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EXPERIMENTS IN REGIONAL OBJECTIVE  
ANALYSIS FOR OPERATIONAL USE

by

A. MAAROUF and L.J. WILSON

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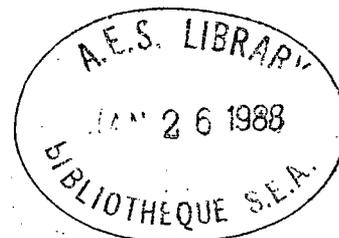
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EXPERIMENTS IN REGIONAL OBJECTIVE ANALYSIS FOR OPERATIONAL USE

by

A. Maarouf and L.J. Wilson



ABSTRACT

An objective analysis technique using second-degree orthogonal polynomials in two or three dimensions is described. The principal advantages of the technique are its capability of operating without an initial guess field and the feasibility of implementing it on existing minicomputers in regional weather offices. Tests of the method indicated that the second-degree polynomial representation yielded acceptable objective analyses. A few analyses of derived meteorological parameters are presented to demonstrate the utility of the method for diagnosis of atmospheric conditions, especially those preceding severe storm occurrences.

ANALYSE RÉGIONALE OBJECTIVE POUR USAGE OPÉRATIONNEL

par

A. Maarouf et L.J. Wilson

RÉSUMÉ

Ce document décrit une technique d'analyse objective utilisant des polynômes orthogonaux du second degré à deux ou trois dimensions. L'aptitude à fonctionner sans champ d'estimation initial et la compatibilité avec les mini-ordinateurs dont disposent les bureaux météorologiques régionaux représentent les principaux avantages de cette technique. Les autres épreuves auxquelles nous avons soumis cette méthode indiquent que la représentation à base de polynômes du second degré fournit des analyses objectives acceptables. Nous présentons également quelques analyses de paramètres météorologiques dérivés afin de démontrer l'utilité de la méthode pour le diagnostic des conditions atmosphériques, surtout de celles précédant les tempêtes violentes.

# EXPERIMENTS IN REGIONAL OBJECTIVE ANALYSIS FOR OPERATIONAL USE\*

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A. Maarouf and L.J. Wilson

(Manuscript received May 27, 1980)

## 1. Introduction

Objective analysis is usually defined as the transformation of an array of irregularly spaced data values into an array of regularly spaced grid-point values. Until recently, the main application of objective analysis has been to prepare initial data fields for input to operational numerical prediction models. With increased regional computer power, objective analysis is now frequently used to replace hand analysis of meteorological data used in diagnosis of atmospheric structures.

The latter application is the subject of this study which has the following objectives:

- 1) To produce a sufficiently accurate and computationally efficient objective analysis method, suitable for operation on a minicomputer, that does not require an initial guess field, and that can provide useful supplementary information for supporting the forecasting function. It is neither intended for use as input to NWP models nor expected to be useful for this purpose;
- 2) To determine the value of such an objective analysis method by testing it on meteorological data fields which are important to forecasting, and for which a good guess field is not readily available.

Three main types of objective analysis methods are discussed in Section 2. A description of the second-degree polynomial analysis method is presented in Section 3, results of validation tests are given in Section 4, and applications of the method are discussed in Section 5.

## 2. Objective Analysis Methods

There are three main types of objective analysis methods used widely at present. These are:

- a) Weighted-Means Method: Each grid-point value is determined by taking a weighted mean of surrounding station values and using it to modify the guess field for the grid point. One of the simplest

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weighted-means methods in common use is that of Cressman (1959), which incorporates a simple weighted function based on the distance between station and grid point. This method required substantial computer time on operational computer systems of the early 1960's, but can now be used operationally on minicomputers over regional domains.

Another weighted-means method in common use is the optimum interpolation method (Gandin, 1963). This differs from the Cressman method only in that weights are determined optimally, by taking into account the characteristic spatial intercorrelations of data values in the field being analysed. Determination of the weights therefore requires a large historical data base so that correlation coefficients can be calculated for each field as a function of the spatial separation of data grid points. This is done once for each field and need not be repeated each time the analysis is run. The correlation functions for many fields are now well known and documented. Optimum interpolation analysis is used operationally by the Canadian Meteorological Centre (Rutherford, 1976) to initialize the CMC spectral model. Data assimilation procedures used in analysis-prognosis cycles are designed so as to eliminate scales of motion smaller than can be treated by the NWP model. Although the optimum interpolation procedure is generally considered to produce the most accurate analysis possible, the associated data rejection criteria are chosen to eliminate data values that may be accurate, but representative of smaller scales than the NWP model can handle.

- b) Polynomial Methods: Grid-point values are determined by fitting a polynomial of a chosen degree to the data points in the vicinity of each grid point. Generally, the higher the degree, the more data values are required to determine the coefficients, the more time-consuming the procedure, and the more accurate the analysis. Polynomial methods were used operationally during the 1950's (Cressman, 1957) but proved unsuitable because of the large errors in data-sparse regions. Although they generally are more time-consuming than weighted-means methods, polynomial methods have proved useful for limited areas where detail is needed, and for special parameters where good guess fields are not available. They do not excessively smooth the data and can produce extreme values between data points. The second-degree polynomial fitting procedure was found to provide a good compromise between computational cost and accuracy of the resulting analysis (Goodin et al., 1979).
  
- c) Spectral Methods: The data field is described in terms of a set of orthogonal functions (Fourier series or spherical harmonics, for example) and the data values are used to find the coefficients of the functions. The entire field is analysed simultaneously, and determination of the coefficients requires the solution of a large set of simultaneous equations. This method is used operationally for the PE model initialization in the United States (Flattery, 1974) using Hough Functions. A variation of this method is called

Normal Modes Initialization, where the data are fit to the analytical solution of a simplified form of the equations used to drive the NWP model. All spectral methods are at present too comprehensive to be considered for regional analysis, and are not suitable for regional domains because their basic functions are global or hemispheric.

### 3. Second-degree Polynomial Method

The second-degree polynomial fitting method was selected, since it purported to be computationally feasible on the existing regional minicomputers, while permitting a reliable and sufficiently accurate analysis, over a small area.

#### a) Two-dimensional Analysis

The polynomial fitting technique seeks to minimize  $X^2$ , the sum of the departures of the fitted values from their corresponding observed field values. For a second-degree polynomial in two dimensions  $x$  and  $y$ , the expression:

$$X^2 = \sum_{k=1}^n \left[ C_k - (a_1 + a_2 x_k + a_3 y_k + a_4 x_k^2 + a_5 x_k y_k + a_6 y_k^2) \right]^2 \quad (1)$$

must be a minimum, where  $C_k$  is the observed (or derived) parameter at point  $(x_k, y_k)$  and the  $a$ 's are the coefficients of the polynomial estimate of the field. The minimum value of  $X^2$  can be determined by setting its derivatives with respect to each of the  $a_i$  equal to zero. Six simultaneous equations result and are solved for the optimum coefficients. The quantity  $C(x, y)$  at any grid point  $(x, y)$  can then be computed:

$$C(x, y) = a_1 + a_2 x + a_3 y + a_4 x^2 + a_5 xy + a_6 y^2 \quad (2)$$

Since low-powered polynomials are not capable of accurately describing the variations over a large area, it is necessary to deal with the analysis, grid point by grid point. The result is usually a fairly rough analysis, having zero-order discontinuities between points. However, this problem can be greatly reduced by giving each observation a weighting factor depending on its distance from the grid point. Endlich and Mancuso (1968) combined a first-degree polynomial fitting with distance weighting in their interpolation technique. They were able to demonstrate the diagnostic value of objective analyses of atmospheric conditions that precede or accompany severe thunderstorms and tornadoes. In the present study we have modified the Endlich and Mancuso method for application to a second-degree polynomial fitting and simplified their weighting function to the form,

$$W(r) = \frac{1}{r^2} \quad (3)$$

where  $r$  is the distance from the station to a grid point measured in units of grid length. Another modification made was to supplement the observations in data-sparse areas by using the nearest two previously computed grid-point values which are each assigned half the weight of a real observation. This could lead to a slightly different analysis in data-sparse areas if the direction of scanning the grid is changed. However, the number of grid points affected by this process is relatively small; furthermore the final analysis seemed much better after this modification was incorporated.

By introducing these modifications we were able to increase the accuracy of the analysis over that of a first-degree polynomial analysis without significantly increasing the computer time. The area used for testing in this study is covered by a  $19 \times 22$  grid (Figure 1), having a grid length of 127 km at  $60^\circ\text{N}$ .

The problem of computing the coefficients  $a_i$  in equation (2) reduces to solving a system of normal equations (for their derivation see Brooks and Carruthers, 1953), written in matrix form as:

$$B A = F \quad (4)$$

where  $A$  is the vector of unknowns  $a_i$ , and  $F$  and  $B$  are known from the observations and their  $x, y$  coordinates. The solution to the matrix equation (4) is:

$$A = B^{-1}F.$$

This solution requires the matrix  $B$  to be non-singular and involves computing its inverse which is considered to be a costly procedure on the computer.

A faster and more efficient approach to the matrix-inversion problem involves using orthogonal polynomials (Dixon, 1969) to reduce the normal equations to a set of independent equations, each yielding one of the unknown coefficients. Following Sokolnikoff and Redheffer (1966), we seek a matrix  $C$  such that the product:

$$C B = D$$

is an orthogonal matrix. Since  $D$  is required to be orthogonal, it follows that:

$$D D' = D' D = I \quad (5)$$

where  $D'$  is the transpose of  $D$ .

On multiplying equation (4) on the left by  $B' C' C$ , we get

$$B' C' C B A = B' C' C F. \quad (6)$$

Since  $B' C' = (C B)' = D'$

we can write equation (6) as:

$$D' D A = D' C F.$$

However, by equation (5)  $D' D = I$ , so that:

$$A = D' C F. \quad (7)$$

Formula (7) gives the solution of the system (4) once a matrix C is determined. The procedure for constructing C is known as the Gram-Schmidt orthogonalization method and will not be presented here (see, for example, Synge, 1957).

b) Three-dimensional Analysis

The polynomial method can easily be expanded to handle the analysis problem in three dimensions. The new fitting polynomial would include the vertical coordinate (pressure (p), for example) in addition to the horizontal coordinates x and y. Expression (2) would then be replaced by:

$$C(x, y, p) = a_1 + a_2x + a_3y + a_4p + a_5x^2 + a_6xy + a_7y^2 + a_8xp + a_9yp + a_{10}p^2. \quad (8)$$

In this case, 10 unknown coefficients must be determined and the solution becomes more costly on the computer. However, the three-dimensional interpolation offers the advantage of incorporating data from significant as well as mandatory pressure levels. This also gives some flexibility in choosing the thickness of the layer to be analysed. Section 5 contains an example comparing the three- and two-dimensional analysis procedures.

c) Data Quality Control

The present polynomial method includes an efficient data checking procedure that operates as follows. The grid (Figure 1) is divided into four subgrids. All the raw data falling inside each subgrid are fitted to a second-degree polynomial and are assigned the same weighting factor ( $w = 1$ ). The resulting polynomial is used to reconstruct the value at the location of each station using expression (2). The residual R is then computed as:

$$R = [C_e(x, y) - C_o(x, y)]^2$$

where  $C_e(x, y)$  is the station value at (x, y) estimated by means of the polynomial and  $C_o(x, y)$  is the corresponding actual observation. A large value of R indicates that the observation is most likely in error. Threshold values of R were found for each field for use as criteria to reject most observational errors, while retaining the good data. After checking all input data and rejecting any errors, the polynomial fitting is applied at each grid point with each observation taking its proper weight.

#### 4. Validation of Objective Analysis

The polynomial objective analysis of a MSL pressure field (Figure 2) was validated by comparing it with a Cressman analysis (Figure 3) and a hand analysis (Figure 4) to check that sufficient accuracy can be obtained over the regional grid used. This comparison shows that the quality of the analysis produced by the polynomial method is comparable to that of the other conventional methods. It should be noted, however, that the polynomial method takes about nine times the computer time required by the Cressman method. A modification was therefore introduced to reduce this time by applying the polynomial fitting only at the grid points separated by 381 km, i.e., three grid lengths on Figure 1, and then using the resulting polynomial at each of these points to compute the values at the surrounding points by substituting their corresponding x and y values. The resulting analysis (Figure 5) proved to be fairly accurate and took about 50% more computer time than that of Cressman.

#### 5. Applications of Objective Analysis to Other Fields

The polynomial method outlined above has been applied to generate objectively analysed fields for other observed and derived quantities at the surface and upper levels of the atmosphere. Among the fields tested during this experiment were surface temperature and dew point, 3-h pressure tendency, cloud amount, upper-level temperature and moisture distributions, various stability indices, thickness, vorticity, divergence and advection. Each field was analysed separately by fitting a second-degree polynomial at each grid point. The nearest 15 stations were used for surface analysis and the nearest 10 stations, for upper-air analysis. The weighting function, equation (3), was applied at each station location. A few examples are presented here to demonstrate their operational usefulness.

##### a) 700-mb Relative Humidity Analysis

The relative humidity was computed from measurements of moisture and temperature for each upper-air station. Two experiments were performed. In the first, the objective analysis was carried out in two dimensions, i.e., using only 700-mb data. The result is shown in Figure 6 for 1200Z, 4 April 1974. In the second experiment the analysis was in three dimensions, including all significant levels between 750 and 650 mb. The coefficients  $a_i$  in expression (8) in this case represent a layer 100 mb thick centred about the 700-mb level. The relative humidity at 700 mb was then obtained by setting p equal to 700 in equation (8). The three-dimensional analysis for the same case is shown in Figure 7. Comparison of Figures 6 and 7 indicates that the three-dimensional analysis tends to produce a more coherent relative humidity field. The apparent effect of the three-dimensional analysis is to give smaller weights to thin moist or dry layers that appear only at 700 mb. In this case (for the tornado outbreak of 4 April 1974) the three-dimensional analysis seems to better describe the moist tongue and the dry prod over the area of tornado activity. The original grid (Figure 1) is shifted southward in Figures 6 and 7 to cover much of the area of severe storm activity south of the Great Lakes.

b) Convective Layer Instability

Rossby (1932) showed that a layer will be convectively unstable if the equivalent potential temperature ( $\theta_E$ ) decreases with height through the layer. Reap and Foster (1979) incorporated a convective instability index ( $\theta^*$ ) in their regression technique for predicting thunderstorms and severe local storms, defined as:

$$\theta^* = \theta_E(700) - [\theta_E(1000) + \theta_E(850)] / 2 \quad (9)$$

Figure 8 shows an objective analysis of  $\theta^*$  for 1200Z, 3 April 1974, prepared by applying the polynomial method to station values of  $\theta^*$  computed from equation (9). Negative values of  $\theta^*$  indicate the existence of convective (potential) instability. Also on the same figure are shown the positions of a tornado line and a squall line that were reported 12 h after the analysis time (Fujita, 1975).

c) 500-mb Vorticity Advection

Vorticity advection patterns are often used by the meteorologist to assess the areas for potential cyclone development, large-scale vertical motion and precipitation. Analyses of 500-mb vorticity advection have been produced operationally by a simple graphical technique using the Ferguson Scale (McPherson et al., 1969), which assumes advection of absolute vorticity by the geostrophic wind. An example is shown in Figure 9 for 1200Z, 9 October 1979. The objectively analysed chart for the same time (Figure 10) was generated by first analysing the actual wind components  $u$  and  $v$  for the 500-mb level, then computing the absolute vorticity and vorticity advection by means of centred differencing.

Comparison of the fields in Figures 9 and 10 shows that their general distributions of PVA and NVA are similar, but their magnitudes are different. It is difficult from this example to assess which field is more accurate. However, it can be argued that the objective method is superior to the graphical method because it computes the advection at many more points distributed uniformly over the grid, uses actual wind data, and involves less smoothing and fewer approximations.

6. Concluding Remarks

A simple technique for objective analysis using orthogonal polynomials in two or three dimensions has been presented. It has been shown that the analyses generated by this method are satisfactory for operational applications. In particular, automated analyses of derived meteorological fields that are not regularly produced by hand could be of considerable interest to the meteorologist. Because of operational computer time constraints, it is not expected that this analysis method will be used for sea-level pressure or other applications where frequent routine analyses are required and reasonable trial fields are readily available. Rather, the polynomial method is of maximum benefit when applied on a demand basis to fields of particular significance in specific weather situations. The forecaster would simply choose from a list the analyses he felt pertinent to the situation on a given day.

An attempt is presently being made to include the analysis of vertical velocity in the list of derived fields that can be produced using the polynomial method. The initial test results are encouraging but additional testing is required.

The preliminary polynomial fitting over the four subgrids used for data quality control might be convenient for generating a guess field for a subsequent Cressman analysis. This might result in a faster two-dimensional analysis. The polynomial method can be made competitive with the Cressman method by making its grid resolution more representative of the data density and by increasing the efficiency of the computer program.

The technique can be expanded to four-dimensional analysis by including the time coordinate. This is potentially useful for future applications incorporating radar, satellite and other irregularly observed data, thus providing continuity of the meteorological fields in both space and time.

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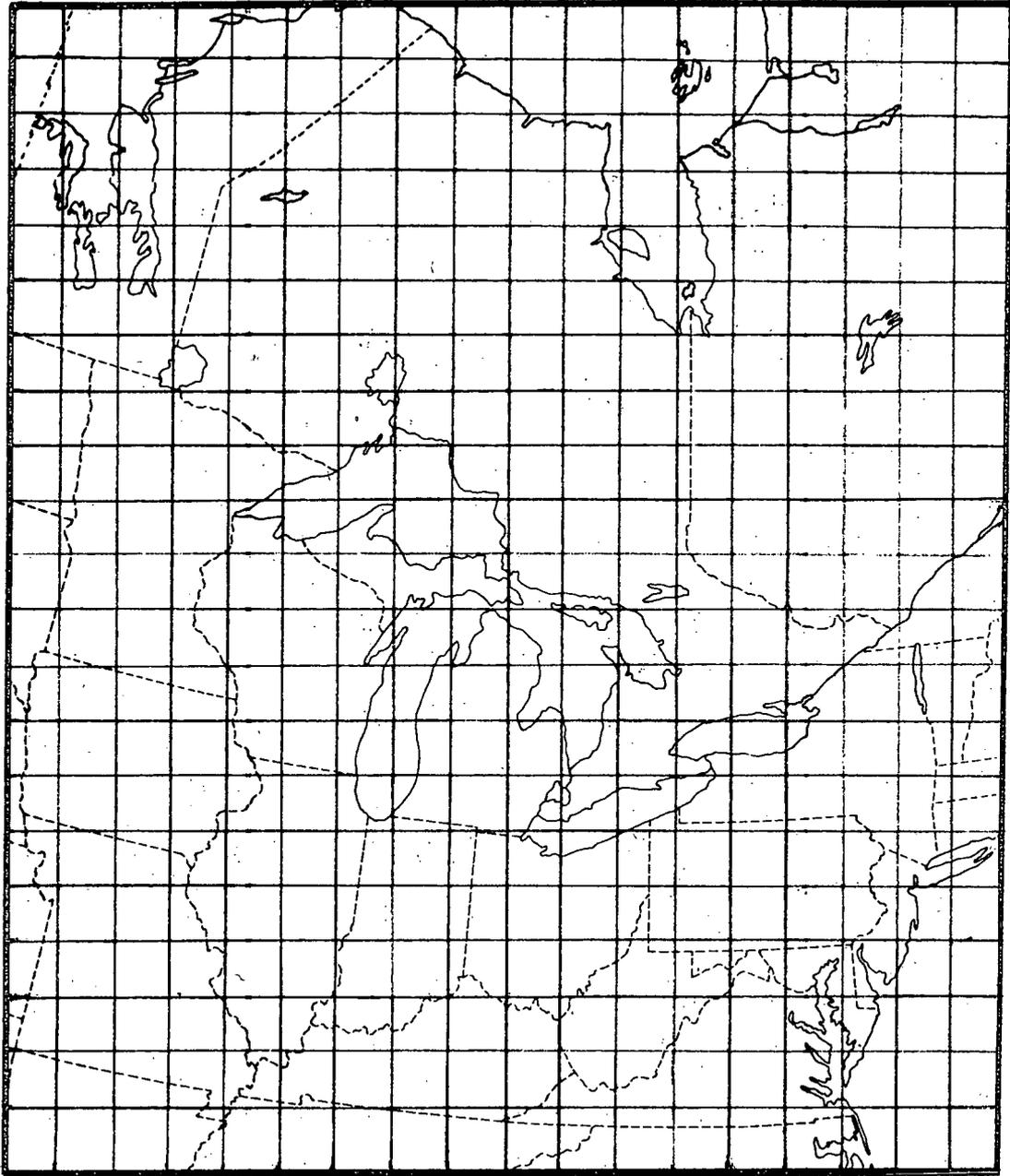


Figure 1

The 19x22 grid used in this study. The grid interval is 127 km at 60°N.

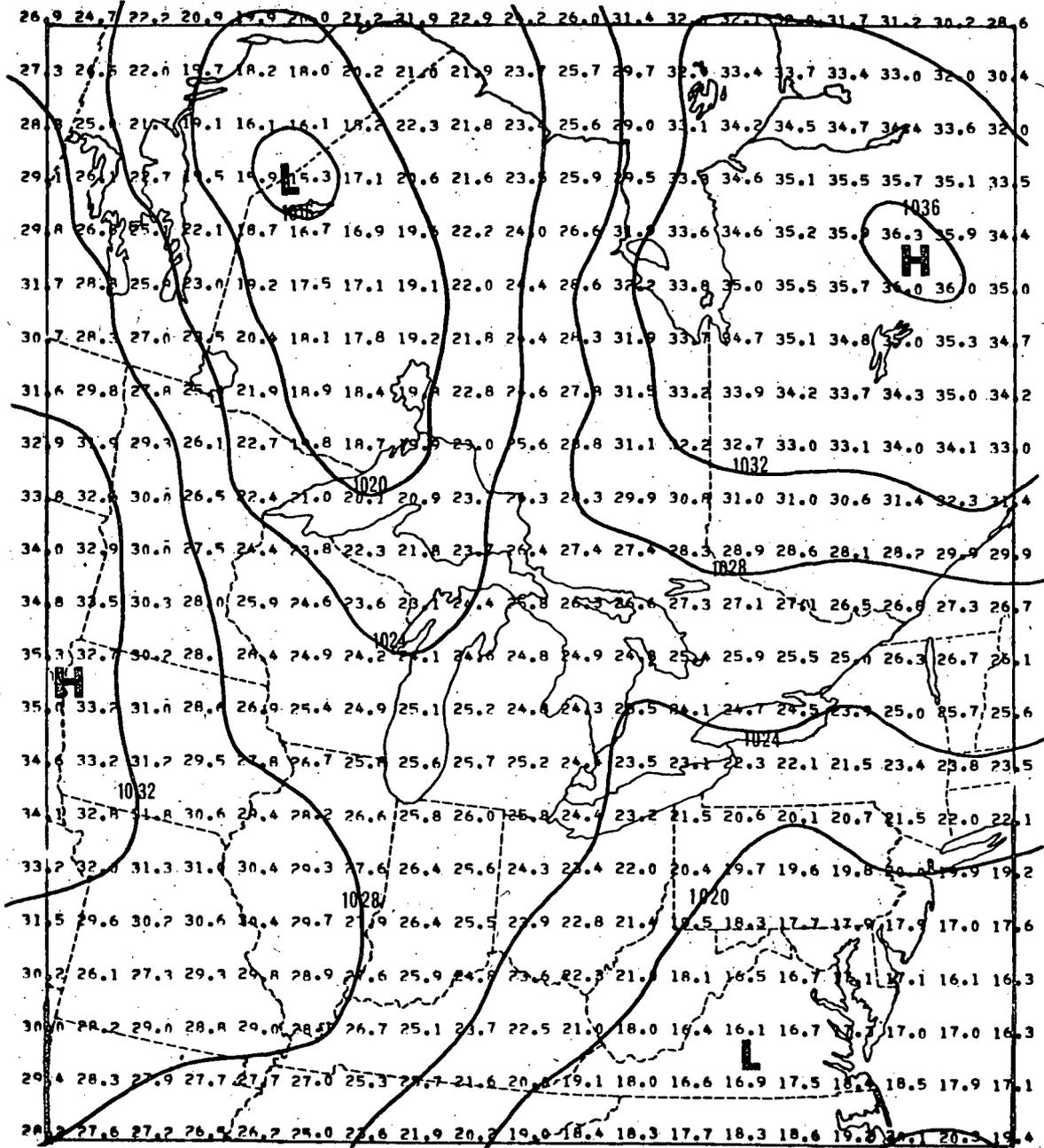


Figure 2

Objective analysis of MSL pressure for 1800Z, 13 December 1979, obtained by the polynomial method.

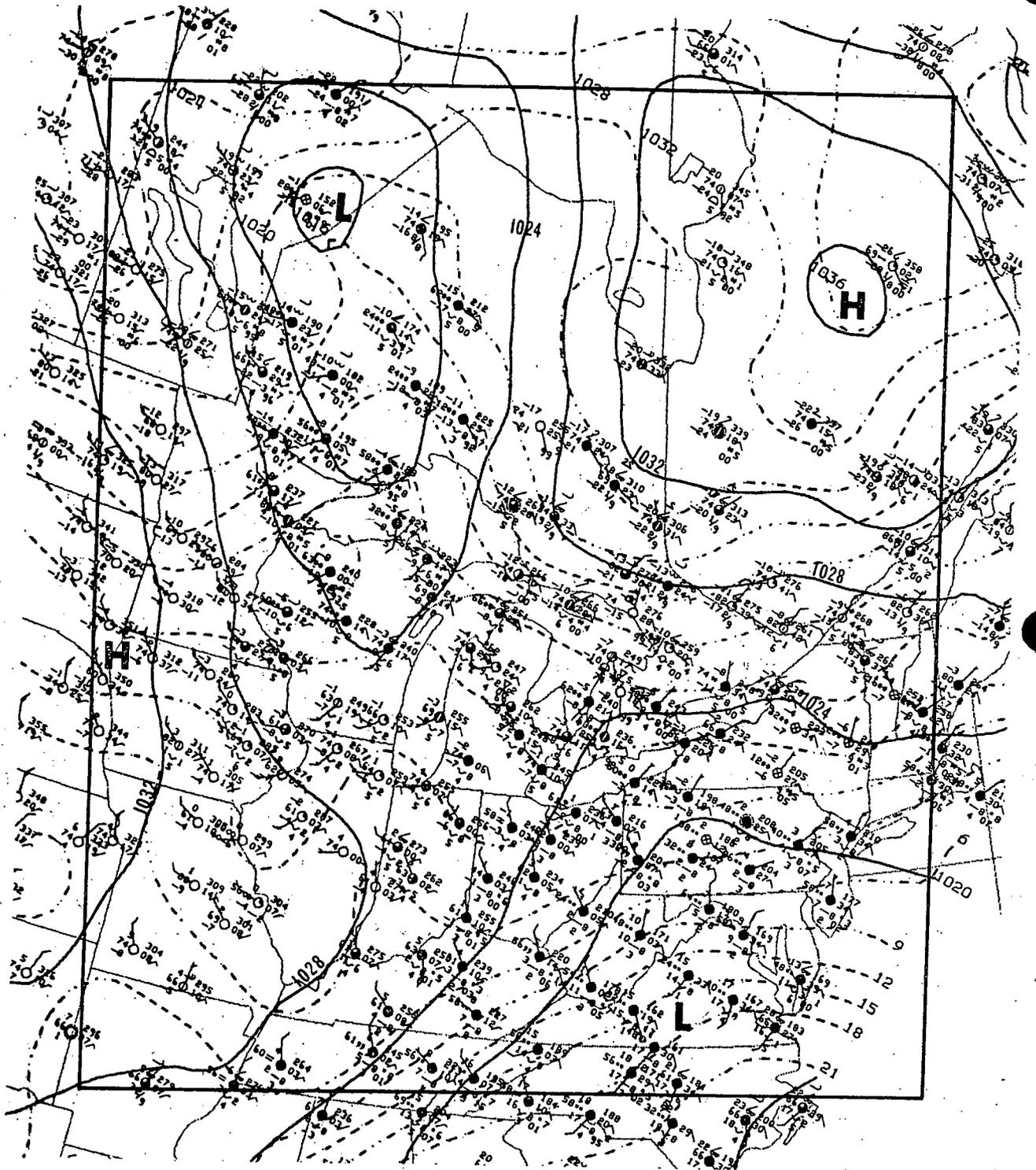


Figure 3

Cressman objective analysis of MSL pressure for 1800Z, 13 December 1979 generated at the Ontario Weather Centre. The dashed lines are isotherms (°C).

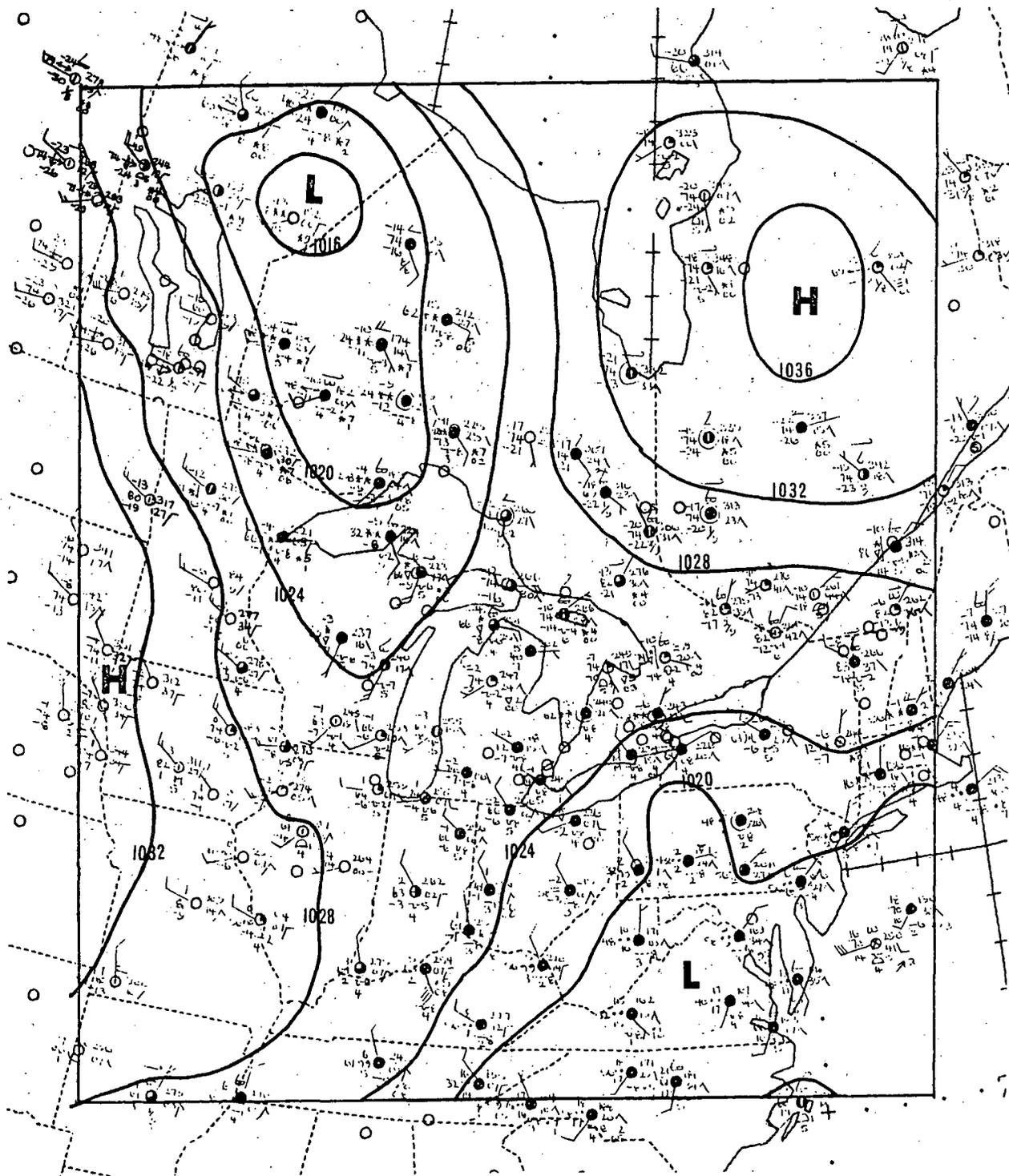
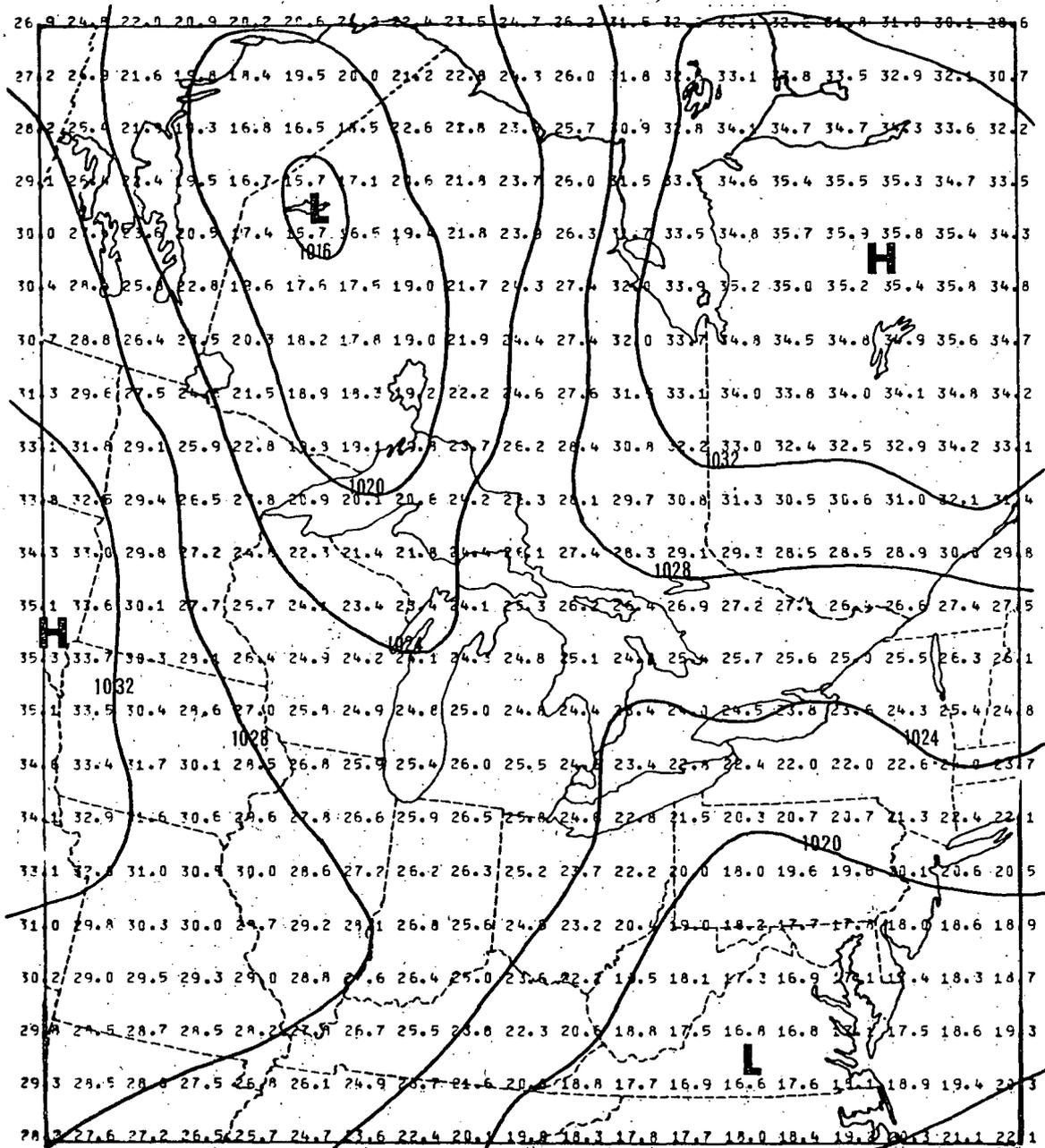


Figure 4

Hand analysis of MSL pressure for 1800Z, 13 December 1979.



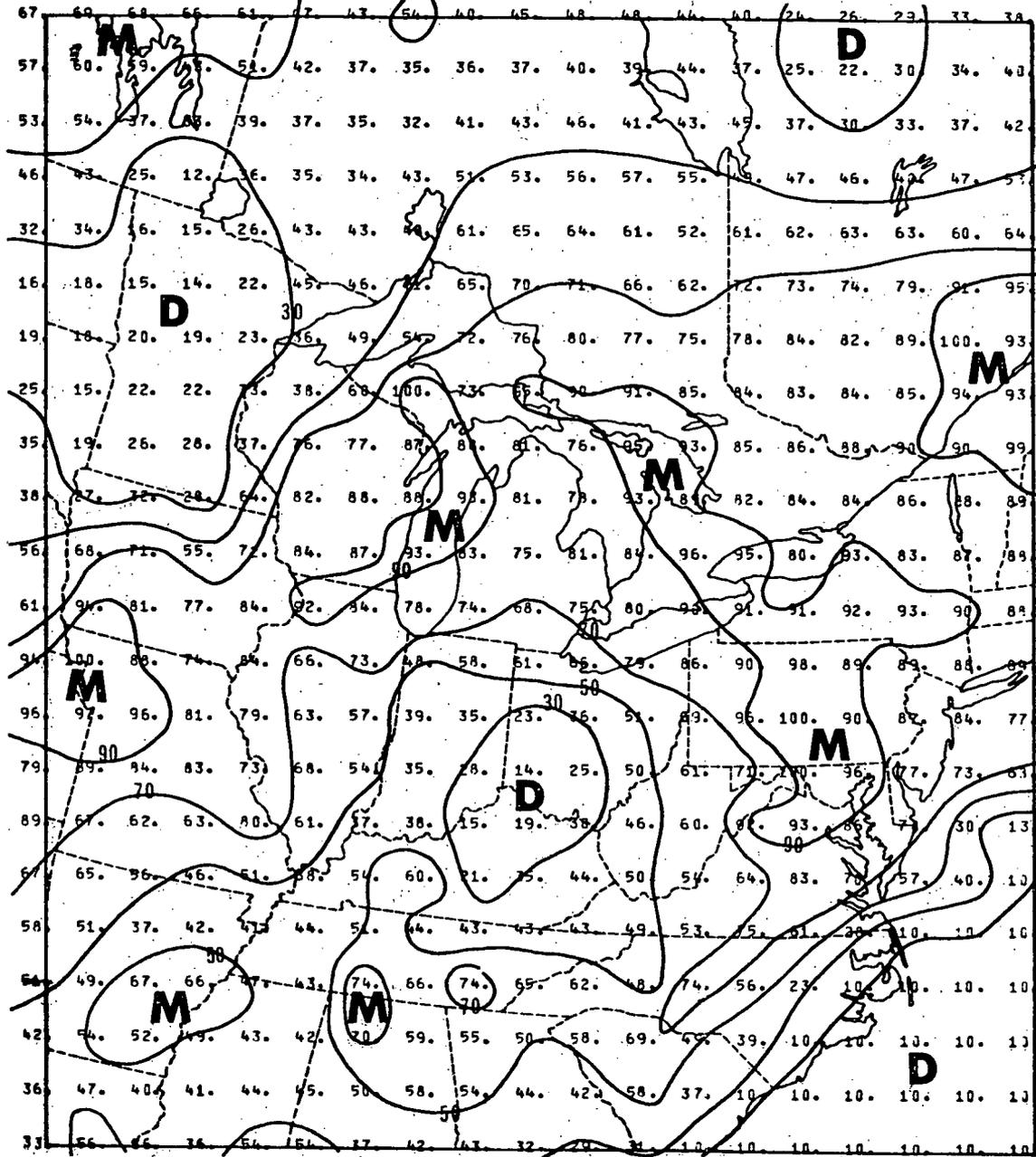


Figure 6

Two-dimensional objective analysis of 700-mb relative humidity (per cent) for 1200Z, 4 April 1974. M: moist; D: dry.

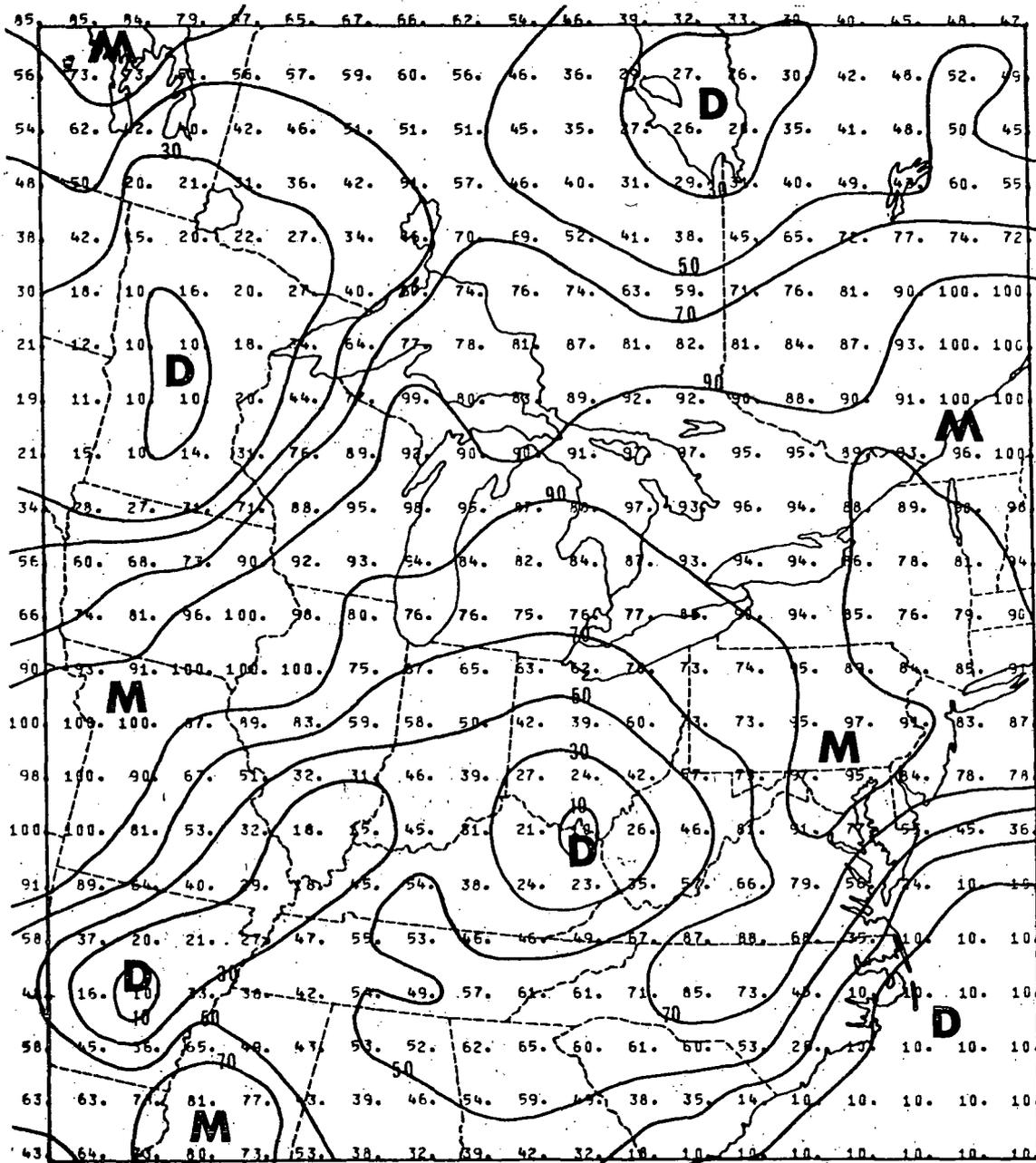


Figure 7

Three-dimensional objective analysis of 700-mb relative humidity (per cent) for 1200Z, 4 April 1974. M: moist; D: dry.

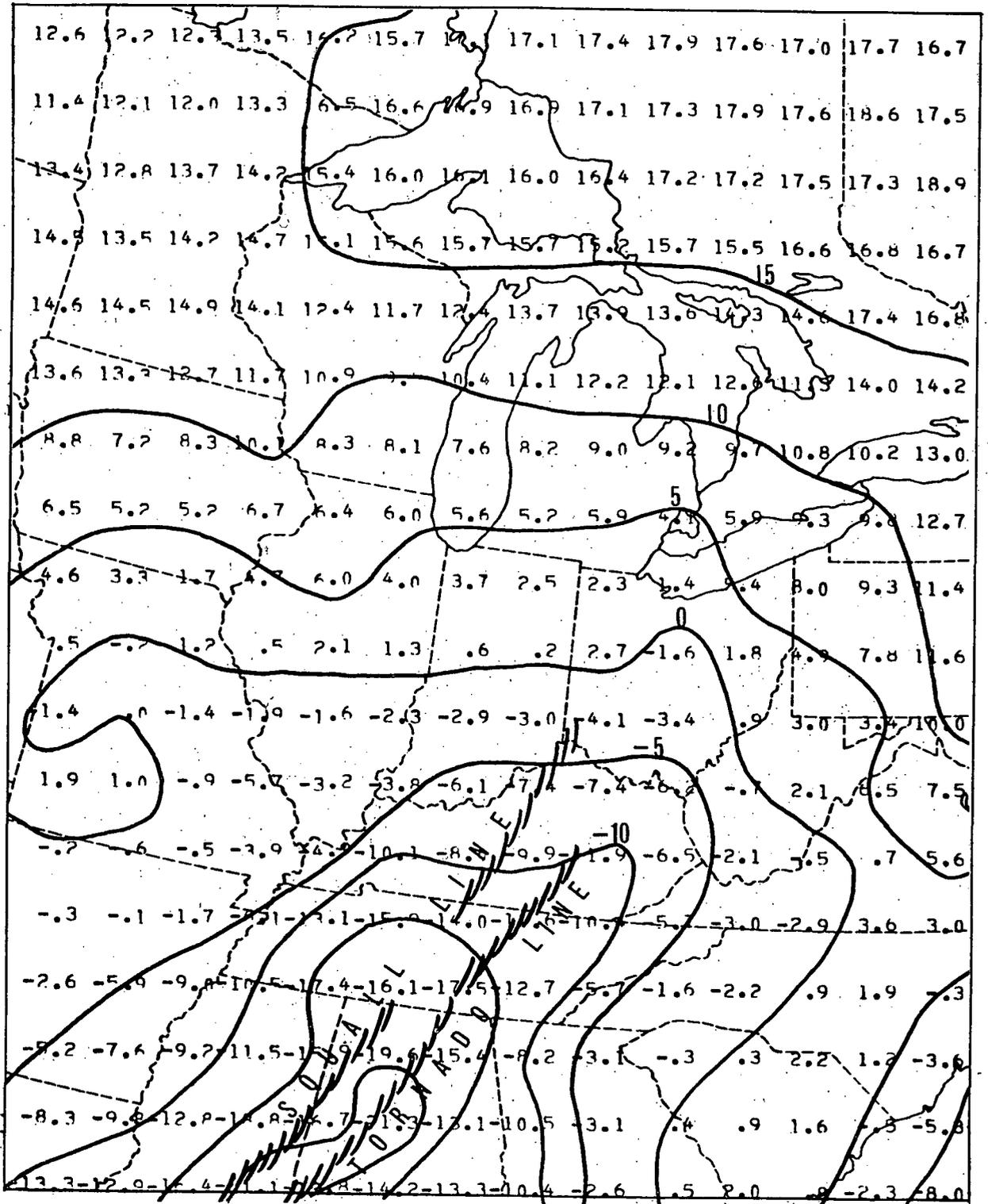


Figure 8

Objective analysis of the convective instability index ( $\theta^*$ ) for 1200Z, 3 April 1974. The squall line and tornado line shown on the figure were reported 12 hours after the analysis time.

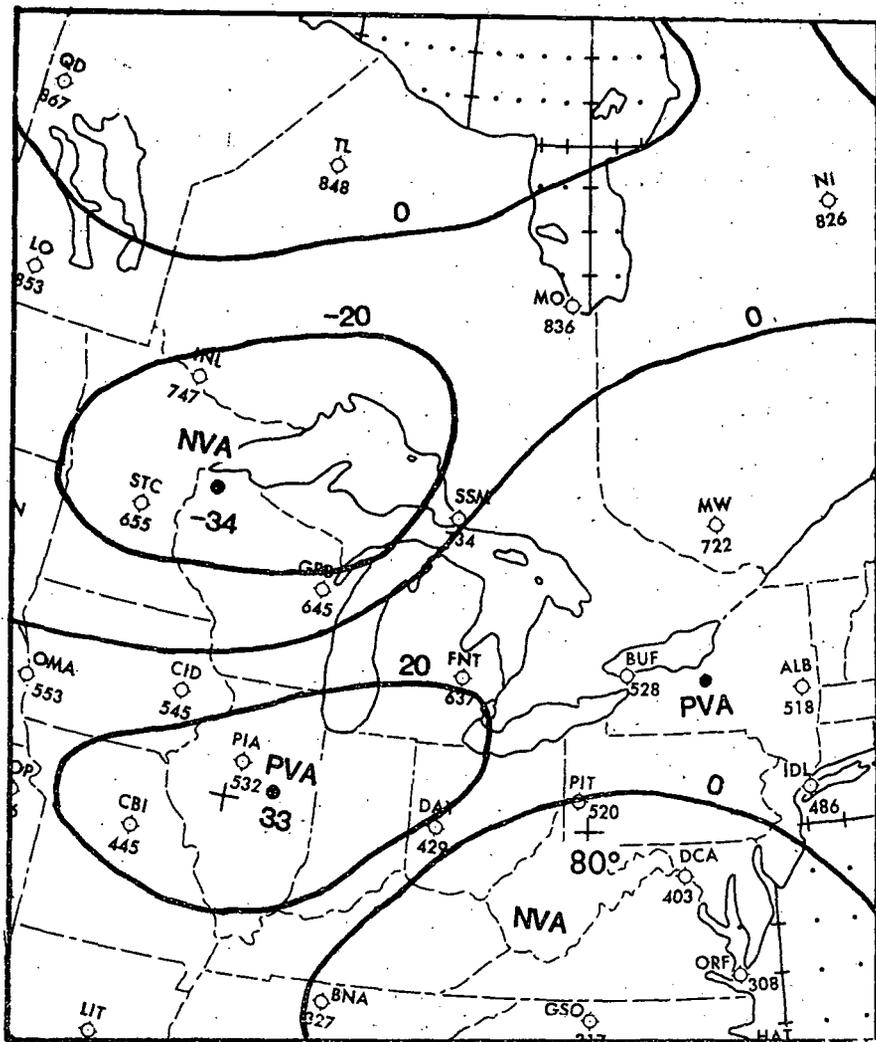


Figure 9

Analysis of the absolute vorticity advection ( $10^{-10} s^{-2}$ ) obtained by the graphical method for 1200Z, 9 October 1979.

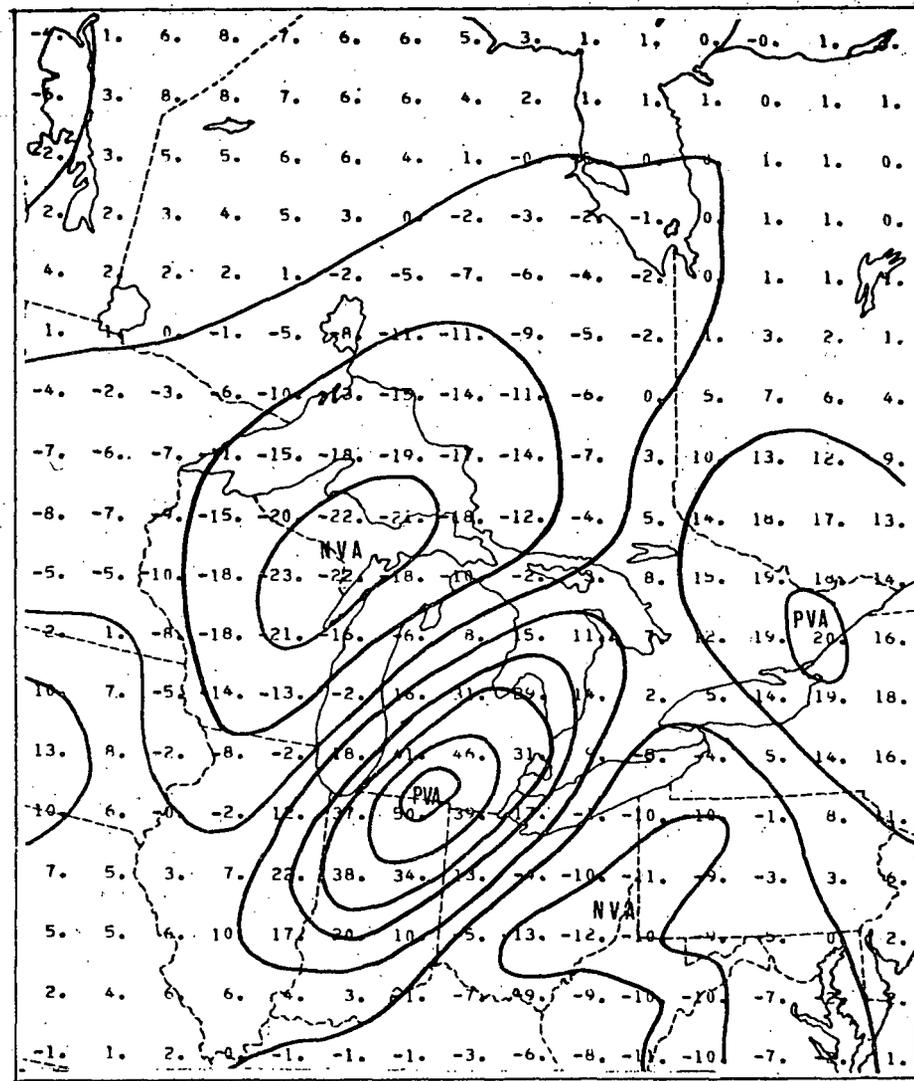


Figure 10

Polynomial objective analysis of the absolute vorticity advection ( $10^{-10} s^{-2}$ ) for 1200Z, 9 October 1979.

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