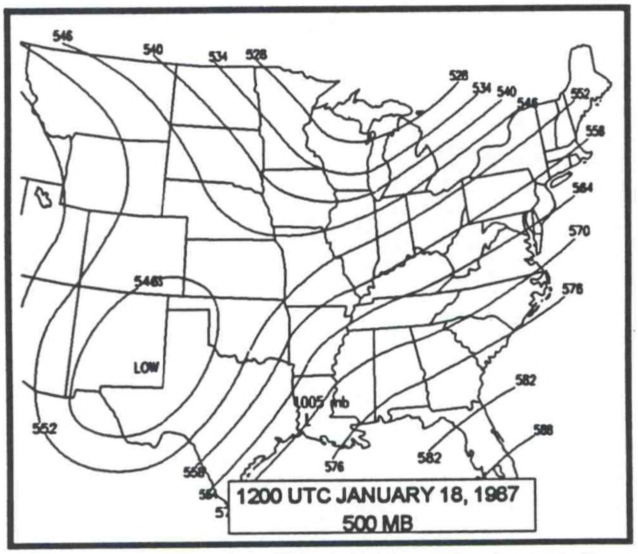


Figure 2.0 500 Millibar pattern with surface low superimposed.

By 1200 UTC, January 19, the surface low had moved to southern Indiana and had intensified from 1005 mb to 996 mb (Figure 2.1). The 500 mb low had moved to southern Missouri while deepening 120 meters. A 300 mb jet maximum (120 to 140 knot, not depicted) continued to move around the base of the upper trough.

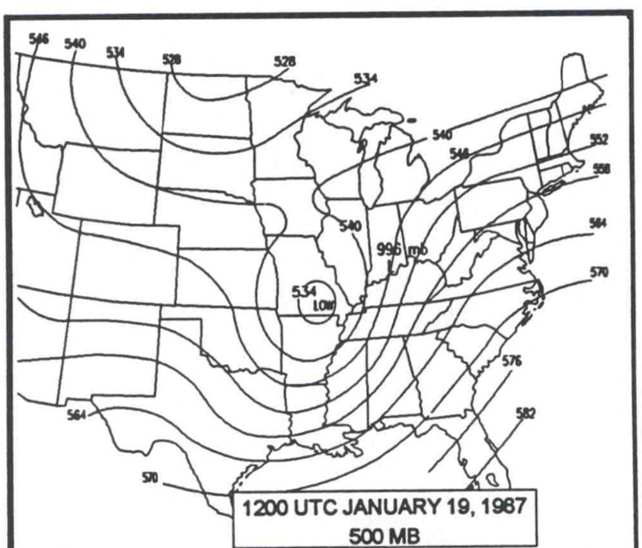


Figure 2.1 500 Millibar pattern with surface low superimposed.

By 1200 UTC, January 20, the surface and 500 mb lows had lost their identities as the dynamic support lent by the upper level jet maximum had moved east into the Atlantic Ocean (Figure 2.2).

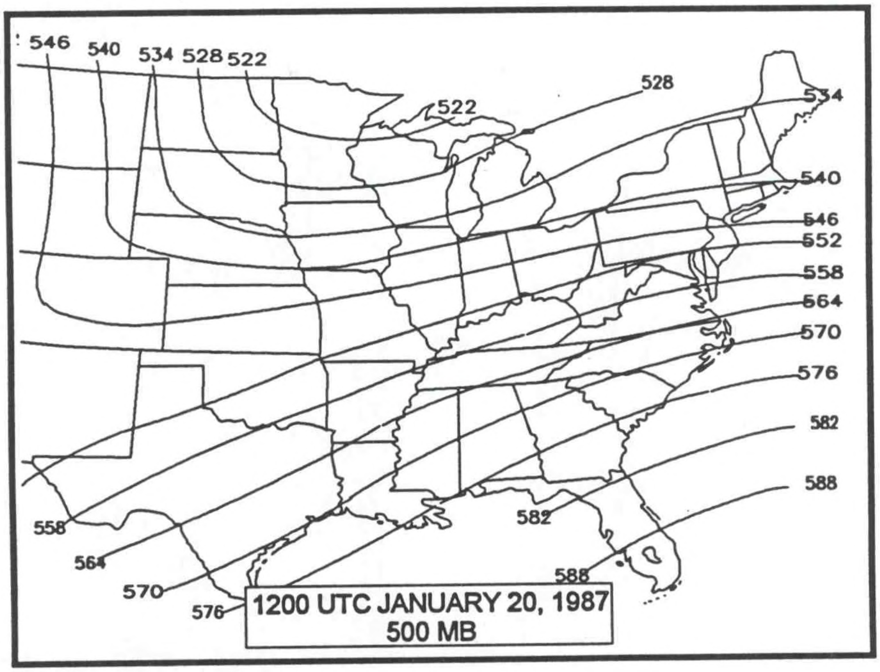


Figure 2.2 500 Millibar pattern.

On an isentropic analysis chart, air moving from higher pressure to lower pressure implies upper vertical motion. Conversely, air moving from lower pressure to higher pressure implies sinking motion. Optimum isentropic lift is usually achieved when the rising air moves perpendicular to the constant pressure levels. The 290K isentropic plot for 1200 UTC, January 18 is shown in Figure 2.3. The 290K surface intersected the 700-750 mb layer (shaded for emphasis) that stretched from central Texas and Oklahoma to southern lower Michigan. Cold and dry air was descending south and east from the northern Plains, while a moist southerly flow at 15-25 knots was pushing west across Oklahoma into the Texas Panhandle. A distinct area of cross-contour flow was noted from Louisiana across Arkansas into Oklahoma. Overrunning precipitation that had developed in this area was being fueled by a field of mixing ratios that reached values as high as 11-12 g/kg near the Gulf of Mexico. The well-defined cross-contour flow and isentropic lift from Louisiana to Oklahoma may have been the combined product of the developing system and the indirect circulation underneath the exit region of the upper-level jet.

The synoptic pattern at 0000 UTC, January 19, included a surface low near the Mississippi/ Tennessee border. The 700 mb low was in eastern Oklahoma and the 500 mb low was in western Oklahoma. The 291K isentropic plot (Figure 2.4) showed a strong cyclonic circulation in Arkansas, Missouri, Kansas and northeast Oklahoma, in the vicinity of the 700 mb low. The circulation helped to enhance the isentropic lift as air was moved from higher to lower pressures by the cross-contour

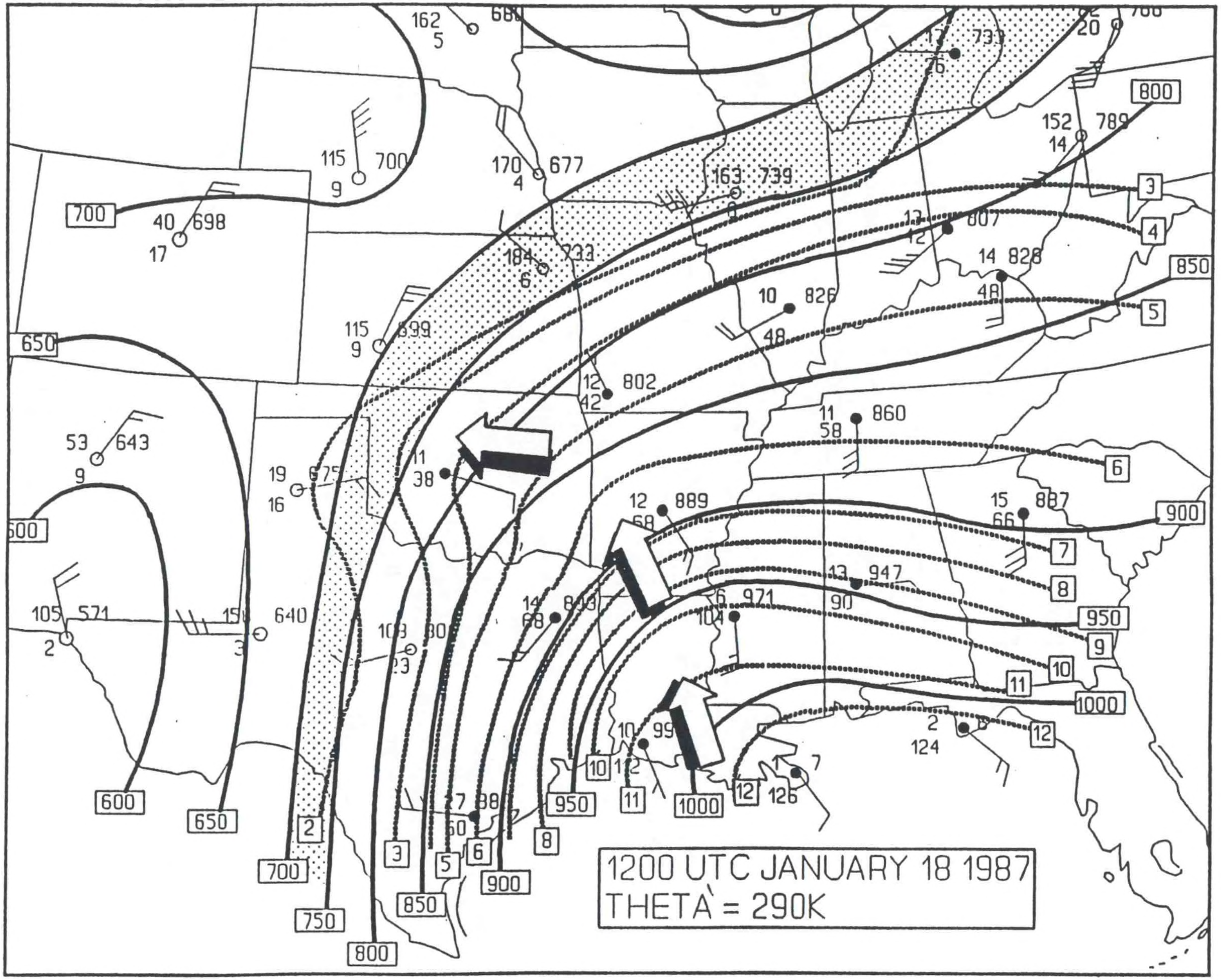


Figure 2.3 290K isentropic plot. Solid lines indicate pressure levels (mb). Dashed lines are mixing ratios analyzed every g/kg. Arrows denote rising motion.

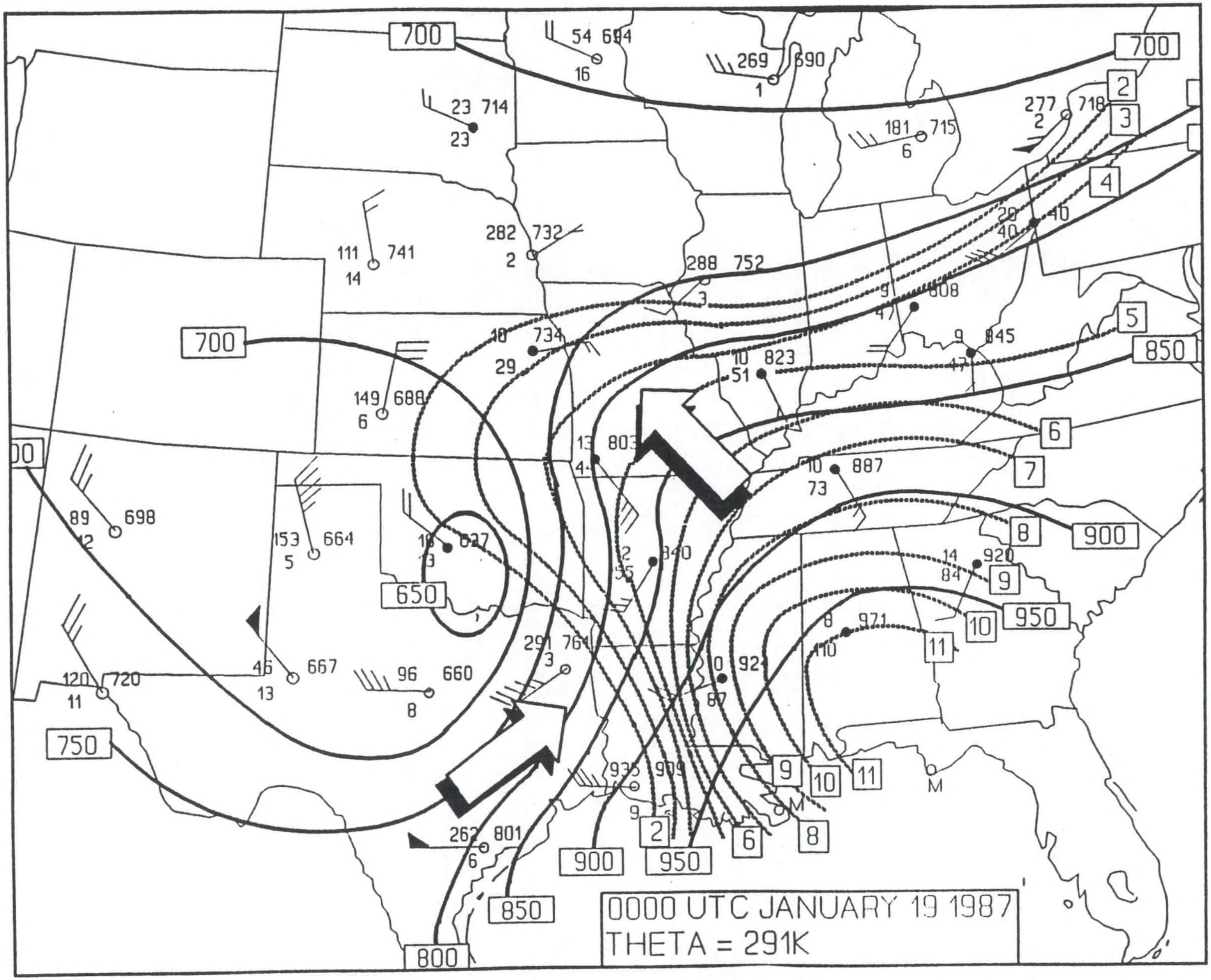


Figure 2.4 **291K isentropic plot. Arrow shown across Missouri denotes rising motion. Arrow in eastern Texas indicates sinking motion.**

flow. This lift was most evident in Missouri where moisture was being advected in by southeast winds to 30 knots at Monett, Missouri. The strong mixing ratio gradient had taken on the appearance of a "bulge" extending northwest from Alabama to Kansas and Oklahoma. Meanwhile, a cold dry wedge was moving east across Texas as air descended from lower to higher pressure and an S-curvature was beginning to develop in the pressure contours.

With the surface low and upper lows expected to track northeast, Missouri and central portions of Illinois and Indiana became the *"area of concern"*. Unfortunately, due to worries about snowfall potential in southern Wisconsin, the 700 to 750 mb layer was positioned there and <u>not</u> over the *"area of concern"* of this case study. Although a somewhat warmer isentropic level (293K for example) could have been plotted to place the 700 to 750 layer over Missouri and Illinois, the mixing ratios in the 750 to 800 layer closely approximated the values seen a little higher up. Ambient mixing ratios in the *"area of concern"* were in the 3-5 g/kg range with the possibility of advecting in 6-7 g/kg mixing ratios from the southeast. However, the variation in wind speeds from Monett, Missouri to Salem, Illinois to Nashville, Tennessee made it difficult to assign an advection speed (an average speed of 18 knots was assumed). With 3-5 g/kg over the *"area of concern"*, the potential for a 6 to 10 inch snowfall appeared quite high. Using the isentropic technique for averaging mixing ratios, the advection of 6-7 g/kg could produce an additional 1 to 2 inches.

By 1200 UTC, January 19, the pressure contours on the 290K isentropic plot (Figure 2.5) were showing the distinct S-curvature of a mature and occluding weather system. The surface low was entering southern Indiana, while the 700 mb low was over central Illinois and the 500 mb low over southern Missouri. There was a widespread area of light snow occurring across the middle Mississippi and Ohio Valley with a band of moderate-heavy snow from Missouri to central Illinois. As with the previous plot, the 700 to 750 mb layer was not positioned directly over the *"area of concern"* due to snowfall concerns for Wisconsin. However, mixing ratio values near the 750 mb layer cut-off indicated mixing ratios in the *"area of concern"* would likely have been in the 3-5 g/kg range as depicted on the 290K plot. The wrap-around circulation of the system continued to pull moisture westward with 6-7 g/kg mixing ratios in northeast Kentucky. Once again, the speed of the advection wind was difficult to determine since no upper air data was available over Indiana and only a weak southeast wind of 5 knots was noted at Dayton, Ohio. The best forecast strategy for situations, such as this, is to use ambient mixing ratio values over the *"area of concern"* as the basis of a maximum snowfall forecast, keeping in mind that <u>strong</u> moisture advection could increase the snowfall totals by a few inches.

The heavy snow would eventually spread from Indiana into northwest Ohio and southeastern lower Michigan. The snowfall map for January 19, 1987 (Figure 2.6), shows the snowfall band over a portion of the *"area of concern"*.

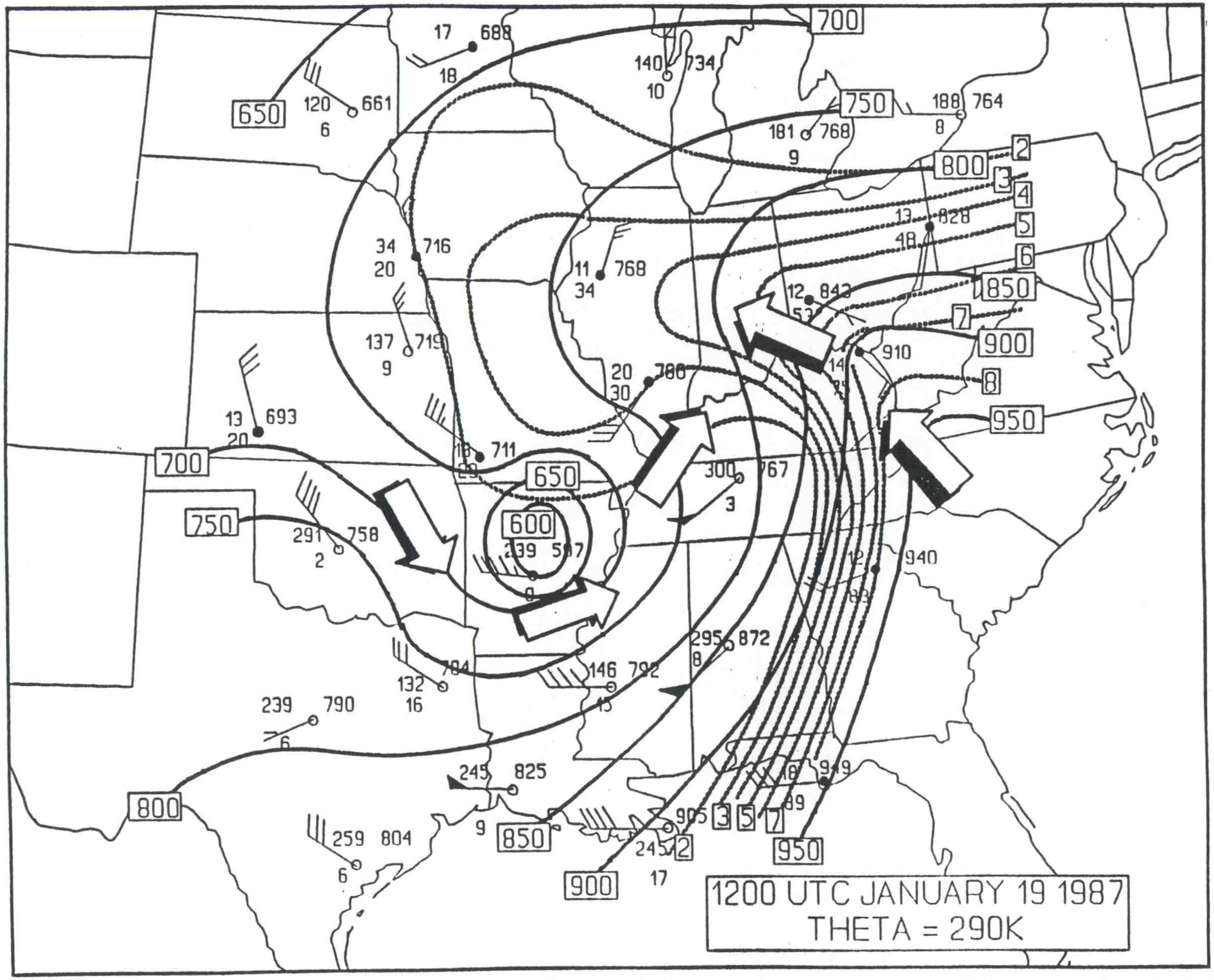


Figure 2.5 290K isentropic plot. Arrows from North Carolina to central Indiana denote rising motion. Other arrows show circulation around the upper trough and sinking air from Arkansas to Indiana.

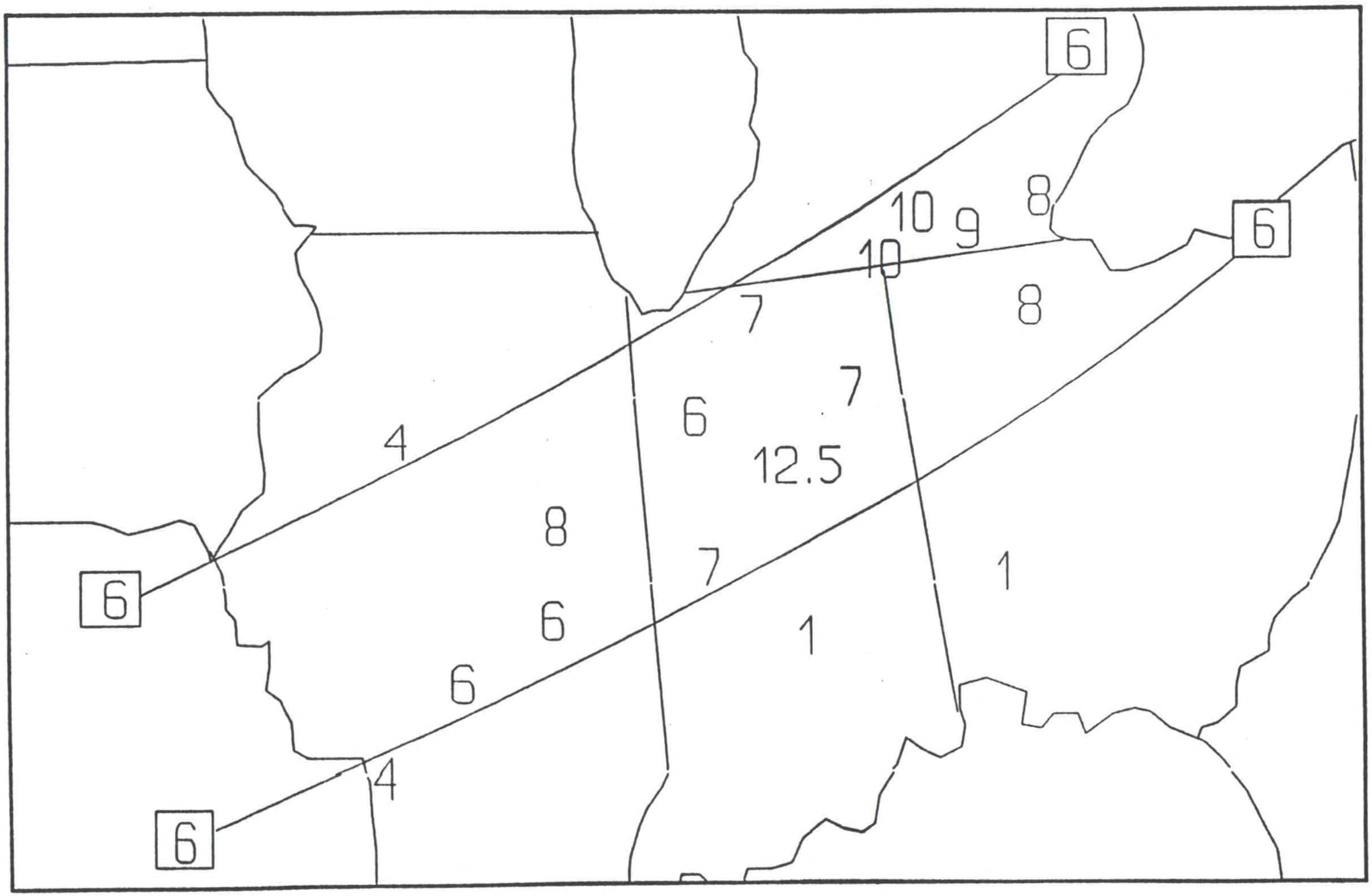


Figure 2.6 Snowfall totals (inches) - January 19, 1987.

C. Heavy Snowfall Event October 31 - November 2 1991

A major winter storm struck Minnesota and northwestern Wisconsin, during the period from October 31 - November 2, 1991. The storm produced strong winds and dumped 2 to 3 feet of snow in that area. It was dubbed *"The MegaStorm"* by the National Weather Service Forecast Office in Minneapolis. This case study is not intended to be a complete and definitive work on this storm, since the emphasis will be on isentropic analyses.

A sequence of surface maps (Figures A-F) from 0600 UTC 1 November to 1200 UTC 2 November 1991 are provided on the following page. The sequence begins with the surface low in northeast Missouri (Figure A) and ends with its position over Lake Superior (Figure F). The extratropical cyclone had originated in southeast Texas.

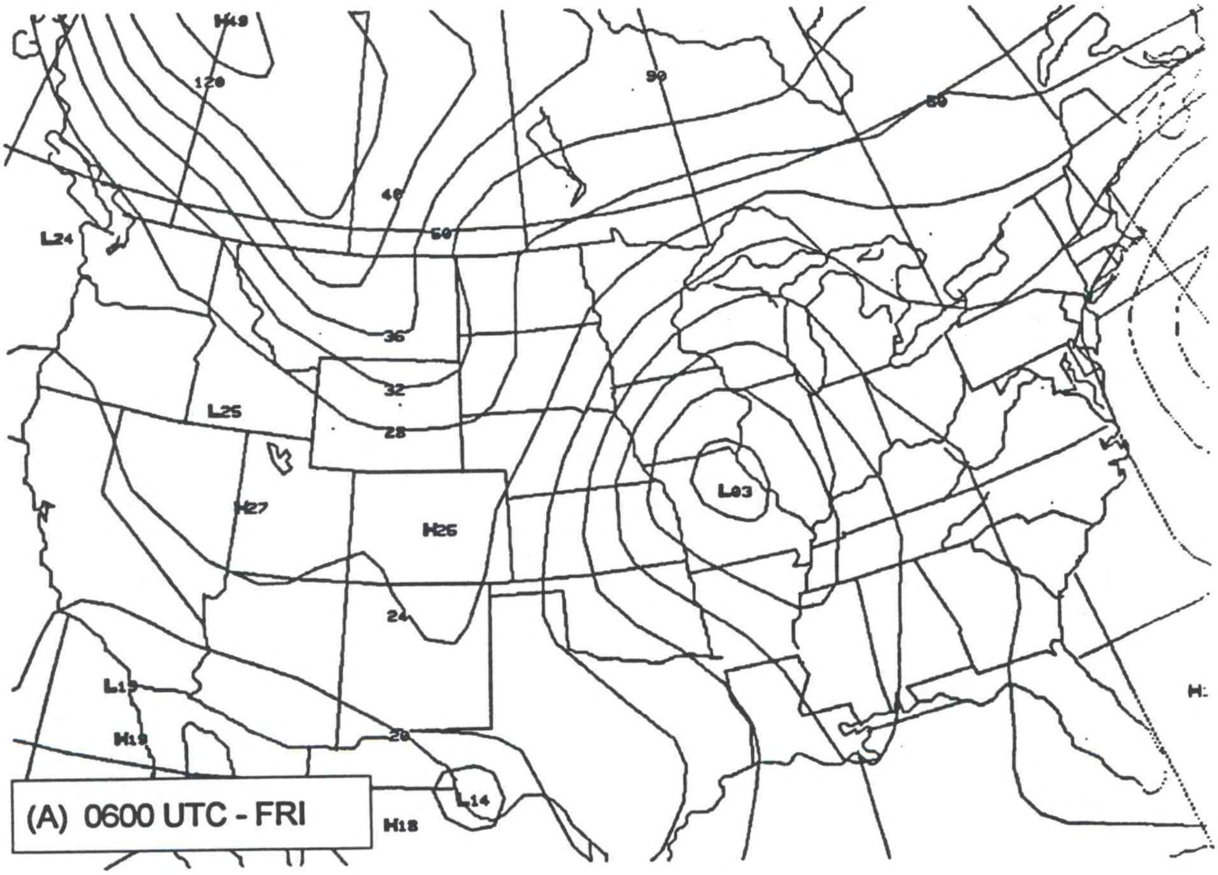
The rapid intensification and slow movement of the storm to the north-northeast, would allow for a large amount of moisture to be drawn into the system from the Gulf of Mexico. The storm was preceded by a period of warm air advection (overrunning) snowfall that produced 1 to 3 inches from Minneapolis to Duluth, Minnesota and in northwest Wisconsin before 0000 UTC 1 November.

In addition to the large volume of moisture being transported northward, mild air (above 0 °C) was reaching well into the middle layer of the atmosphere (700 mb) over Wisconsin and Minnesota. One of the forecast difficulties associated with this winter storm was determining the exact geographic location of the change-over from rain to snow. Although all of Minnesota would remain cold enough for snow, Wisconsin would experience a mixture of precipitation types including rain, snow, freezing rain and sleet.

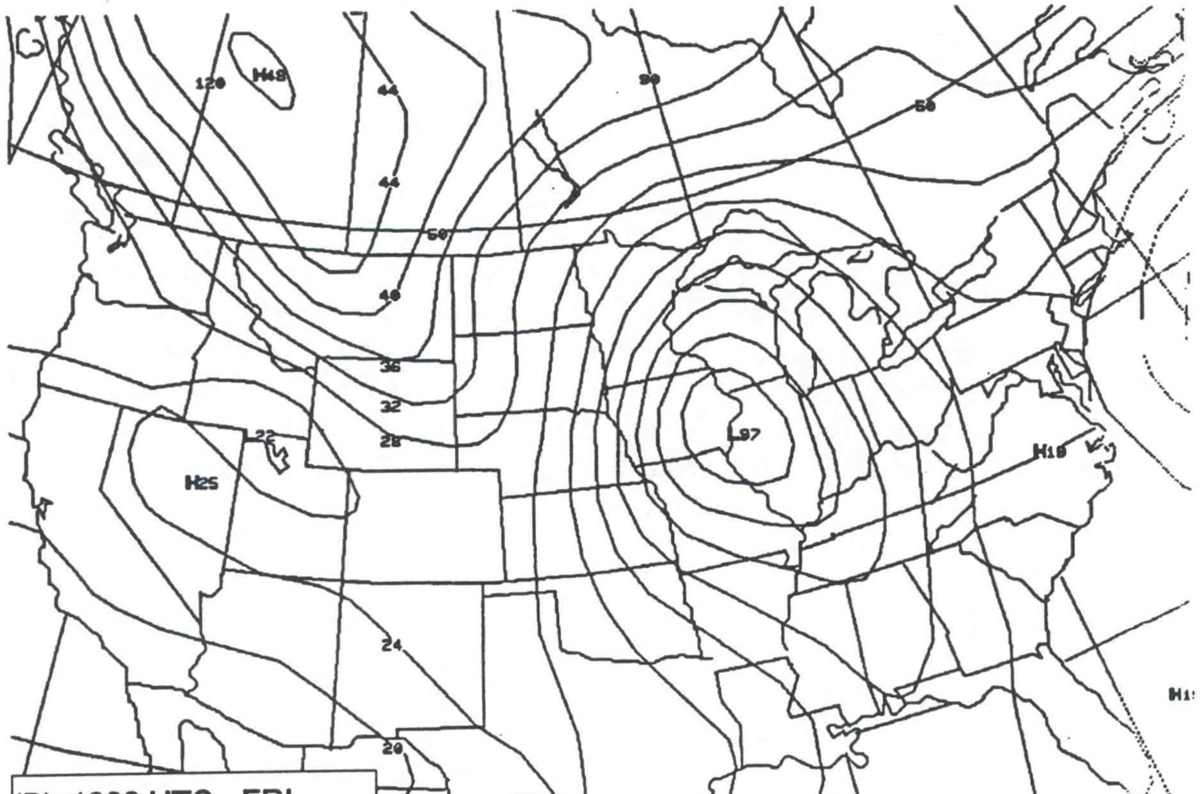
This snow event differs from the other case studies in this paper, since the time duration for this event surpassed 48 hours. This necessitates a slightly different approach that provides a *cumulative* method of forecasting snowfall when the initial 12-hour period is exceeded. The *cumulative* method emphasizes steps 6 and 7 of **The Technique**. However, these steps must be carried out for each and every 12-hour period that the snow event is in progress. The main purpose of the *cumulative* method is to provide a **"nowcast"** tool that can be used when snow continues to accumulate during an extended winter storm.

To briefly summarize Steps 6 and 7:

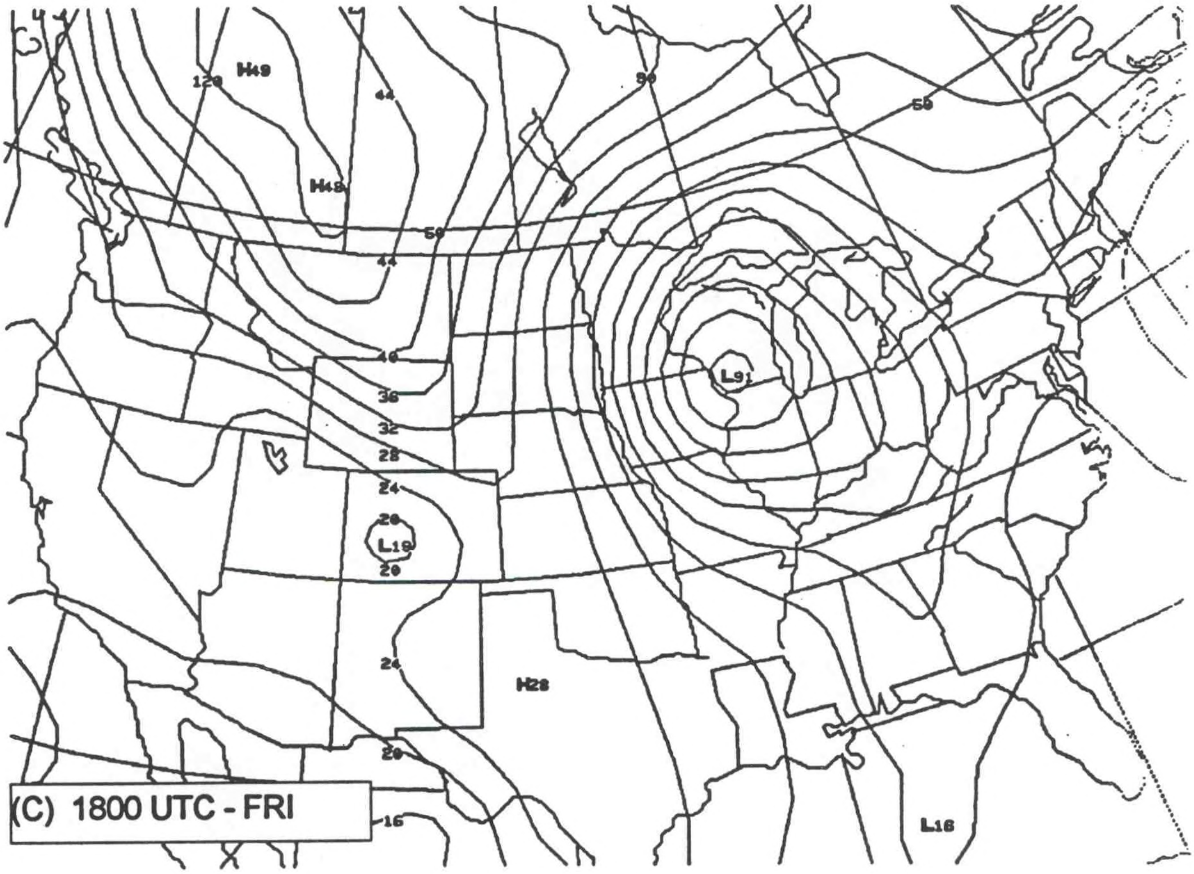
6. Determine an effective mixing ratio value for the 12-hour period. This can be calculated by <u>averaging</u> the ambient mixing ratio over the *"area of concern"* and the maximum mixing ratio that can be advected into this area.



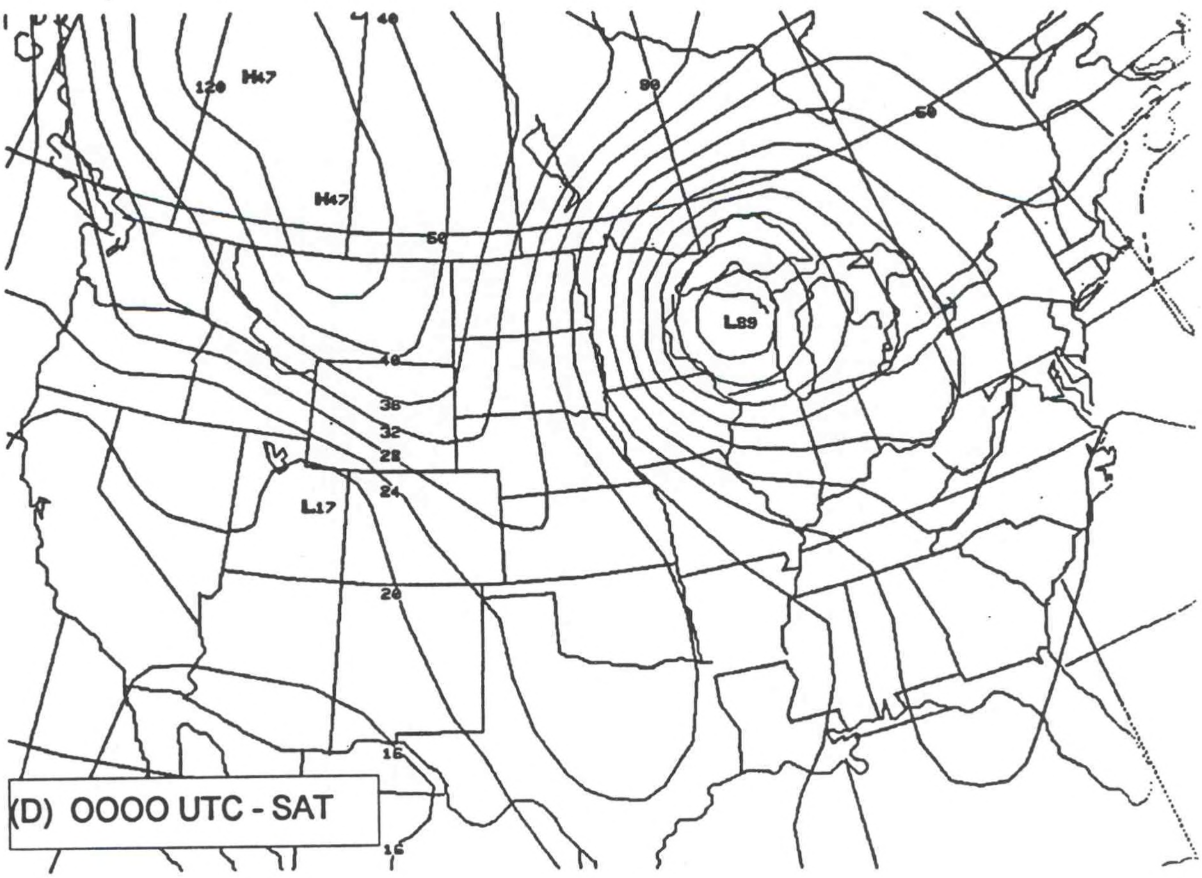
(A) 0600 UTC - FRI
L03
H26
L25
H27
L24
L14
H18



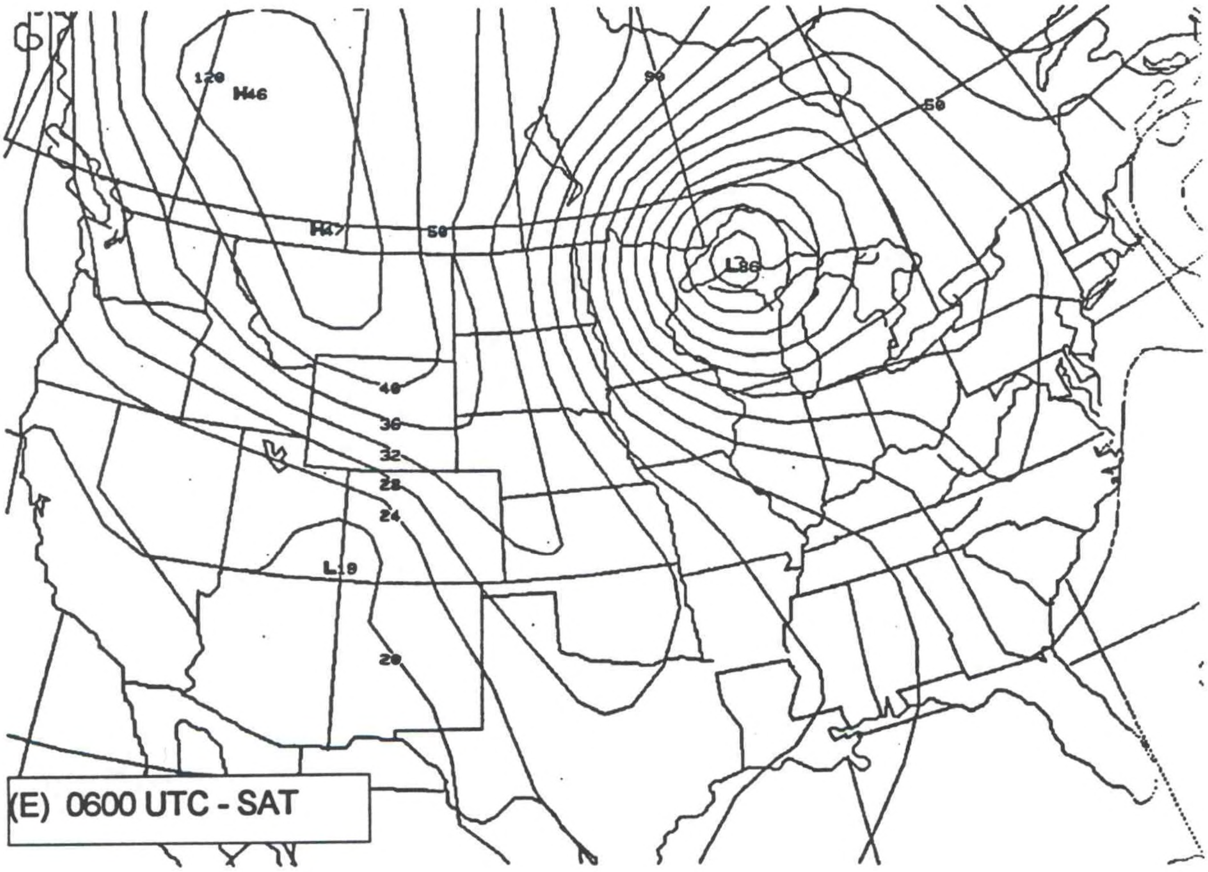
(B) 1200 UTC - FRI
L97
H25
H48

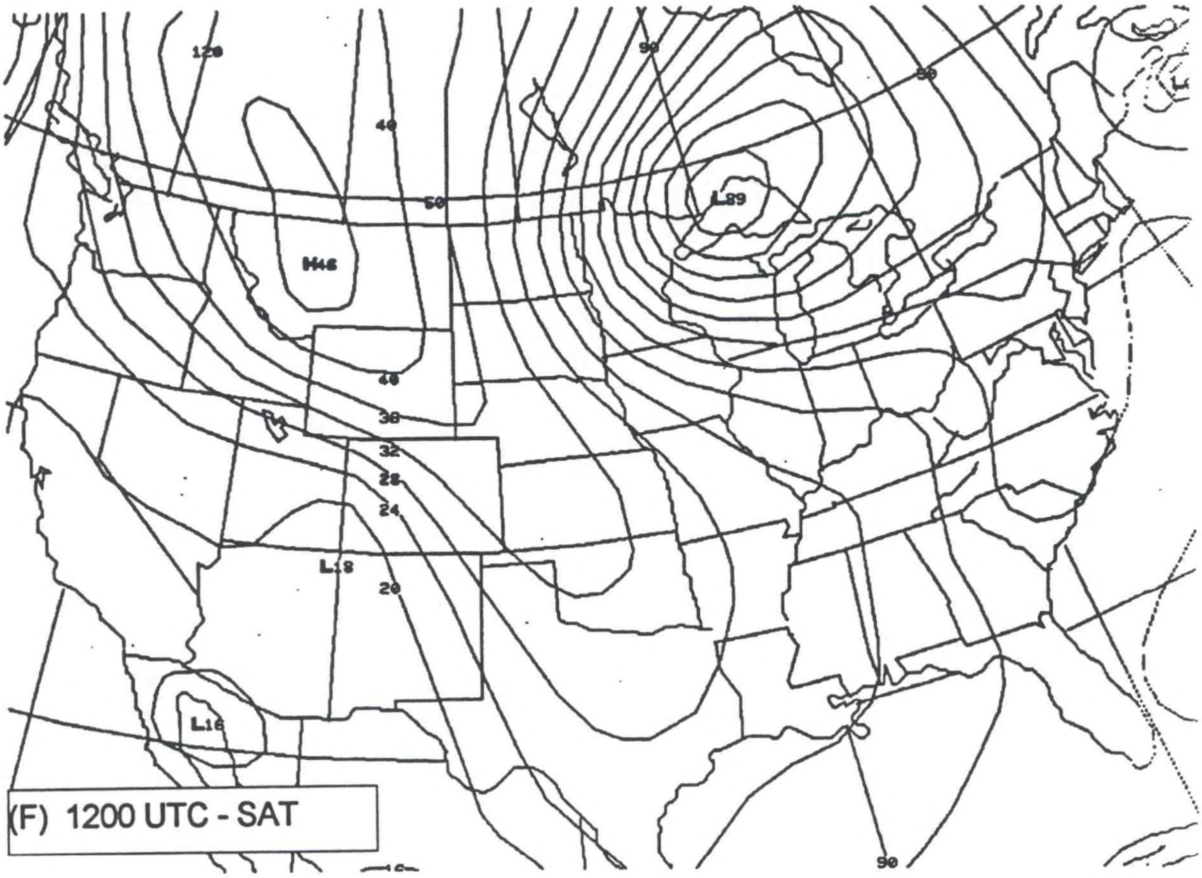


(C) 1800 UTC - FRI



(D) OOOO UTC - SAT


(E) 0600 UTC - SAT


(F) 1200 UTC - SAT

7. Determine whether the strong dynamic forcing (lift) necessary for maximum snowfall (i.e. extra-tropical cyclone, vorticity maximum, jet streak, etc.) will exist for most or just part of the 12-hour period. This will be a subjective opinion based on analyses and observations or an opinion based partially or wholly on model output. However it is made, this determination will have an impact on whether the potential" snowfall is actually realized.

The 295K isentropic plot at 0000 UTC 1 November (Figure 3.0) placed the 700 to 750 mb layer over Minnesota and extreme northwest Wisconsin. A tight mixing ratio gradient was already evident from this area southward. Mixing ratios from 3-4 g/kg over the *"area of concern"* increased to a high value of 10.4 g/kg at Paducah, Kentucky.

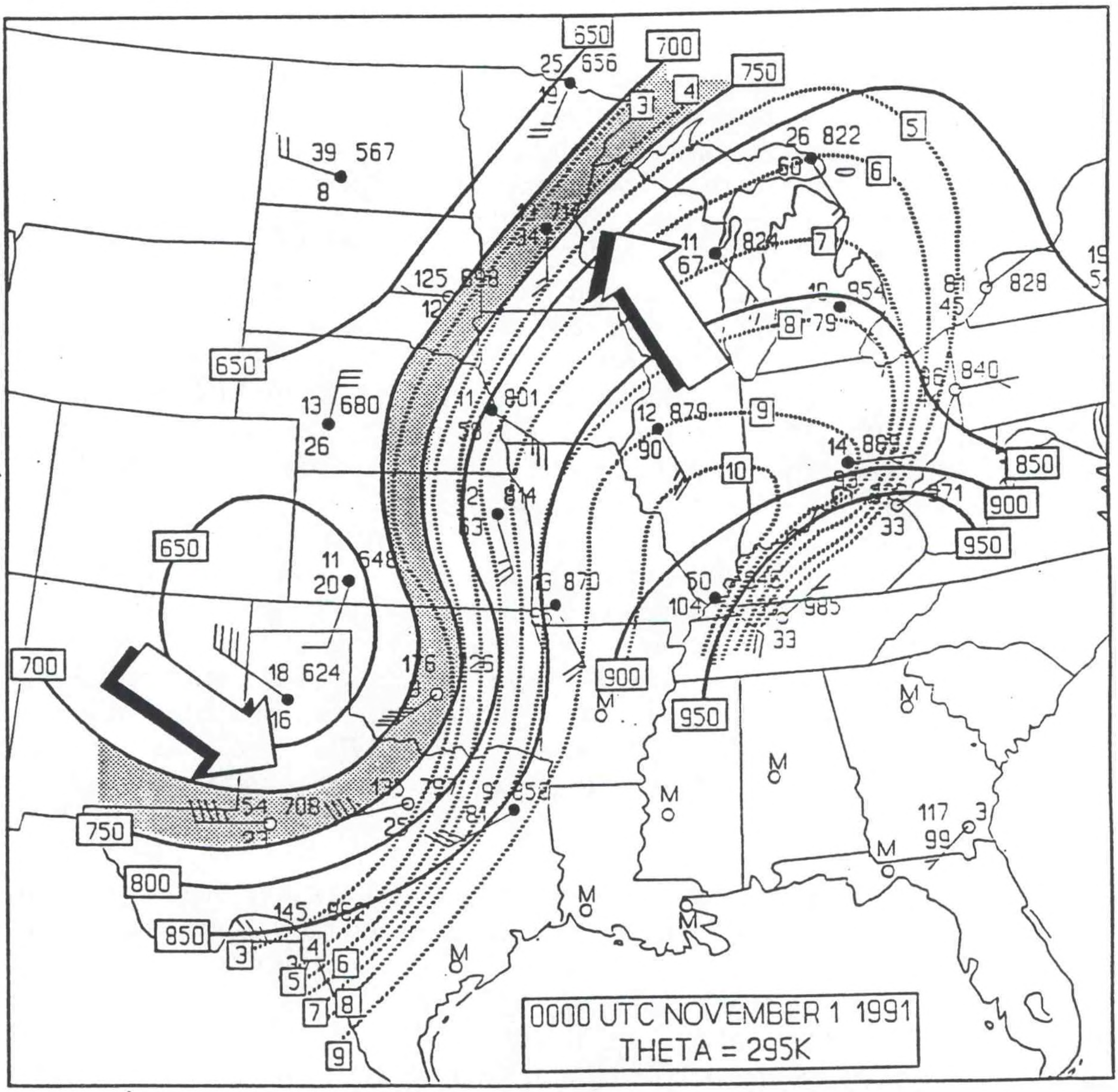


Figure 3.0 295K isentropic plot. The 700-750 mb layer is shaded for emphasis. Arrow over Wisconsin denotes rising motion, while arrow over the Texas Panhandle shows sinking motion.

A 30 knot southeast wind at Green Bay, Wisconsin suggested that the air that would arrive in the Duluth area 12 hours later, would come from a point over southern Lake Michigan (a distance of just over 400 miles). A parcel of air moving along this trajectory on the 295K isentrope could theoretically rise 145 millibars during the next 12 hours or roughly at the rate of 3.4 microbars per second.

At 0000 UTC, the analyzed mixing ratio value at Minneapolis was about 5 g/kg and the interpolated mixing ratio at Duluth, 3.5 g/kg. With a maximum mixing ratio of 8 g/kg, over southern Lake Michigan, the averaged 12 hour mixing ratio for Minneapolis would be 6.5 g/kg and 5.5 g/kg for Duluth. This would yield *maximum* snowfall amounts of 13 inches and 11 inches respectively for the 12-hour period.

Officially, Minneapolis received 11.6 inches during this period and Duluth measured 7.7 inches. In extreme northwest Wisconsin, the town of Luck reported 9 inches. Several cooperative observers in this same area near the Minnesota border reported snowfall totals of 8 to 12 inches by 1200 UTC, but it is not certain whether the observers' snow fell within the 12-hour window.

At 1200 UTC, the 295K isentropic surface was used again since it continued to place the 700 to 750 mb layer over the "*area of concern*" (Figure 3.1). This fortunately also allowed continuity with the 0000 UTC plot. The 295K surface had only dropped slightly (from 717 mb to 721 mb) at Saint Cloud, MN between 0000 UTC and 1200 UTC. The pressure contour and mixing ratio fields continued to push northward and intensify as the warm advection became more pronounced from the Gulf of Mexico to the Great Lakes region.

A cold, dry pocket of air wrapped around from the Dakotas through Kansas and into Missouri. Southeast winds had strengthened to 50 knots at Peoria, Illinois and 35 knots at Green Bay, but were only about 10 knots at Saint Cloud. This wind field implied that strong convergence was occurring in the area bounded by these stations and this was confirmed by the dense gradient of mixing ratios as the moisture *piled* into eastern Minnesota and northwest Wisconsin. The mixing ratio at Minneapolis had increased to near 6 g/kg and to an interpolated value of slightly over 4 g/kg at Duluth.

The storm was now located near Moline, Illinois and had deepened to 997 mb (Figure B). It was expected to remain on a track to the north-northeast which would keep northwest Wisconsin and eastern Minnesota in the heavy snow area. With the possibility that the 9 g/kg mixing ratio entering southern Wisconsin would be advected into the "*area of concern*" (Figure 3.1), the averaged values for Minneapolis and Duluth were 7.5 g/kg and 6.5 g/kg, respectively. The *maximum* snowfall for the next 12 hours could be an additional 15 inches at Minneapolis and 13 inches at Duluth. However, since the forecast models were moving the surface

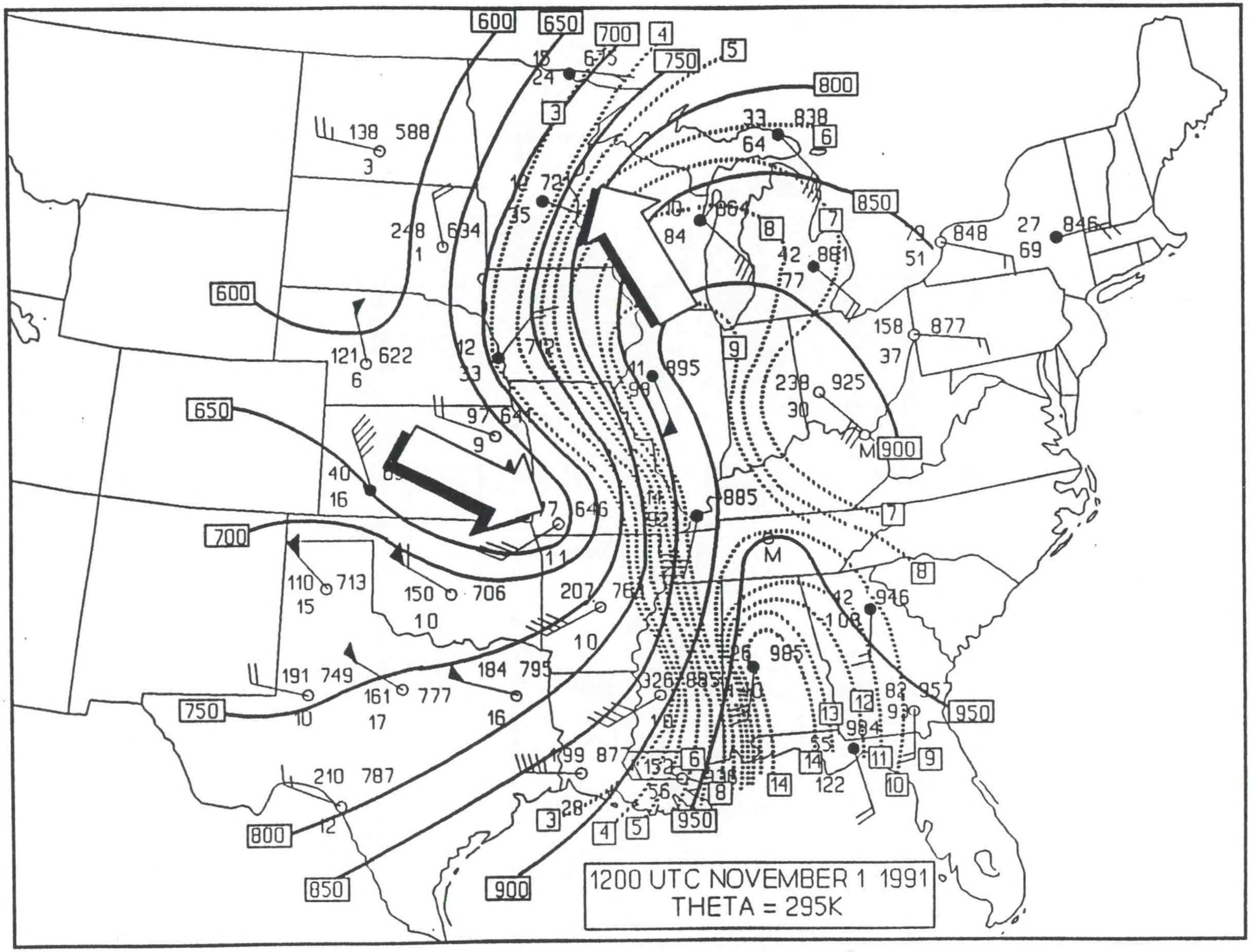


Figure 3.1 295K isentropic plot. Arrow over Wisconsin signifies rising motion. Arrow over Kansas shows entrainment of dry air and sinking motion.

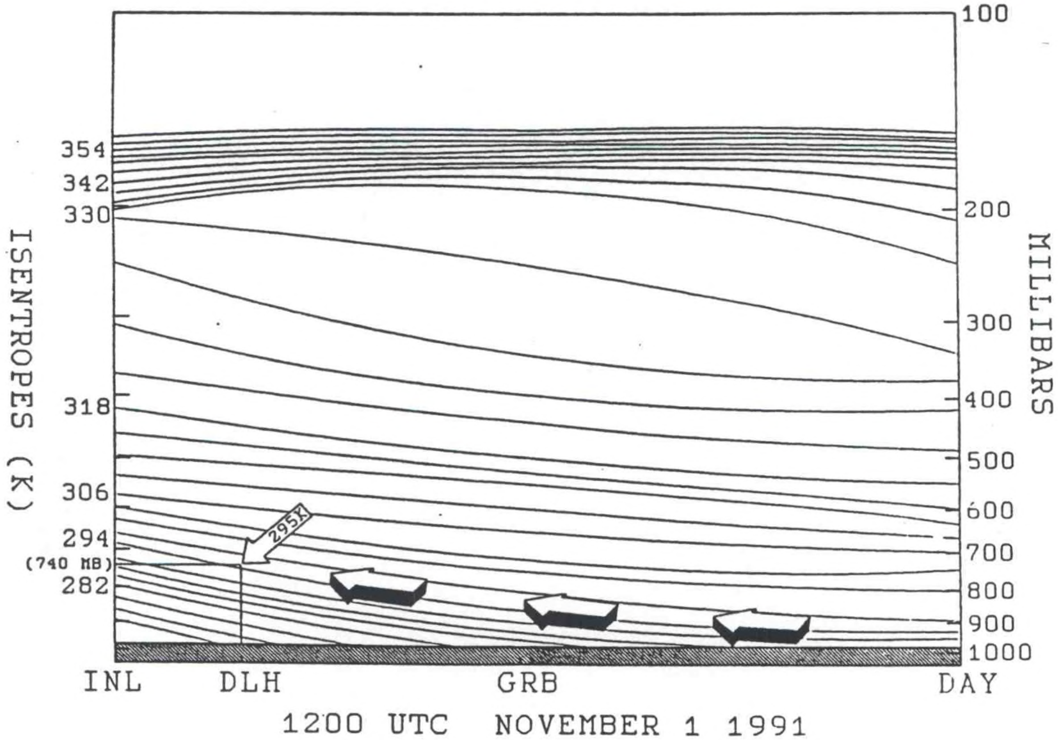
low to the northeast of Minneapolis during the latter part of this period (Figure D), the maximum potential snowfall would not be realized at Minneapolis because as the low moved north:

1. The lift dynamics would be on the decrease, and
2. The moist southeast flow would be cut off.

Officially, the measured snowfall at Duluth was 13.8 inches (near the maximum potential) with 9.3 inches at Minneapolis (well short of the potential maximum) during this 12 hour period.

At 0000 UTC 2 November, the 295K isentropic surface continued to place the 700-750 mb layer over northwest Wisconsin and northeast Minnesota (Figure 3.2). The 295K isentropic surface had provided 24 hours of continuity over the same area which, in itself, may be a rarity associated only with the most intense of winter cyclones. This was likely due to the strong circulation that wrapped a good deal of mild air around the storm. This kept the isentropic surfaces from rising by balancing out the evaporative cooling that was occurring over the heavy precipitation area.

The diagram below shows the isentropic cross-section used to locate the 700-750 mb layer over Duluth and the *"area of concern"*. In this case, the closest cross-section available extended from International Falls, Minnesota to Green Bay to Dayton, Ohio. The cross-section bisected the *"area of concern"*, parallel to the prevailing flow. Once the approximate location of this layer over Duluth was identified, the isentrope corresponding best to this point was plotted. Note, the upward lift supplied by the flow moving along the sloping isentropic surfaces.



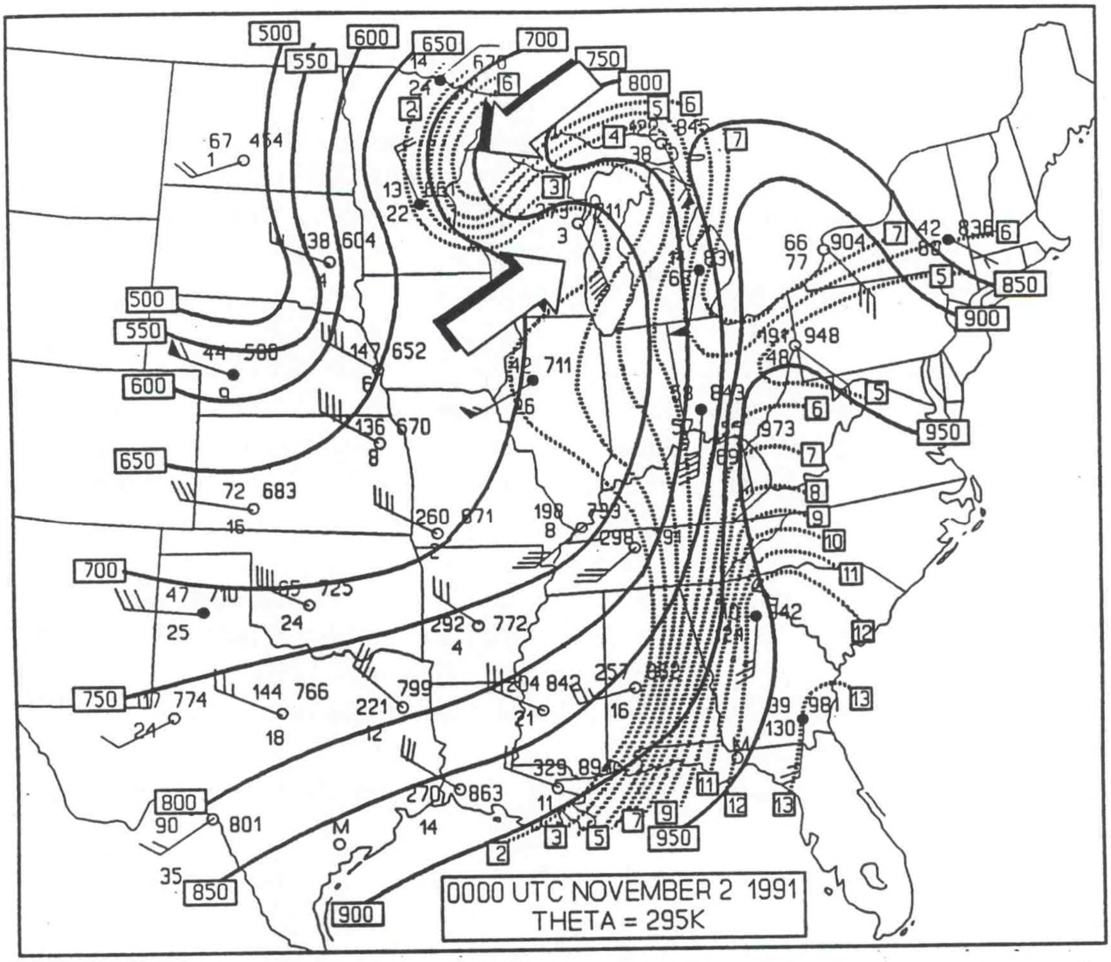


Figure 3.2 **295K isentropic plot. Arrow over northwest Wisconsin denotes wrap-around circulation and area of higher mixing ratios. Arrow over southwest Wisconsin shows dry air intrusion.**

It was also apparent from this isentropic plot that the strong circulation was keeping the coldest air just outside of the *"area of concern"*. However, the cold and dry air that was being drawn into the region behind the storm had shifted the pressure and mixing ratio isolines farther to the east and north. The moist southeast low level jet earlier noted at Peoria (Figures 3.0 and 3.1) had become a dry southwest low level jet as the cold air advection forced the 295K surface upward from 895 mb at 1200 UTC (Figure 3.1) to 711 mb at 0000 UTC (Figure 3.2). The 295K isentropic surface at Green Bay had also risen to 711 mb as the cold air surged in around the upper low, even though the wind at Green Bay was still southeast at 40 knots.

The intense circulation around the storm had contorted the isobars into a pronounced S-curve signature. This was also reflected in the moisture gradient field as the mixing ratios wrapped around to the west across northern Wisconsin.

The surface low at this time had deepened to 989 mb (Figure D) and had been dubbed *"The MegaStorm"*. The central pressure would eventually drop to 986 mb over Upper Michigan at 0600 UTC 2 November (Figure E) before beginning to fill (Figure F).

The mixing ratios by 0000 UTC 2 November over the *"area of concern"* were around 3 g/kg at Minneapolis and just over 6 g/kg at Duluth (Figure 3.2). No additional moisture advection was expected at this point. The ambient mixing ratio values could convert to 6 and 12 inches respectively. However again, the dry air advection and decreasing lift would limit potential snowfall during the next 12 hours as the low moved north across Lake Superior.

Therefore, instead of the maximum potential snowfall of 6 inches, Minneapolis received an additional 3.8 inches. At Duluth, 9.2 inches fell instead of a possible maximum of 12 inches between 0000 and 1200 UTC 2 November. Duluth would go on to record another 4.4 inches between 1200 UTC 2 November and 0000 UTC 3 November.

During the 48-hour period between 0000 UTC 1 November and 0000 UTC 3 November, Minneapolis recorded 24.9 inches and Duluth 35.1 inches. Total accumulations for the event were 27.7 inches and 36.5 inches, respectively. Most locations in extreme northwest Wisconsin reported snowfalls between 24 and 30 inches for the storm (Figure 3.3).

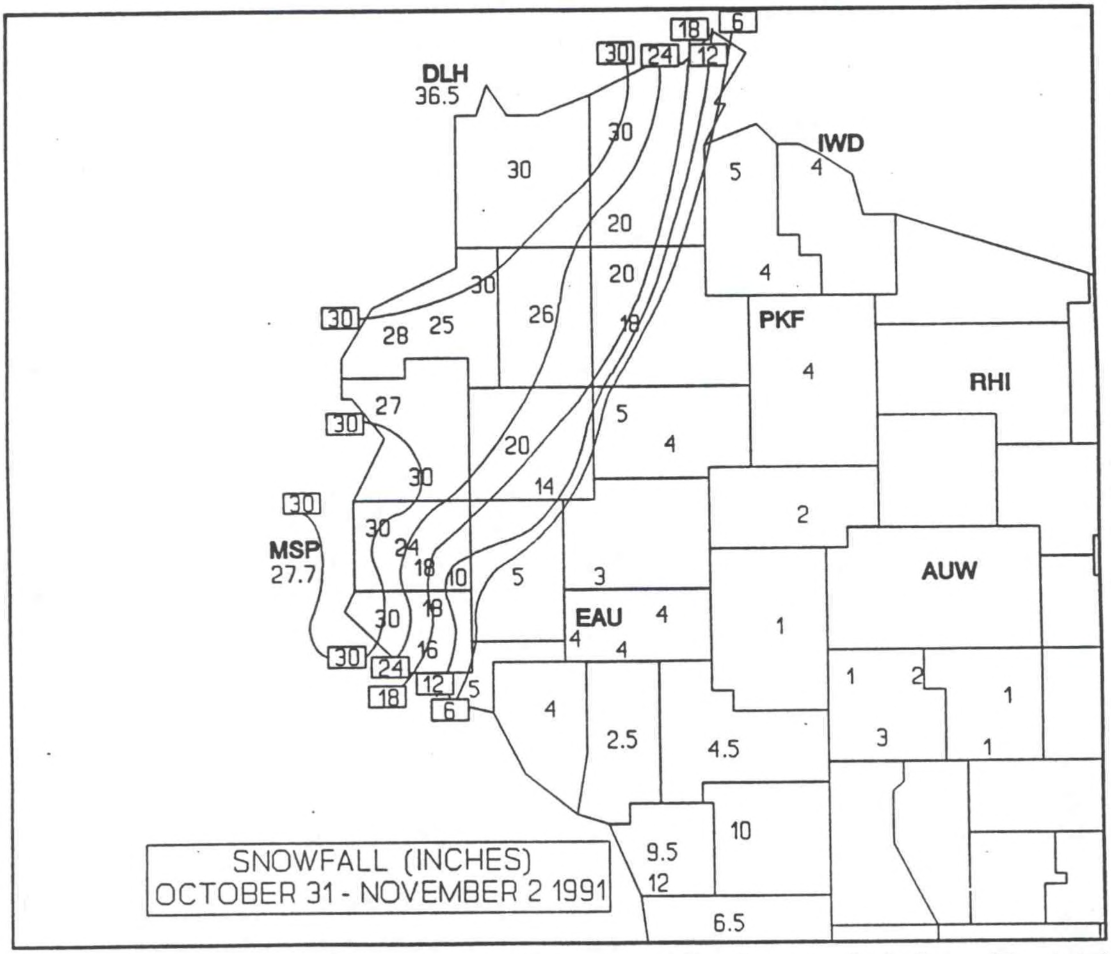


Figure 3.3 Snowfall totals for northwest Wisconsin analyzed every six inches. The totals for the adjacent cities of Minneapolis and Duluth, Minnesota are also included.

6. FUTURE APPLICATIONS

During the past winter, our office began to utilize data from the wind profiler network installed across the central portion of the U.S. to fill in the wind information void between rawinsonde releases. The profiler network can supply hourly wind plots at standard pressure levels and individual wind profilers can provide hourly time sections, hodographs, and other derived fields. When used in conjunction with analyzed isentropic information, the profiler network can be used to confirm or adjust the advection forecast outlined in Step 6 of **The Technique**. The more pertinent hourly wind plots would be the 900 mb (FMA), 850 mb (8MA), and 700 mb (7MA) levels. The wind profiler network has been proving to be a new and exciting way to watch the development of wind fields, especially the low level jets associated with extra-tropical cyclones.

Operational use of PCGRIDDS (Meier, 1993), using gridded data from the NGM and Eta models, with its ability to forecast isentropic surfaces, is proving to be another powerful tool for the field forecaster. After downloading the gridded model data from Kansas City into our ORAT (Operational/Research And Training) computer, we use the hand-analyzed isentropic surface determined by **The Technique** as our "reference" surface. After comparing the model initialization with our reference for accuracy, a series of isentropic surfaces are computed from 12 to 48 hours. Each isentropic surface depicts pressure contours, mixing ratios, and a wind field in knots. The PCGRIDDS computer program allows us to determine a range of potential temperatures, for example 280-290K, which are set to run with a temperature interval of 2 degrees Kelvin. The selected isentropic temperature surface is followed every 12 hours as long as it keeps the 700-750 mb layer over the *"area of concern"*. However, once the continuity is broken, another potential temperature is chosen that maintains the 700-750 mb layer over the *"area of concern"*. The mixing ratio analysis on the isentropic surface can be set to produce isolines every one gram per kilogram, which provides an excellent moisture field resolution. A word of caution may be necessary here. All of the forecasted isentropic information obtained from PCGRIDDS will only be as good as the gridded model data itself. If it becomes apparent that the data is incorrect during the initial 12-hour period, the forecaster will still be able to make necessary adjustments to the data to get some benefit from the information. In one particular situation last winter, a forecaster detected a low level jet on the profiler network where the gridded model data was only showing a 10-15 knot wind. This information allowed the forecaster to successfully increase the amount of moisture advection (maximum mixing ratio) and the corresponding snowfall forecast.

7. CONCLUDING REMARKS

An operational forecaster should expect to spend about 30 minutes analyzing isentropic information upon the receipt of new upper air data. An isentropic cross-section usually runs on AFOS in less than one minute, while the tailored isentropic plot generally takes 3 or 4 minutes. It is important to reemphasize that a detailed analysis of the mixing ratios, preferably every 1 g/kg, is essential in observing how moisture fields advance and recede during the lifecycle of a winter storm or snow event.

The availability of quantitative moisture values (isentropic mixing ratios) on a real-time basis (every 12 hours) has become an important asset to the field forecaster. With the capability of looking at overlying moisture fields (depending on the number of isentropic temperature surfaces plotted), a three-dimensional world of moisture advection can be utilized to predict maximum snowfall in a pre-defined area. However, it is beyond the scope of this paper to delve into the various "rules of thumb" that pre-define the *"area of concern"* for heavy snowfall. The mixing ratio forecast technique detailed in this paper helps to answer the question of "how much", but *not* the question of "where". There are many excellent papers and computer programs available that deal with the forecast placement of heavy snowfall. The isentropic forecast procedure outlined in this paper is not a stand-alone technique, but should be part of a comprehensive approach that includes all of the tools and data at the forecaster's disposal.

8. ACKNOWLEDGEMENTS

I wish to thank the forecast staff at WSFO Sullivan/Milwaukee, Wisconsin for their encouragement and willingness to experiment with this snowfall forecasting technique. My appreciation to Tim Oster for his comments on the initial draft of this paper and to Theodore W. Funk, WSFO Louisville for his helpful critique of this manuscript. I also wish to thank Steve Davis for his help and advice on using $\text{DRAWPERFECT}_{\text{TM}}$ to generate the graphics included in this paper.

9. REFERENCES

Byers, H. R., 1959: General Meteorology. 3rd Edition. McGraw-Hill Inc., New York, 353.

Bothwell, P. D., 1985: AFOS Data Analysis Programs, NOAA Tech. Memo. NWS SR-114, Fort Worth, Texas, 73.

Chaston, P., 1989: The Magic Chart for Forecasting Snow Amounts. *Nat. Wea. Dig.*, **14**, 20-22.

Little, C. D., 1985: Isentropic Plotter. NOAA Eastern Region Computer Programs and Problems, NWSA ERCP-No.29, NOAA, U.S. Dept. of Commerce, 10 (rev. December 1989).

Meier, K. W., 1993: *PCGRIDDS User's Manual,* Scientific Services Division, NWS Western Region, 27.

10. BIBLIOGRAPHY

Anderson, J. L., 1984: The Use and Interpretation of Isentropic Analysis. NOAA Tech. Memo. NWS WR-188, NWS Western Region, Salt Lake City, UT, 40.

__________, 1984: Isentropic Objective Analysis. NOAA Western Region Computer Programs and Problems, NWS WRCP-No. 47, NOAA, U. S. Dept. of Commerce, 16.

Moore, J. T., 1988: Isentropic Analysis and Interpretation: Operational Applications to Synoptic and Mesoscale Forecast Problems. St. Louis University, Dept. of Earth and Atmospheric Sciences, St. Louis, MO, 116.

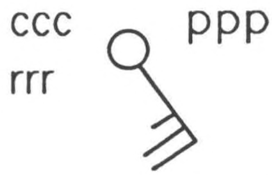
Oliver, V. J. and M. B. Oliver, 1945: Forecasting the Weather with the Aid of Upper-Air Data. *Handbook of Meteorology.* McGraw-Hill Inc., New York, 813-857.

Uccellini, L. W., 1976: Operational Diagnostic Applications of Isentropic Analysis. *Nat. Wea. Dig.*, 1, 4-12.

__________, L. W., D. Keyser, K. F. Brill, and C. H. Wash, 1985: The President's Day Cyclone of 18-19 February 1979: Influence of Upstream Trough Amplification and Associated Tropopause Folding on Rapid Cyclogensis. *Mon. Wea. Rev.*, **113**, 962-988.

Wilson, L. J., S. Sick, and B. Marcis, 1980: Operational Application of Isentropic Analysis to the Diagnosis of Severe Convective Weather Threat Areas. *Preprints - Eighth Conference on Weather Forecasting and Analysis*, Denver, AMS (Boston), 166-173.

Isentropic Plot
Station Model



ppp = pressure of isentropic surface (mb)

ccc = difference (mb) between pressure at isentropic surface and condensation pressure

rrr = mixing ratio (g/kg x 10)
wind speed (knots)

Definition:

An isentropic surface chart depicts meteorological parameters on a surface of constant potential temperature θ. Potential temperature is defined as the temperature a parcel of air would have if it were transported adiabatically to a pressure of 1000 mb. This definition allows the potential temperature to be computed as:

$$\theta = T\,(1000/P)^{R/C_p}$$

T = temperature P = pressure
R = the gas constant
C_p = the specific heat of dry air at constant pressure

APPENDIX B

"RULES OF THUMB" FOR HEAVY SNOW BAND PLACEMENT

The "rules of thumb" listed below were extracted from many different papers, publications, and other sources. They were compiled into The Winter Book, a WSFO Sullivan/Milwaukee station manual, by forecaster John Haase.

The heavy snow band is located:

1. 120 to 150 miles left of the surface low track.

2. 90 miles left of the 850 mb low track.

3. Along the track of the 700 mb and/or 500 mb low.

4. Vicinity of 500 mb vorticity maximum (vort max) path: varies from 60 miles left of the vort max in open trough or shear zone, to 150 miles left of vort max in circulation center or closed low.

5. North of the 700 mb closed contour.

6. Just to the north of the 164 height line at 200 mb.

7. Between the -2 °C to -5 °C temperature at 850 mb.

8. Between the 534 to 540 thickness contours.

9. Near the mean 500 mb temperature of -30 °C.

10. At the surface temperature of 27 to 35 °F.

11. Between the -5 °C to -10 °C temperature at 700 mb (a few offices in the northern part of the U.S. prefer to use -11 °C).

Other rules and techniques:

12. K index values of 10 to 20 needed in source region for heavy snow.

13. Various satellite techniques for placement of heavy snow bands (Morrison, Johnston, among others).

NWS CR 47 Practical Application of a Graphical Method of Geostrophic Wind Determination. C.B. Johnson, November 1971 (COM 71-01084).
NWS CR 48 Manual of Great Lakes Ice Forecasting. C. Robert Snider, December 1971 (COM 72-10143).
NWS CR 49 A Preliminary Transport Wind and Mixing Height Climatology, St. Louis, Missouri. Donald E. Wuerch, Albert J. Courtois, Carl Ewald, Gary Ernst, June 1972 (COM 72-10859).
NWS CR 50 An Objective Forecast Technique for Colorado Downslope Winds. Wayne E. Sangster, December 1972 (COM 73-10280).
NWS CR 51 Effect on Temperature and Precipitation of Observation Site Change at Columbia, Missouri. Warren M. Wisner, March 1973 (COM 73-10734).
NWS CR 52 Cold Air Funnel Clouds. Jack R. Cooley and Marshall E. Soderberg, September 1973, (COM 73-11753/AS).
NWS CR 53 The Frequency of Potentially Unfavorable Temperature Conditions in St. Louis, Missouri. Warren M. Wisner, October 1973.
NWS CR 54 Objective Probabilities of Severe Thunderstorms Using Predictors from FOUS and Observed Surface Data. Clarence A. David, May 1974 (COM 74-11258/AS).
NWS CR 55 Detecting and Predicting Severe Thunderstorms Using Radar and Sferics. John V. Graff and Duane C. O'MalleyJune 1974 (COM 74-11335/AS).
NWS CR 56 The Prediction of Daily Drying Rates. Jerry D. Hill, November 1974 (COM 74-11806/AS).
NWS CR 57 Summer Radar Echo Distribution Around Limon, Colorado. Thomas D. Karr and Ronald L. Wooten, November 1974 (COM 75-10076/AS).
NWS CR 58 Guidelines for Flash Flood and Small Tributary Flood Prediction. Lawrence A. Hughes and Lawrence L. Longsdorf, October 1975 (PB247569/AS)
NWS CR 58 (Revised) March 1978 (PB281461/AS)
NWS CR 59 Hourly Cumulative Totals of Rainfall - Black Hills Flash Flood June 9-10, 1972. Don K. Halligan and Lawrence L. Longsdorf, April 1976 (PB256087).
NWS CR 60 Meteorological Effects on the Drift of Chemical Sprays. Jerry D. Hill, July 1976 (PB259593).
NWS CR 61 An Updated Objective Forecast Technique for Colorado Downslope Winds. Wayne E. Sangster, March 1977 (PB266966/AS).
NWS CR 62 Design Weather Conditions for Prescribed Burning. Ronald E. Haug, April 1977 (PB268034).
NWS CR 63 A Program of Chart Analysis (With Some Diagnostic and Forecast Implications). Lawrence A. Hughes, December 1977 (PB279866/AS).
NWS CR 64 Warm Season Nocturnal Quantitative Precipitation Forecasting for Eastern Kansas Using the Surface Geostrophic Wind Chart. Wayne E. Sangster, April 1979 (PB295982/AS).
NWS CR 65 The Utilization of Long Term Temperature Data in the Description of Forecast Temperatures. Arno Perlow,November 1981 (PB82 163064).
NWS CR 66 The Effect of Diurnal Heating on the Movement of Cold Fronts Through Eastern Colorado. James L. Wiesmueller, August 1982 (PB83 118463).
NWS CR 67 An Explanation of the Standard Hydrologic Exchange Format (SHEF) and Its Implementation in the Central Region. Geoffrey M. Bonnin and Robert S. Cox, April 1983 (PB83 193623).
NWS CR 68 The Posting of SHEF Data to the RFC Gateway Database. Geoffrey M. Bonnin, April 1983 (PB83 222554).
NWS CR 69 Some Basic Elements of Thunderstorm Forecasting. Richard P. McNulty, May 1983 (PB83 222604).
NWS CR 70 Automatic Distribution of AFOS Products Created at the NOAA Central Computer Facility via Hamlet (RJE) PunchStream. Billy G. Olsen and Dale G. Lillie, November 1983 (PB84 122605).
NWS CR 71 An Investigation of Summertime Convection Over the Upper Current River Valley of Southeast Missouri. Bartlett C. Hagemeyer, July 1984 (PB84 222389).
NWS CR 72 The Standard SHEF Decoder Version 1.1. Geoffrey M. Bonnin, August 1984 (PB85 106508).
NWS CR 73 The Blizzard of February 4-5, 1984 Over the Eastern Dakotas and Western Minnesota. Michael Weiland, October 1984 (PB85 120087).
NWS CR 74 On the Observation and Modeling of the Slope Winds of the Upper Current River Valley of Southeast Missouri and Their Relationship to Air-Mass Thunderstorm Formation. Bartlett C. Hagemeyer, June 1985 (PB85 226926/AS).
NWS CR 75 Complete Guide to Canadian Products in AFOS. Craig Sanders, July 1985 (PB85 228153/AS).
NWS CR 76 The Reliability of the Bow Echo as an Important Severe Weather Signature. Ron W. Przybylinski and William J. Gery, September 1985 (PB86 102340).
NWS CR 77 Observation of Bow Echoes with the Marseilles Radar System. John E. Wright, Jr., September 1985 (PB86 102340).
NWS CR 78 Statistical Analysis of SHEF Coding Errors. Robert S. Cox, Jr., January 1986 (PB86 145141).
NWS CR 79 On the Midwestern Diurnal Convergence Zone on the West Side of the Warm Season Bermuda High. Bartlett C. Hagemeyer, March 1986 (PB86 171378).
NWS CR 80 Some Characteristics of Northeast Kansas Severe Weather 1963-1984. Larry W. Schultz, March 1986 (PB86 173952/AS).
NWS CR 81 The Severe Thunderstorm Outbreak of July 6, 1983 in Southeast Idaho, Western Wyoming and Southwest Montana. Gary L. Cox, April 1986 (PB86 184322/AS).
NWS CR 82 Some Proposals for Modifying the Probability of Precipitation Program of the National Weather Service. Wayne E. Sangster and Michael D. Manker, July 1986 (PB86 226636/AS).
NWS CR 83 Deformation Zones and Heavy Precipitation. Henry Steigerwaldt, August 1986 (PB86 229085/AS).
NWS CR 84 An Overview of the June 7, 1984 Iowa Tornado Outbreak. Charles H. Myers, August 1987.
NWS CR 85 Operational Detection of Hail by Radar Using Heights of VIP-5 Reflectivity Echoes. Richard B. Wagenmaker, September 1987.
NWS CR 86 Fire Weather Verification: The Forecaster Does Make a Difference. Therese Z. Pierce and Scott A. Mentzer, December 1987 (PB88 140744).
NWS CR 87 Operational Use of Water Vapor Imagery. Samuel K. Beckman, December 1987 (PB88 140751).
NWS CR 88 Central Region Applied Research Papers 88-1 Through 88-7. NWS Central Region, Scientific Services Division, May 198 (PB88-210836).
NWS CR 89 Compendiums of Information for the Missouri Basin River Forecast Center and the North Central River ForecastCenter. NWS Central Region, Scientific Services Division, June 1988 (PB88-226204).
NWS CR 90 Synoptic-Scale Regimes Most Conducive to Tornadoes in Eastern Wyoming ▮ A Link Between the Northern Hemispheric Scal Circulation and Convective-Scale Dynamics. William T. Parker and Edward K. Berry, July 1988 (PB88-231337).

Continued on Back Cover.

NWS CR 91 Heavy Snowfall in Northwest Wyoming. Michael S. Weiland, September 1988 (PB89 109524).

NWS CR 92 On the Utility of a Geographic Information System in Modelling Climatic Suitability. Bartlett C. Hagemeyer, September 1988 (PB89 109516).

NWS CR 93 The Synoptic and Meso-Alpha Scale Meteorology of Wyoming Flash Floods. Joseph A. Rogash, October 1988 (PB89 117709)

NWS CR 94 The Removal of Stagnant Winter Air Masses From Wyoming's Wind River Basin. Gary L. Cox and Jeffrey M. Graham, November 1988 (PB89 128664).

NWS CR 95 Floods Along Des Plaines and Fox Rivers: September-October 1986. Thomas L. Dietrich, February 1989 (PB89 152797/AS)

NWS CR 96 A Case Study Evaluation of Satellite-Derived Rainfall Estimates and Their Application to Numerical Model Precipitatio Forecast Verification. Glenn A. Field, May 1989 (PB89 194591).

NWS CR 97 Central Region Applied Research Papers 97-1 through 97-6. NWS Central Region, Scientific Services Division, July 198 (PB89 213375/AS).

NWS CR 98 The Record Rainfall of August 13-14, 1987 at Chicago, Illinois. Paul Merzlock, November 1989.

NWS CR 99 Central Region Applied Research Papers 99-1 through 99-7. NWS Central Region, Scientific Services Division, November 1989 (PB90 151325).

NWS CR 100 A Guide to Forecasters in Judging Weather Impact on Growth Environments and Farm Operations in the Midwest. John W. Kottke, December 1989 (PB90 141011).

NWS CR 101 Numerical Solutions to the Shallow Water Equations as Applied to a Local Meteorological Forecast Problem. Eric R. Thaler, March 1990 (PB90 191230).

NWS CR 102 Postprint Volume National Weather Service Aviation Workshop Kansas City, Missouri, December 10-13, 1991. NWS Central Region, Scientific Services Division, March 1992 (PB92-176148).

NWS CR 103 An Investigation of Two Microburst Producing Storms Using A Microburst Recognition Algorithm. David Eversole, January 1994 (PB94-156577).

NWS CR 104 Lincoln ASOS Temperature Test January 13-15, 1993, Gregory Grosshans and Phil Clark, March 1994 (PB94-159993).

NOAA SCIENTIFIC AND TECHNICAL PUBLICATIONS

The National Oceanic and Atmospheric Administration was established as part of the Department of Commerce on October 3, 1970. The mission responsibilities of NOAA are to assess the socioeconomic impact of natural and technological changes in the environment and to monitor and predict the state of tha solid Earth, the oceans and their living resources, the atmosphere, and the space environment of the Earth.

The major components of NOAA regularly produce various types of scientific and technical information in the following kinds of publications.:

PROFESSIONAL PAPERS--Important definitive research results, major techniques, and special investigations.

CONTRACT AND GRANT REPORTS--Reports prepared by contractors or grantees under NOAA sponsorship.

ATLAS--Presentation of analyzed data generally in the form of maps showing distribution of rainfall, chemical and physical conditions of oceans and atmosphere, distribution of fishes and marine mammals, ionospheric conditions,etc.

TECHNICAL SERVICE PUBLICATION--Reports containing data, observations, instructions, etc. A partial listing includes data serials; prediction and outlook periodicals; technical manuals, training papers, planning reports, and information serials; and miscellaneous technical publications.

TECHINCAL REPORTS--Journal quality with extensive details, mathematical developments, or data listings.

TECHNICAL MEMORANDUMS--Reports of preliminary, partial, or negative research or technology results, interim instructions, and the like.

Information on availability of NOAA publication can be obtained from:

NATIONAL TECHNICAL INFORMATIN SERVICE
U.S. DEPARTMENT OF COMMERCE
5285 PORT ROYAL ROAD
SPRINGFIELD, VA 22161