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Objective Determination of Sea Level Pressure from Upper Level Heights

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ESSA TECHNICAL MEMORANDUM

WEATHER BUREAU

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OBJECTIVE DETERMINATION OF SEA LEVEL PRESSURE FROM UPPER LEVEL HEIGHTS

William Klein, Frank Lewis and John Stackpole

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SYSTEMS DEVELOPMENT OFFICE

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"OBJECTIVE DETERMINATION OF SEA LEVEL PRESSURE FROM UPPER LEVEL HEIGHTS"

By

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ABSTRACT

Maps based on 17 years of grid point data are presented showing the geographical and monthly distribution of the standard deviation of sea level pressure over maritime and continental areas of the Northern Hemisphere. The proportions of the pressure variability which can be explained by simple correlation with the local 700-mb. height and by multiple correlation with the field of 700-mb. height are also mapped on a hemispheric basis. The additional variance explained by including concurrent information at the 850-mb. and 500-mb. levels is determined by screening regression. Finally, a computerized method of translating a numerical forecast of the upper level circulation into its corresponding sea level pressure forecast is derived and illustrated.

I   INTRODUCTION

Experience with numerical weather prediction during the past decade has demonstrated that both baroclinic and barotropic models give better results in the mid-troposphere than at sea level. As a result, prognostic charts transmitted over facsimile by the National Meteorological Center (NMC) in Suitland, Md., are still prepared objectively aloft but subjectively at the surface.

The purpose of the present study is to develop a completely objective method of translating an upper level height forecast into its accompanying chart of sea level pressure. This is accomplished by applying the screening technique to a historical file of observed maps and then applying the resultant regression equations to numerical prognostic heights. A similar combination of statistical and dynamical techniques has been used for objective prediction of surface temperature, clouds, and precipitation [1].

In an earlier paper multiple regression equations were derived for sea level pressure at 70 points in and near North America by applying the screening technique to 10 years of 5-day mean 700-mb. height, with all data expressed as departures from normal at a rather coarse grid of points [2]. Later this work was extended to the problem of specifying daily sea level pressure from simultaneous daily 700-mb. height over the entire Northern Hemisphere. This was done separately for every other month of the year by applying the screening program to each day of 1200 GMT[1] grid point data in the historical file of the Extended Forecast Division of the National Meteorological Center [3].

Two separate derivations were made, one for the even grid of points, shown by dots in figure 1 for every 10 degrees of latitude from 20°N to 90°N, and the other for the odd grid, shown by boxes in figure 1, for every 10 degrees of latitude from 25°N to 75°N. The period of record began on January 1, 1947, in most of the western hemisphere, on January 1, 1948 in most of the Arctic and northern Siberia, and on January 1, 1951, at low latitudes of the eastern hemisphere. No derivation was made in the tropics because of inadequate data. Since the input data ended on December 31, 1963, there were 17 years of data in the western hemisphere, 16 years in the Arctic, and 13 years in the eastern hemisphere.

II   CLIMATOLOGY

As a by-product of this investigation, considerable data of climatological interest were obtained. One example is the geographical and

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[1]Prior to June 1, 1957, the sea level maps were based on 1230 GMT data, and the 700 mb. maps on 1500 GMT data. The small errors introduced by these time differences have been neglected in this study.

monthly distribution of the standard deviation of sea level pressure.[2] The results are presented in map form in figure 2.

In all cases the principal variation is in the meridional direction, with sharply decreasing values from about 60°N. southward. There is also considerable zonal variation, however, with smaller values over North America and Asia and larger values over oceanic areas.

In all months centers of maximum appear at both sea level and 700 mb. in the vicinity of the semi-permanent Icelandic and Aleutian lows. Additional maxima are found along the northern border of the Soviet Union or in the Arctic Ocean on most of the charts. Secondary minima frequently appear in parts of Canada and Greenland. The effects of tropical cyclones are reflected in weak centers or ridges of maximum during the summer months off the coasts of Formosa and Mexico. Otherwise there is generally little difference in the patterns between different months, but the magnitudes are roughly twice as great in winter as in summer.

Another statistic of climatological interest is the simple linear correlation coefficient between simultaneous values of sea level pressure and 700-mb. height directly overhead. This local correlation is illustrated in map form in figure 3. Its geographical distribution also exhibits little seasonal variation. It exceeds 0.8 in most of the Atlantic, Pacific, and Arctic throughout the year, with maximum values greater than 0.95 off the coast of Iceland during all months except July and over the Aleutians in January and November. High correlations over maritime areas reflect the prevalence of equivalent barotropic conditions in which lows are generally cold and highs warm.[3]

On the other hand, the coefficients of figure 3 are less than 0.5 in many continental areas where baroclinic conditions prevail. A well-defined axis of minimum correlation is located in the Great Plains during all months, with values as low as 0.35 in January. This area is characterized by shallow cold highs and warm lows, so that local 700-mb. height is a rather poor indicator of sea level pressure. Local coefficients of less than 0.5 also occur in southern portions of North America and Asia and over North Africa, where poor data and small variability permit errors of analysis, reduction, and observation to lower the correlation.

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[2] Here the variability within the month has been neglected, so that standard deviations for March, May, September, and November are somewhat greater than they would be if only values from the same day of the month had been used.

[3] Some of this effect may be spurious because of sparse data over oceans and consequent 700-mb. analysis by upward extrapolation from sea level, but the agreement in oceanic areas of good data like northwest Europe or the Aleutians lends credence to the results.

III SPECIFICATION

Figure 3 tells how well we could specify sea level pressure from just one 700-mb. height directly overhead. In order to obtain improved results, a screening regression program was applied to select additional heights which contribute significantly and independently to the pressure.

Some multiple regression equations for March resulting from this procedure are illustrated in figure 4. The equation on the left is for the sea level pressure at 50°N., 10°W., just southwest of the British Isles. The most important single predictor of pressure at this point is the simultaneous 700-mb. height at the same point, which explains 90% of the pressure variance. The height which contributes the most additional information is located ten degrees to the east. Combination of this height with the first one explains 93% of the variance of pressure at the first point. Since no additional predictor is able to increase the explained variance[4] by even 2%, the screening process was stopped at this step in order to stabilize the results on independent data.

The final specification equation is written on the extreme left, where the heights appear in the order selected. The positive sign of the first regression coefficient indicates that when heights are high at 50°N., 10°W., pressures are high there also; and conversely for low values. The negative sign of the second regression coefficient indicates that northerly flow between low heights at the second point and high heights at the first point favors high pressure, presumably through cold air advection; and conversely for low pressure under warm air advection produced by southerly flow.

This point has the closest relation between pressure and height of any point in the Northern Hemisphere during March. In all other respects, however, its equation is typical of the equations derived at maritime locations of the Atlantic, Pacific and Arctic.

A different type of equation, typical of continental areas, is illustrated on the right side of figure 4 for the sea level pressure in March at 55°N., 105°E., just west of Lake Baikal in Siberia. Here the local 700-mb. height is not selected as one of the predictors. Instead the day of the year and heights 10 degrees to the north, 10 degrees to the west, and about 1700 miles to the northwest are selected, with explained variance increasing gradually from 44% to 60%.

Figure 5 shows the percent of the pressure variance explained by the specification equations during the course of the year. Little difference in pattern is discernible from month to month, but values are somewhat lower in summer, and there is considerable geographical variation. Maxima in excess of 80% occur over the maritime areas of the Arctic, Pacific, Atlantic, and Europe, where equivalent barotropic conditions prevail. Minima under 60% are found over continental areas of North America and east Asia, where

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[4] Also called reduction of variance or coefficient of determination and equal to the square of the multiple correlation coefficient.

baroclinic and mountain effects complicate the relation between pressure and height. The patterns of figure 5 are generally similar to those for the local correlation (fig. 3) and for the standard deviation of pressure (fig. 2). This demonstrates the dependence of the explained variance upon both the local pressure-height relation and the general level of pressure variability.

Figure 6 maps the standard error of estimate of predictions made from the specification equations. In about 68% of the cases, for a normal distribution, the error in specifying pressure from observed heights should be less than the values shown in this figure. Largest errors (7 mb.) can be expected in January and March in portions of Canada and Siberia, where the specification is poor; while smallest errors (less than 2 mb.) should occur throughout the year in the tropics, where variability is very low.

Figure 7 summarizes values averaged on a hemispheric basis as a function of latitude for the month of March. The upper curves show the correlation coefficients between sea level pressure and 700-mb. height, plotted first for strictly local values and then for the multiple correlation coefficients of the final specification equations. The difference between the two curves represents the improvement obtained by considering the entire field of 700-mb. height instead of just the local height. Both correlations diminish sharply at low latitudes, where analysis and observational errors become of great importance because of small pressure variability. This is illustrated by the lower curves, which give, first the standard deviation of observed sea level pressure, and then the standard error of estimate of the specification equations, both in millibars. The difference between these two curves gives some idea of the improvement over climatology yielded by the specification equations. This difference is greatest at high latitudes, where both the standard deviation and the multiple correlation are largest. The difference is smallest at low latitudes, but here variability is so small that the standard errors of 2 mb. are approaching the noise level anyway.

IV   APPLICATION

In order to apply the daily specification equations on a routine basis, a program was written for the IBM 7094 which solves the multiple regression equations at each of 469 grid points, interpolates by harmonic analysis to give predicted pressures at each of 1977 points of the grid used in numerical weather prediction $\lfloor 4 \rfloor$, and then makes use of the electronic curve-follower to draw isobars. By means of this program, a completely mechanical map of the sea level pressure distribution over the Northern Hemisphere can be obtained in a few minutes from any 700-mb. map.

Objective pressure forecasts were made by this method from the NMC 36-hour baroclinic 700-mb. prognoses $\lfloor 5 \rfloor$ twice each day during an independent test period of March 1964. Figure 8 gives a sample forecast (left) along with its verifying map (right). The forecasts were verified by means of the S-1 score, a measure of relative pressure gradient error which varies from 0 for a perfect prediction through 100 for no skill to 200 for the worst possible forecast. The score for this particular map over the North

American area was 65, but the average score for all 62 forecasts in the sample was 75, as shown in table 1. This was superior to the average score of 91 made by persistence, about equal to the score of 74 obtained for sea level forecasts made by the Reed dynamic model $/6/$ for the same sample, and inferior to the average score of 63 yielded by the 30-hour prognoses prepared subjectively by experienced forecasters at NMC. It should be remembered, however, that the forecasters had the benefit of 6 hours later sea level data.

The average absolute pressure error in millibars was also computed for each forecasts, with scores summarized on the right side of table 1. The relative rank in terms of this statistic was generally similar to that obtained using the S-1 score, except for an interchange of order between the objective specifications and the Reed numerical model.

It is apparent from figure 8, as well as from routine inspection of the daily maps, that the objective forecasts tend toward excessive smoothness of pattern and tend to eliminate small-scale details which are frequently observed on actual sea level pressure charts. In this respect the objectives look more like space - or time - means than like forecasts prepared by conventional or dynamical methods. For this reason they have been found quite useful in preparing 5- and 30-day mean predictions and are applied routinely for this purpose in the Extended Forecast Division of NMC. However, they are considered too smooth for daily forecasting.

V   IMPROVEMENTS

In order to obtain improved short range forecasts, some experiments were recently conducted in which sea level pressures in North America were specified from concurrent values of upper level height at the 850-mb. and 500-mb. levels. Figure 9 shows the grid of points used, where the distance between points is equal to twice the grid interval used in numerical weather prediction $/4/$. Pressures at 49 points inside the dashed lines were screened as a function of heights at 94 points inside the solid lines. Since only seven years of record, from 1959 to 1965, and only one value per day, at 0000 GMT, were available, adjacent months were combined in order to increase the sample size, instead of treating each month separately as before $/3/$.

Figure 10 shows a typical multiple regression equation derived for the months of July and August. The most important single predictor for specifying the sea level pressure at the grid point located at the asterisk (51°N., 85°W.) is the 850-mb. height at the same point. This variable, by itself, would explain 67.5 percent of the pressure variance, with a standard error of estimate of 3.2 mb. The predictor which adds the most independent information is the 500-mb. height at the same point, which, taken in conjunction with the first variable, raises the explained variance to 82.1% and lowers the standard error to 2.4 mb. The third variable selected is the 850-mb. height at 58°N., 86°W., which raises the explained variance to 85.0% and lowers the standard error to 2.2 mb. The fourth predictor selected is the day of the year, producing an explained variance of 86.5% and a standard error of 2.1 mb.

The screening process was stopped at this point because no additional variable could raise the explained variance by even 1%. The synoptic explanation of the final multiple regression equation shown at the bottom of the figure is straightforward. The first variable gives the local effect such that high heights at 850 mb. go with high pressures at sea level, and conversely for low heights and pressures. The negative sign before the next term indicates that high heights at 500 mb. tend to produce warm thickness and hence low sea level pressure, and conversely for low heights, which are associated with cold air and high pressure. The third term indicates that pressure systems tend to tilt northward from sea level to 850 mb. The fourth term accounts for the normal increase of sea level pressure with time from July 1 to August 31.

Figure 11 maps the explained variance obtained for all 49 points during July and August, using the 1% cut-off criterion described previously. There are several large areas with values greater than 90%, and values are greater than 80% in all areas except the extreme Southwest. This represents a marked improvement over results obtained earlier for the 700-mb. level specification in July (figure 5). For the entire area shown in this slide, the average number of predictors is four and the average explained variance is 83%, compared to only 55% for pressures specified previously from 700-mb. heights. One reason for low values in the Southwest is small pressure variability in that area. As a result, the standard error of estimate for the new equations, figure 12, is just as small in that area as it is in most parts of the map. The overall average is only 1.3 mb., compared to 2.3 mb. for the July 700-mb. specification (figure 6).

A good indication of the superiority of the new method over the old one is shown in figure 13, which maps the difference in explained variance between the two sets of equations. The new results are better in all areas, with maximum improvement of over 40 percent in three regions of the map.

The improvement over the old equations is even more marked during winter, as shown by figure 14, which maps the explained variance for the new equations during January and February. Values exceed 90% almost everywhere north of the 30th parallel. The overall average is 87%, compared to 59% for the 700-mb. specification in the same area. Figure 15 maps the difference in explained variance between the two results for January. Although the new method is everywhere superior, the improvement is greatest in mid continent and smallest over both oceans. This is another indication of the customary baroclinicity over continental areas.

Figure 16 shows the new standard errors of estimate for January-February. Values are less than 2 mb. over a large portion of the map, and the overall average of 2.3 mb. is just half the average of 4.6 mb. obtained previously for 700-mb. heights over the same area in January (figure 6).

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VI   CONCLUSION

Since the new specification equations based on 850-mb. and 500-mb. heights appear so promising, it is planned to extend them to other parts of the hemisphere and to other months of the year. A program will then be written to apply them to numerical forecasts of 850- and 500-mb. heights produced by either the baroclinic or the barotropic mesh model. Whether the resulting objective forecasts of sea level pressure will prove superior to the 1000-mb. height forecasts produced dynamically from the NMC primitive equation model $\sqrt{7\_7}$ remains to be seen.

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5. Cressman, G. P., 1963: "A Three-Level Model Suitable for Daily Numerical Forecasting," Technical Memorandum No. 22, National Meteorological Center, U. S. Weather Bureau, Washington, D. C., 27 pp. + 15 pp. of figures.

6. Reed, R. J., 1963: "Experiments in 1000-mb. Prognosis," Technical Memorandum No. 26, National Meteorological Center, U. S. Weather Bureau, Washington, D. C., 31 pp. + 11 pp. of figures.

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Table 1

Verification of 36-hour sea level pressure forecasts over North America for 62 cases of March 1964 in terms of the S-1 score and the average absolute error. (In each case, the lower the score, the better.)

Type of Forecast	S-1 Score	Error (mb.)
Objective (specification)	75.3	6.1
Persistence (last observed)	91.0	8.6
Reed model (dynamic)	74.1	7.1
Conventional (NMC)	63.3	5.2
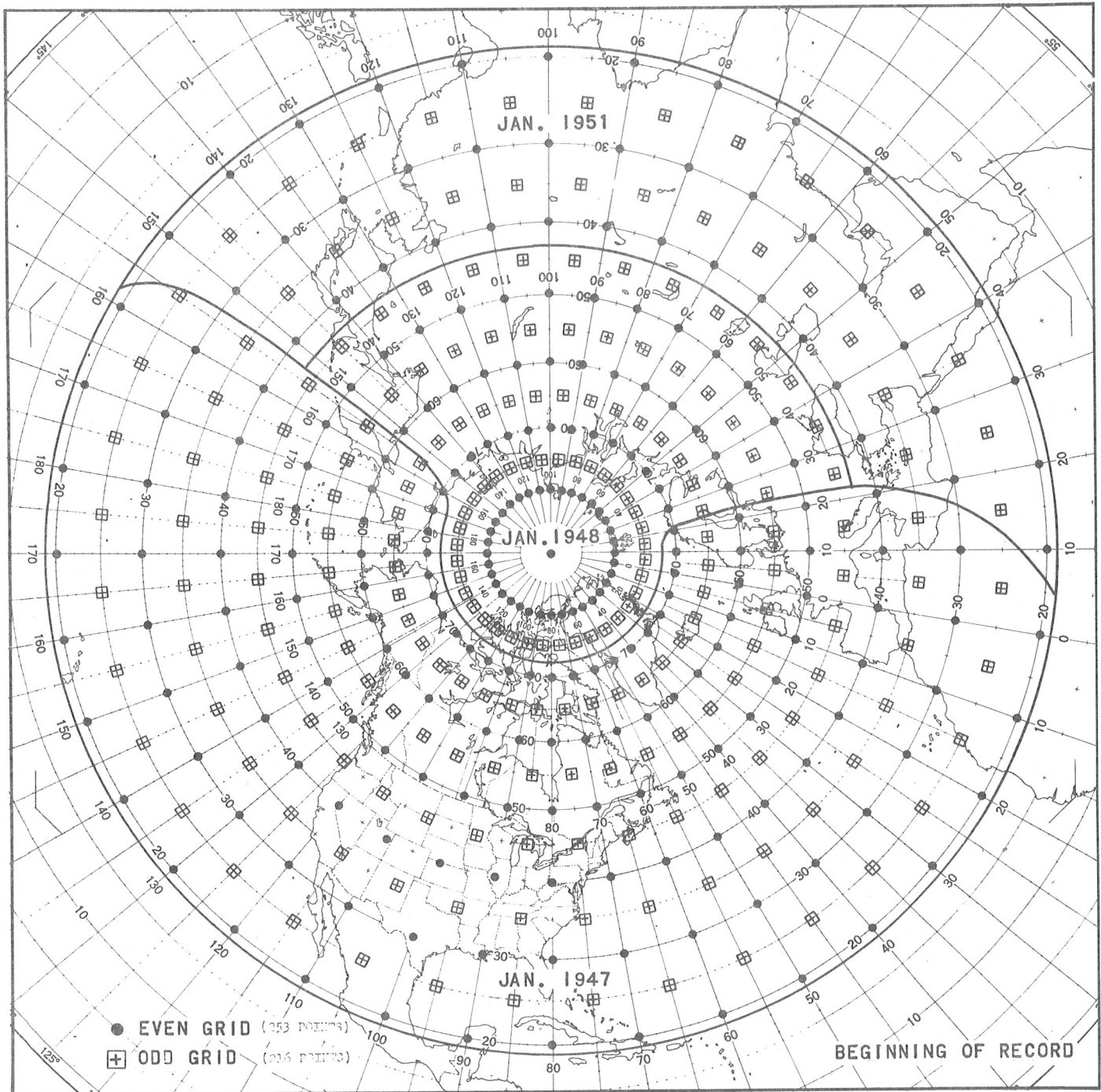
Figure 1. – Diamond grid of points for which 700-mb. data were processed and first month used in derivation. Equations were derived for 253 points in the even grid (dots) and 216 points in the odd grid (squares).

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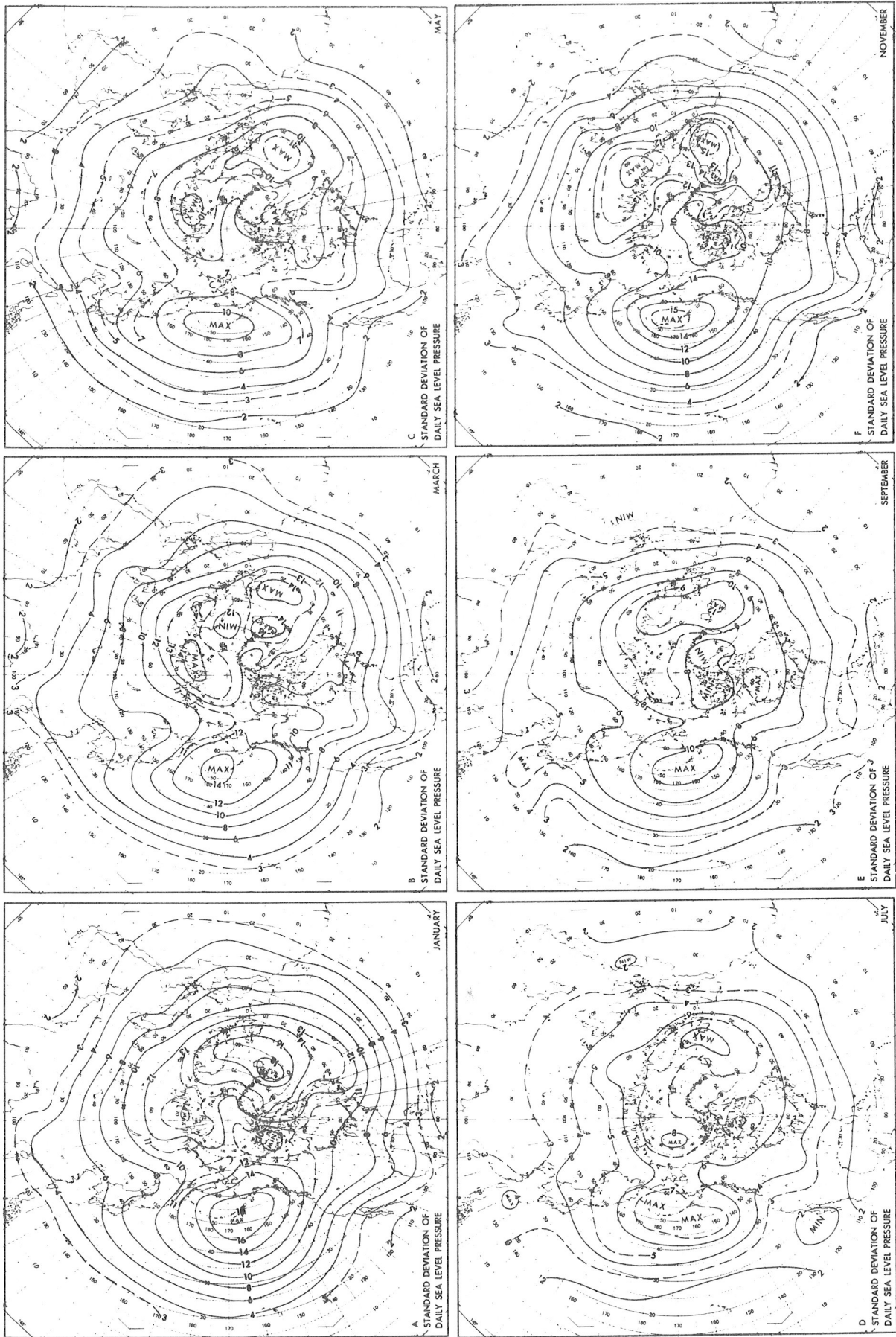
Figure 2. – Standard deviation of daily sea level pressure for the months shown. Isopleths are in milli-bars, with centers labeled as maximum or minimum.

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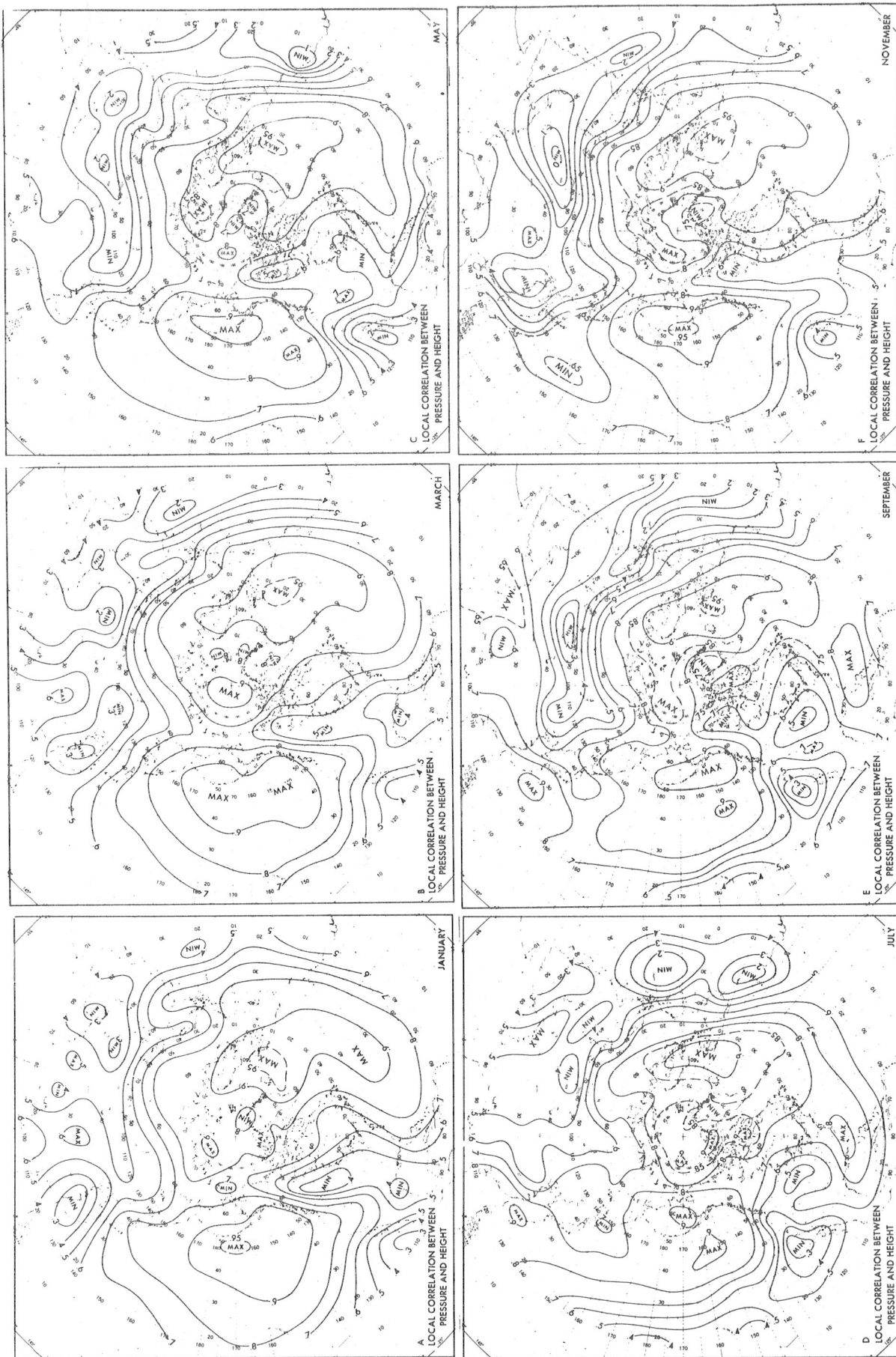
Figure 3. - Simple linear correlation coefficients for months shown between daily values of sea level pressure and concurrent 700-mb. height at the same point, with centers labeled as maximum or minimum.
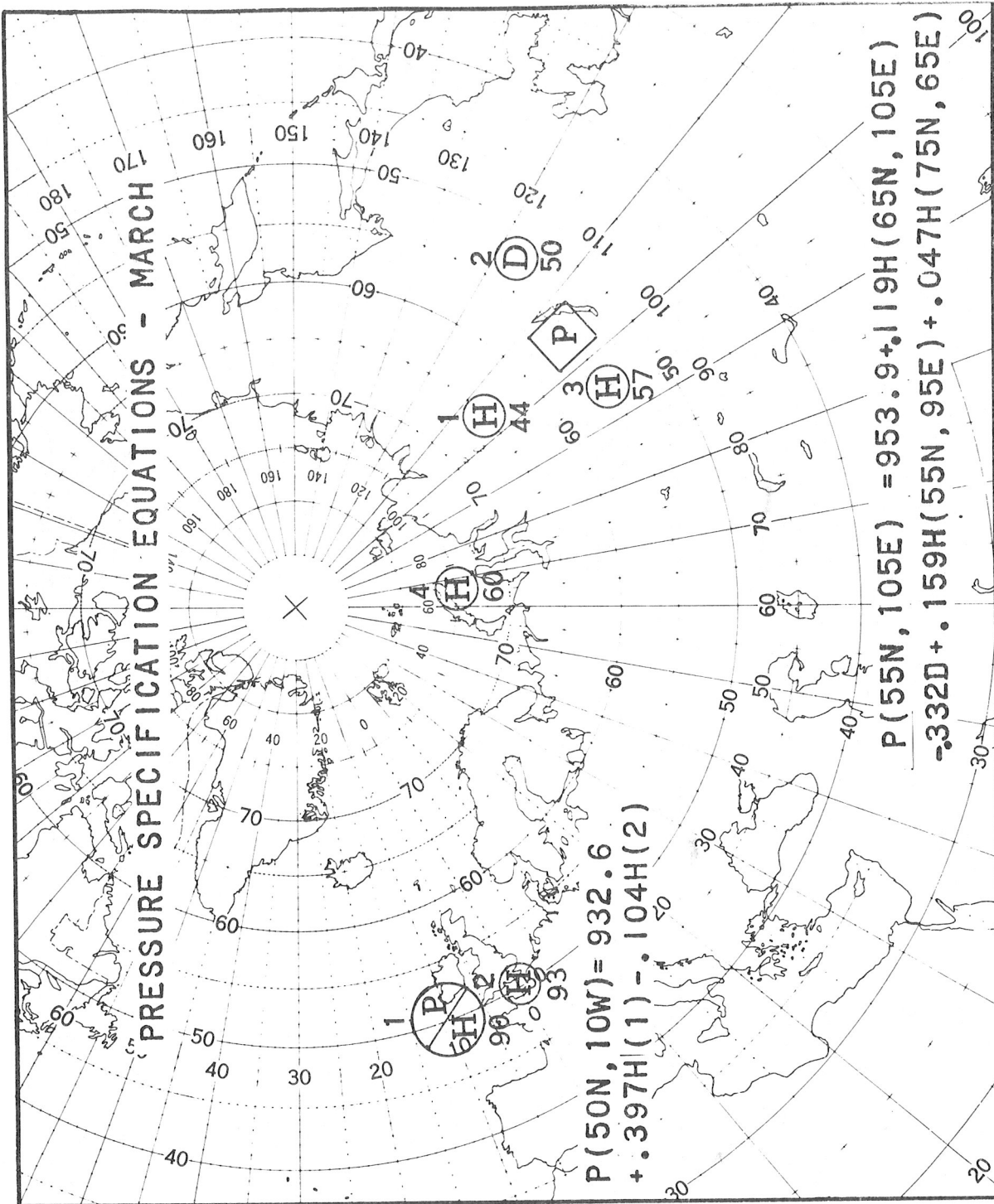
Figure 4. — Multiple regression equations used in specifying sea level pressure (P in mb.) during March. The left side is for the pressure at 50°N., 10°W. as a function of the concurrent 700-mb. height (H in tens of feet minus 700) at the same point and 10° to the east. The right side is for pressure at 55°N., 105°E. as a function of height at the points indicated and also of the day of the month (D). In both cases the location of the selected height is given by the open circle, the order of selection by the number above, and the percent of variance explained after inclusion of the given predictor by the number below.
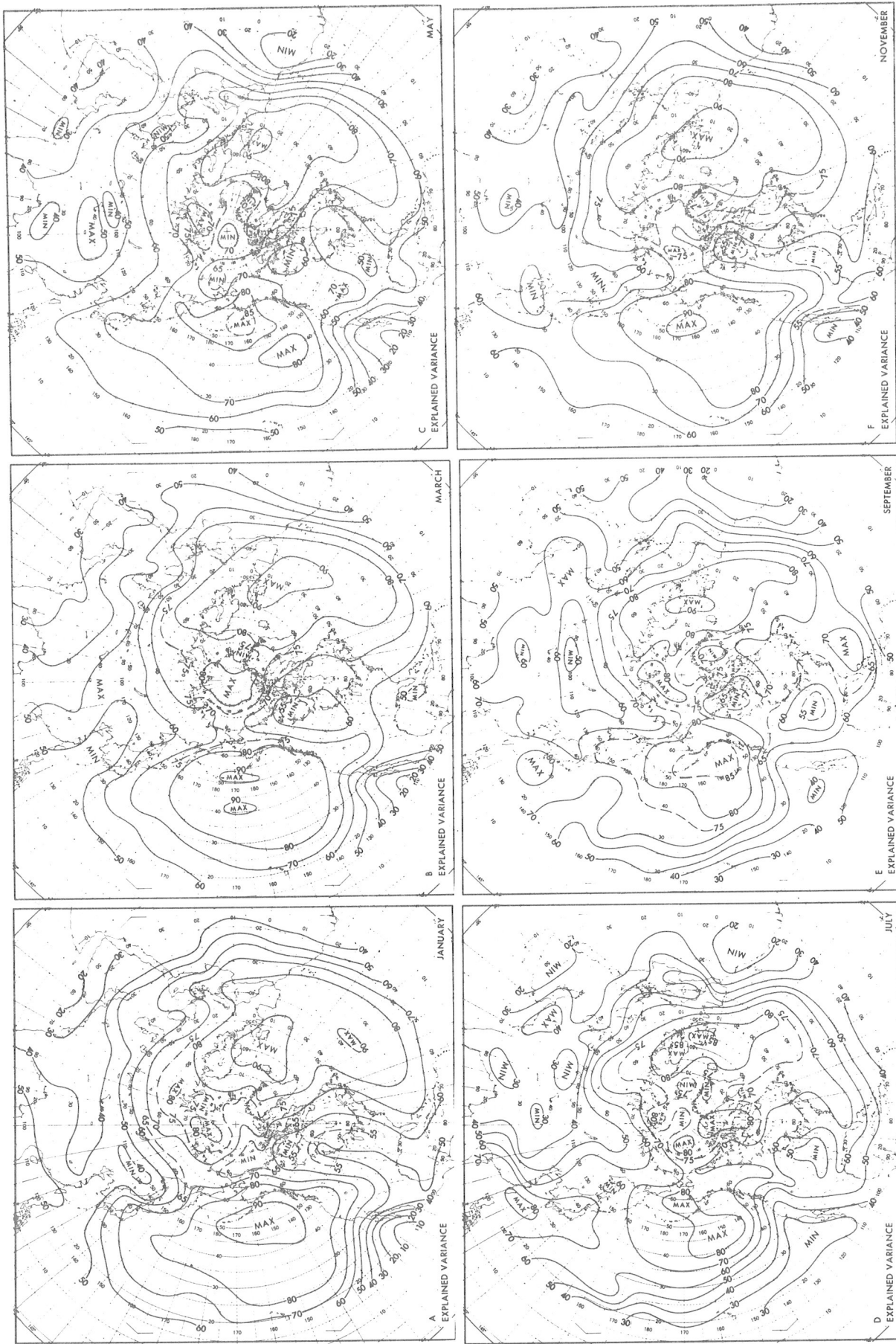
Figure 5. - Percent of variance of sea level pressure explained by specification equations of the type shown in figure 4 during months indicated, with centers labeled as maximum or minimum.
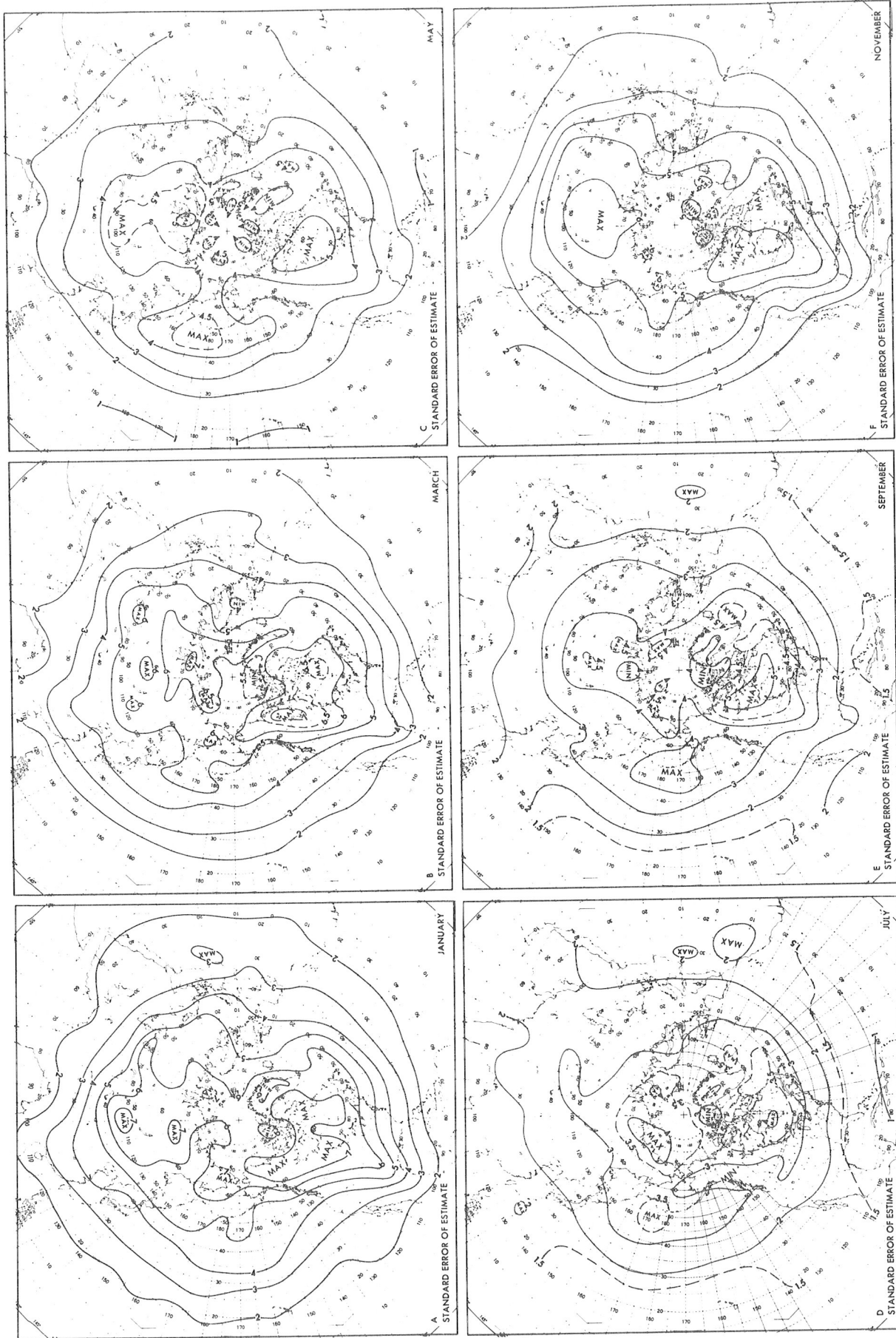
Figure 6. – Standard error of estimate (mb.) in specifying sea level pressure from concurrent 700-mb. heights for months shown, with centers labeled as maximum or minimum.
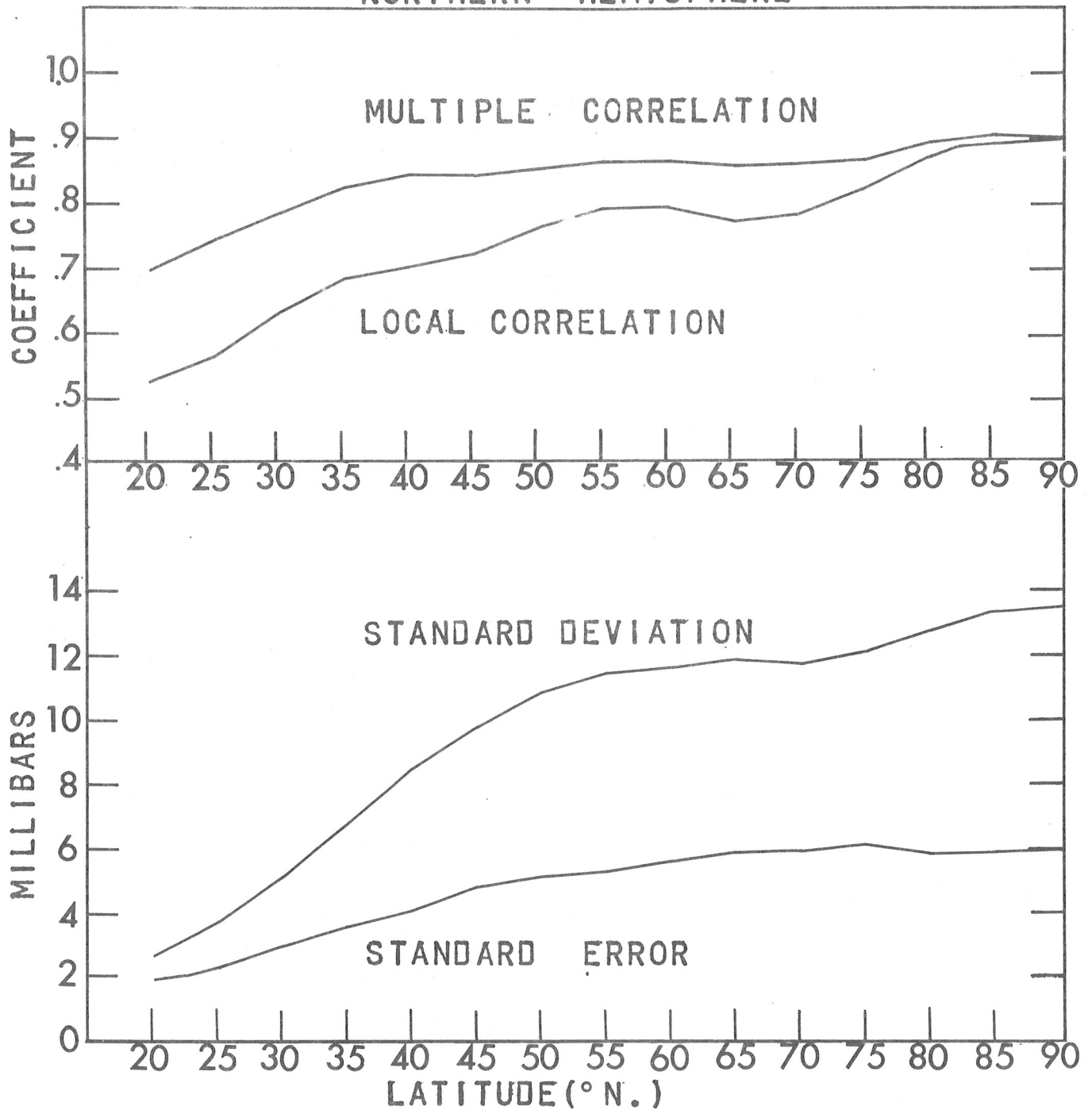
Figure 7. - Values during March averaged over the Northern Hemisphere as a function of latitude for: (a) the multiple correlation between observed pressures and those given by the specification equations, (b) the local correlation between pressure and height at the same point, (c) the standard deviation of observed pressure, and (d) the standard error of estimate for pressures forecast from the specification equations.

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OBSERVED SEA LEVEL PRESSURE
VALID 12Z, MARCH 21, 1964

OBJECTIVE SEA LEVEL PRESSURE
VALID 12Z, MARCH 21, 1964
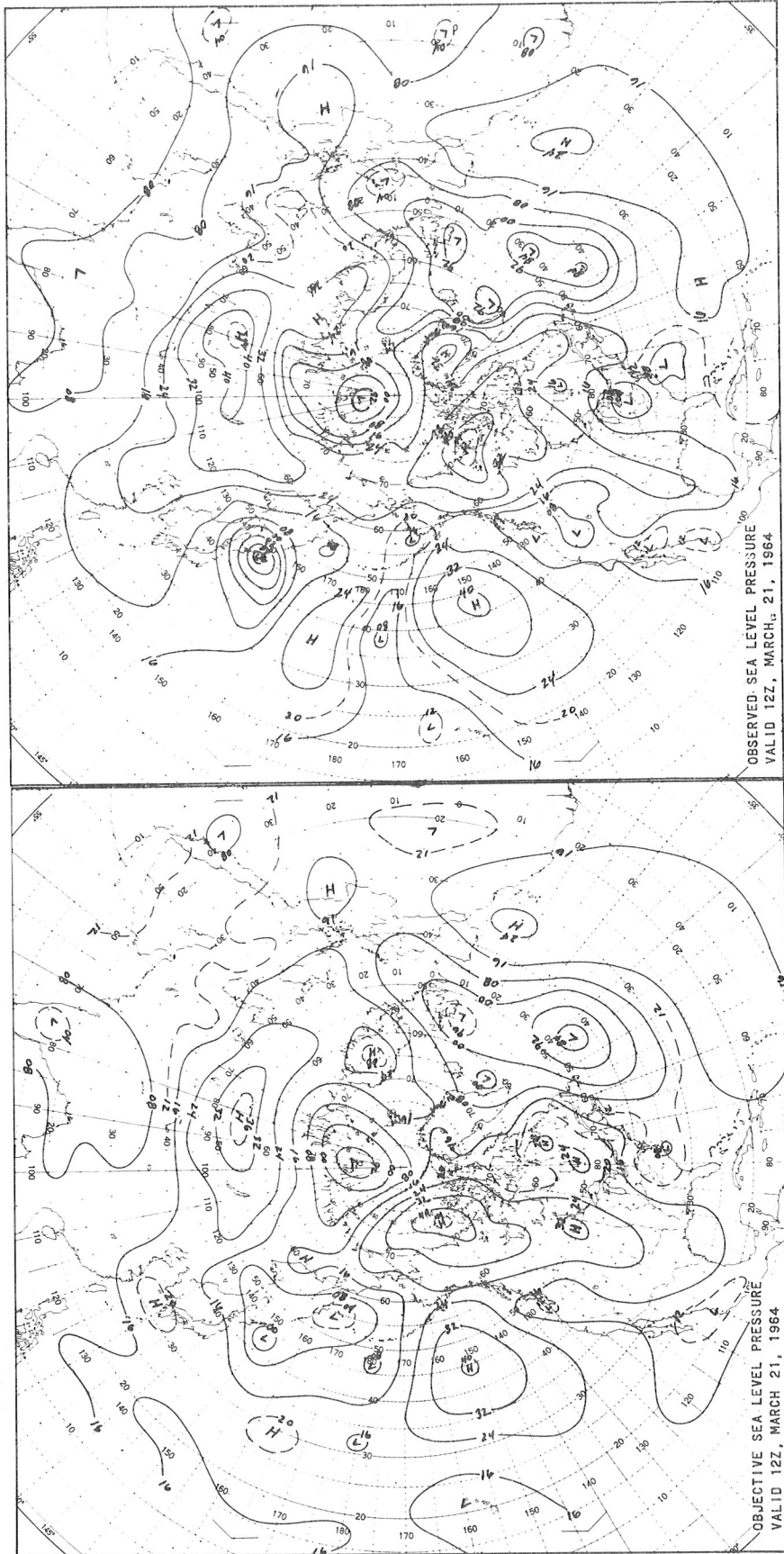
Figure 8. – Objective forecast of sea level pressure made by applying the March specification equations to the 36-hr. baroclinic prognostic 700-mb. heights valid at 1200 GMT, March 21, 1964, with verifying map on the right. Isobars are drawn for every 8 mb., with intermediate lines dashed, and labeled with last two digits only.
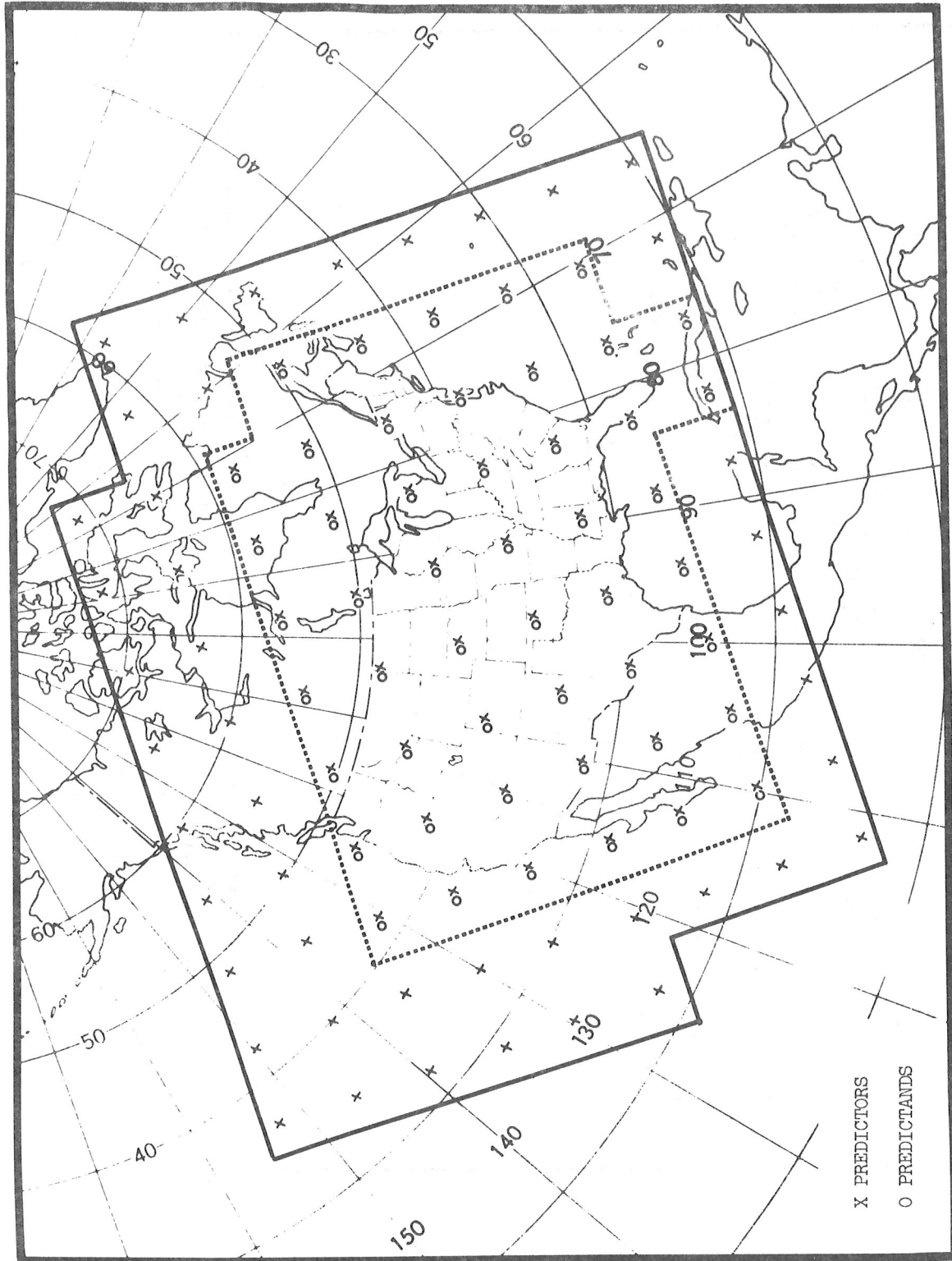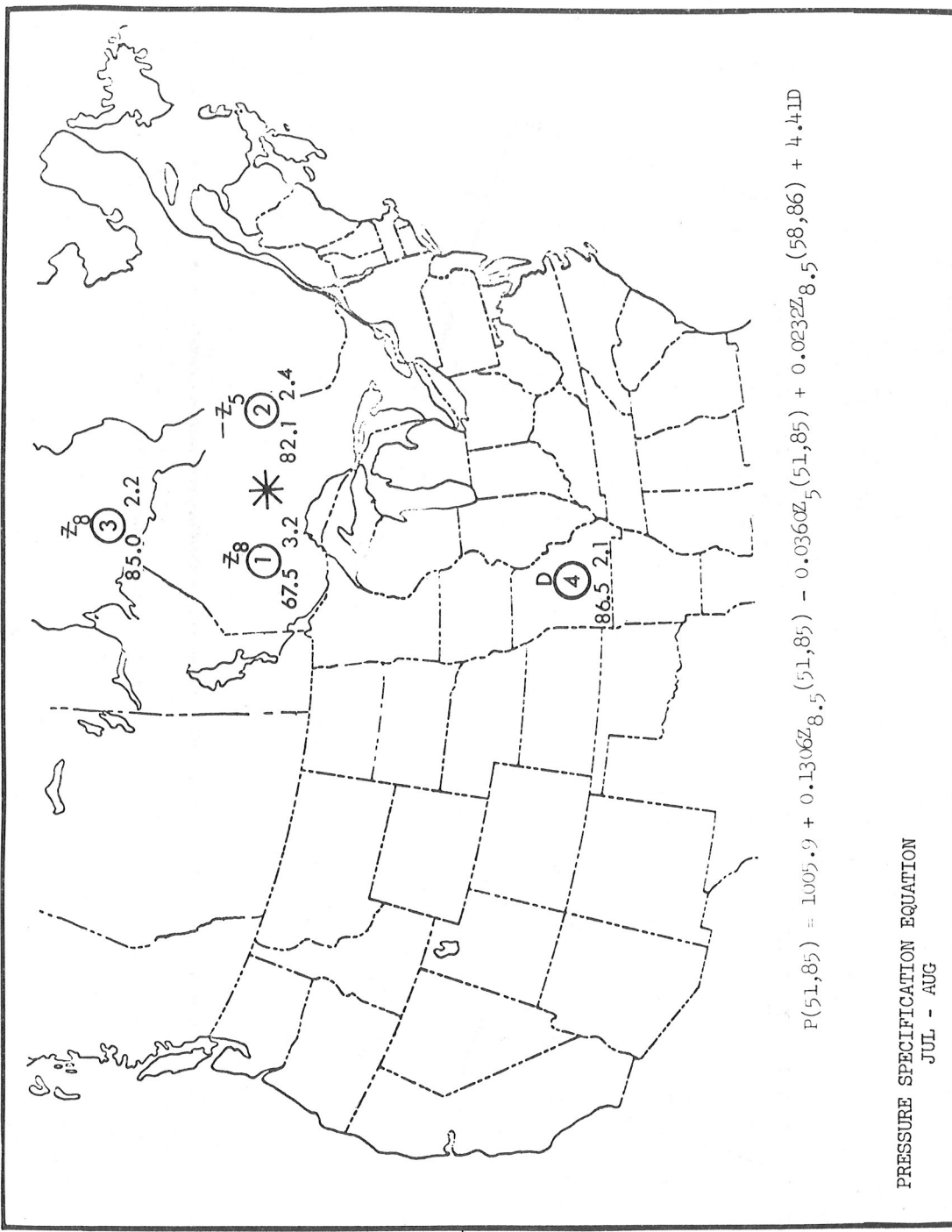
Figure 9. - Square grid of points for which 850-mb. and 500-mb. data were processed. Sea level pressures at 49 points inside the dashed lines were screened as a function of heights at 94 points inside the solid lines.

X PREDICTORS

O PREDICTANDS

$$P(51,85) = 1005.9 + 0.1306Z_{8.5}(51,85) - 0.036\alpha Z_5(51,85) + 0.0232Z_{8.5}(58,86) + 4.41D$$

PRESSURE SPECIFICATION EQUATION
JUL - AUG

Figure 10. - Multiple regression equation for specifying sea level pressure (P in mb.) at 51°N., 85°W. during July and August as a function of the concurrent 850- and 500-mb. heights (Z_8 and Z_5 in ft.) at the same point, the 850-mb. height at 58°N., 86°W., and the day of the year (D). The order of selection is given by the number inside the circle, the percent of variance explained after inclusion of the given predictor by the number on the left, and the standard error of estimate (in mb.) by the numbers on the right.
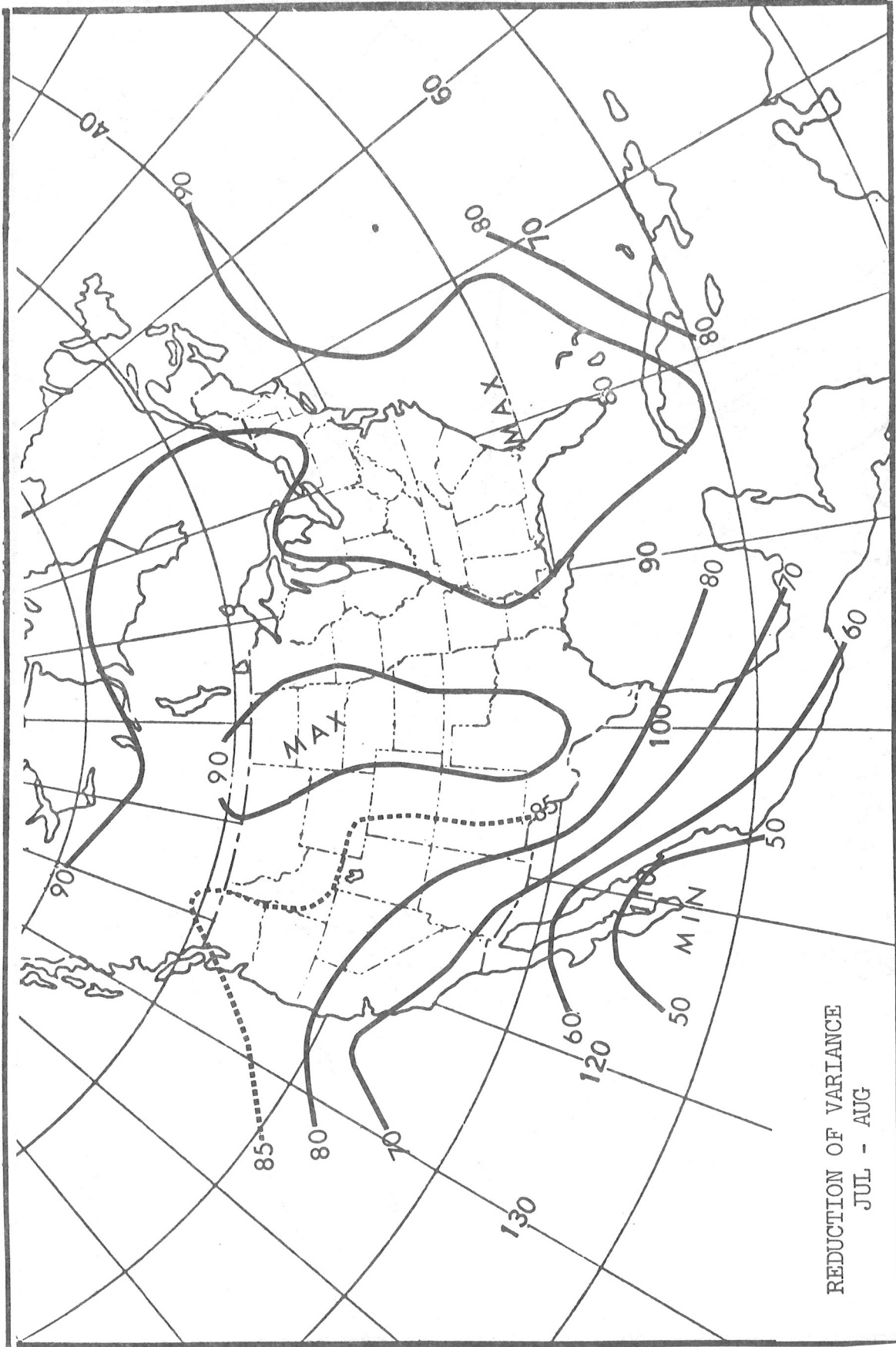
Figure 11. - Percent of variance of sea level pressure explained by specification equations of the type shown in figure 10, with centers labeled as MAX or MIN.

REDUCTION OF VARIANCE
JUL - AUG

Figure 12. – Standard error of estimate (mb.) for equations of the type shown in figure 10, with centers labeled as MAX or MIN.
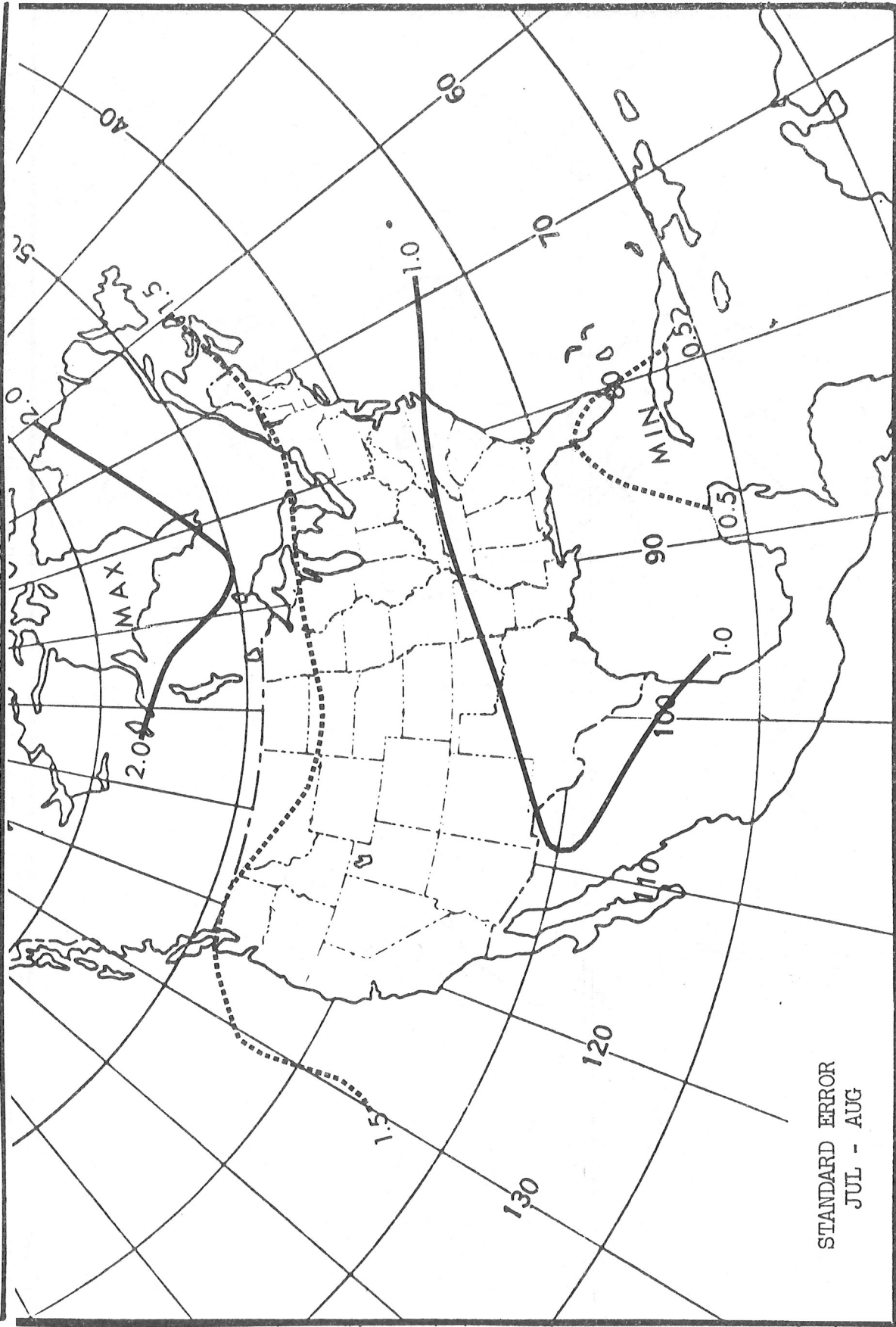
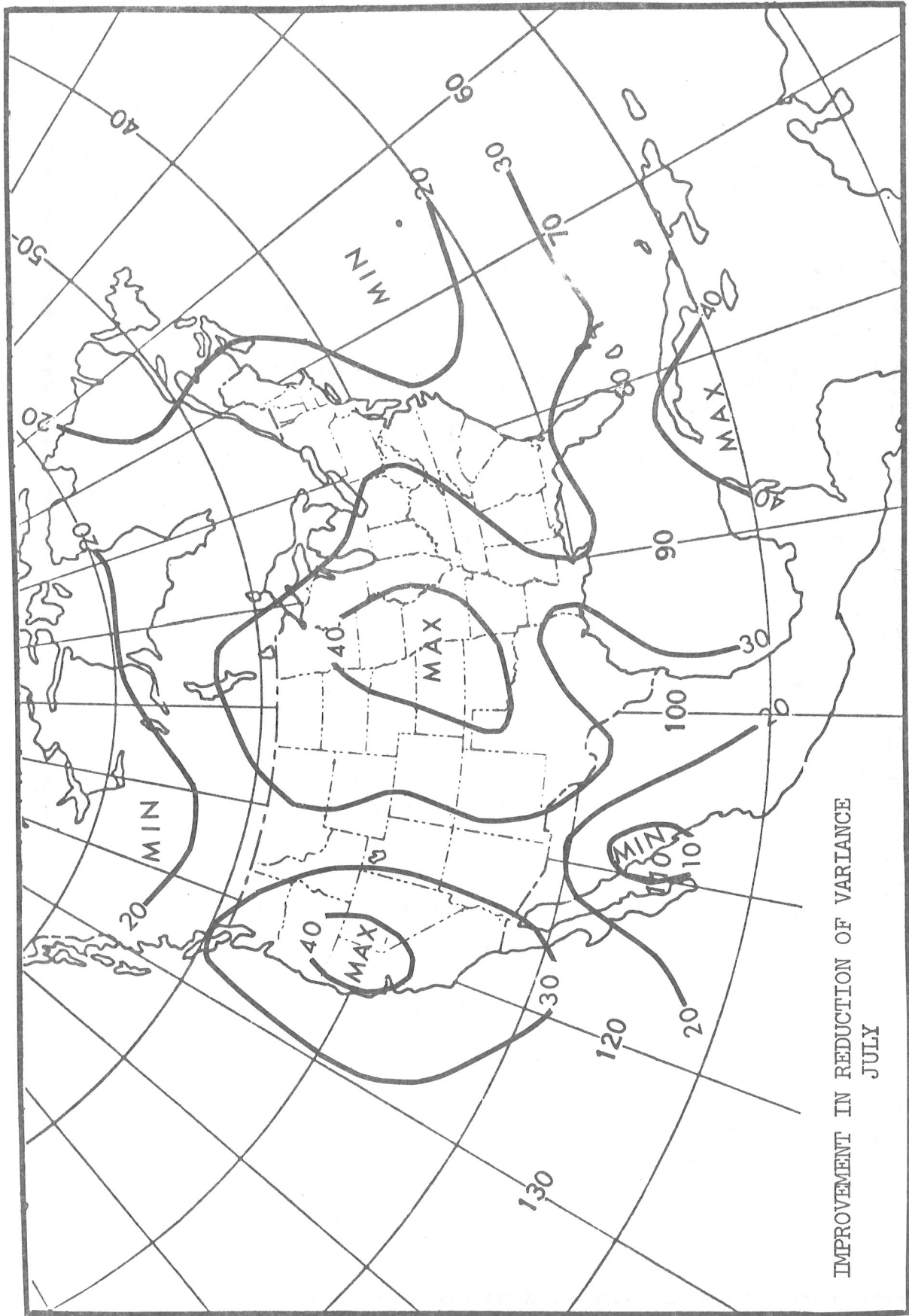STANDARD ERROR
JUL - AUG

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IMPROVEMENT IN REDUCTION OF VARIANCE
JULY

Figure 13. - Difference between percent of pressure variance explained by 850- and 500-mb. heights during July and August (figure 11) and percent explained by 700-mb. heights during July (figure 5.)
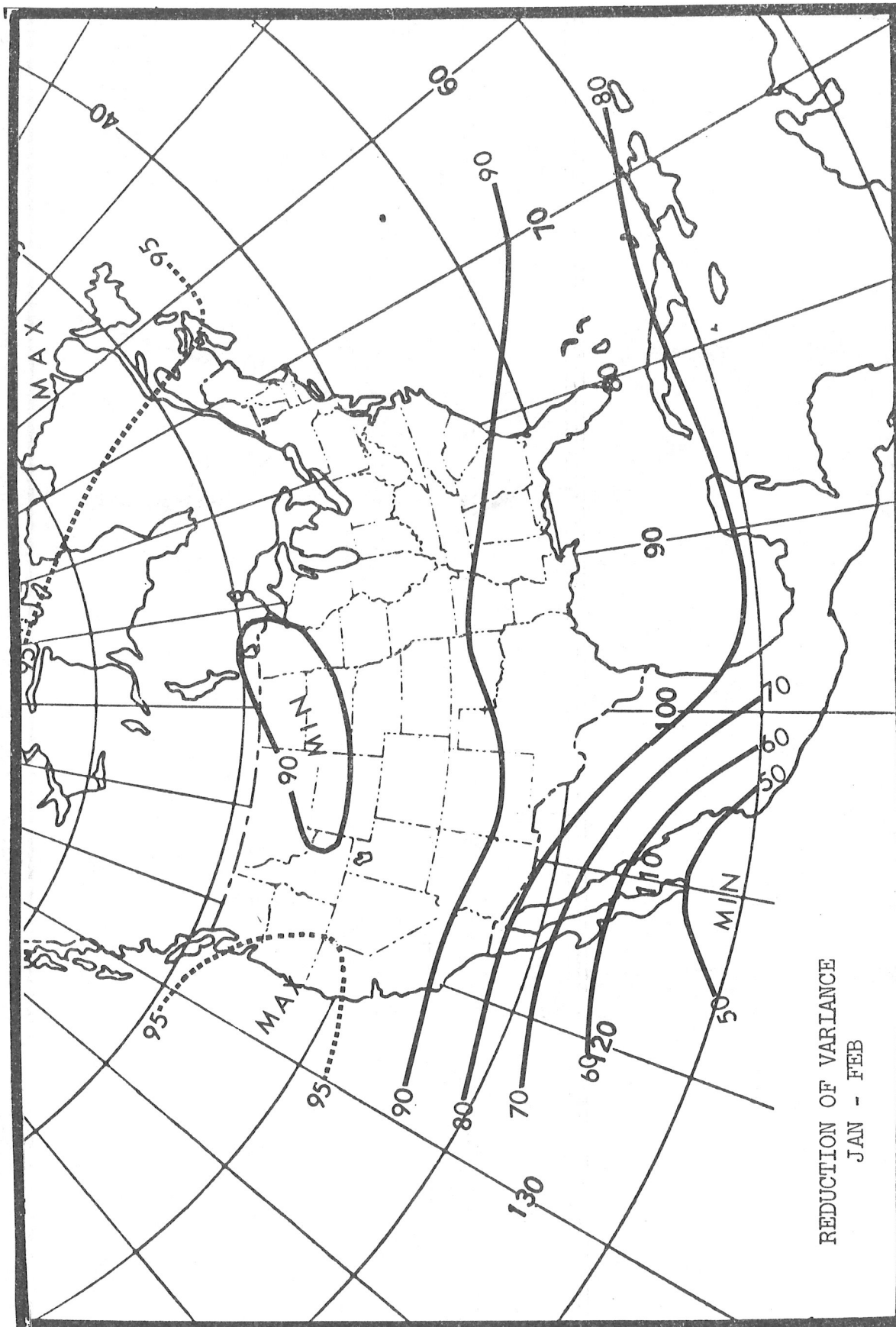
REDUCTION OF VARIANCE
JAN - FEB

Figure 14. - Same as figure 11 for January and February.

STANDARD ERROR
JAN - FEB
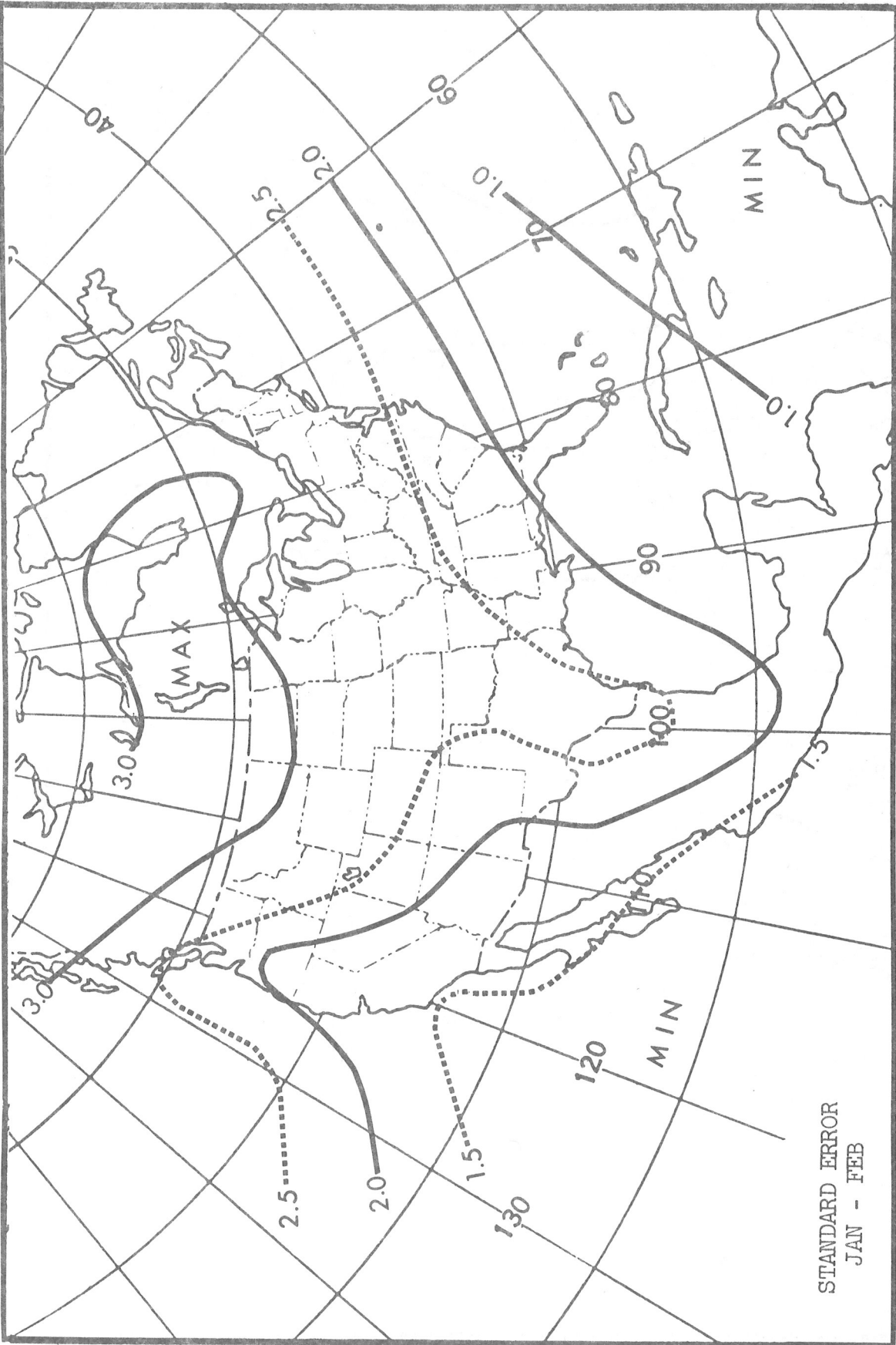
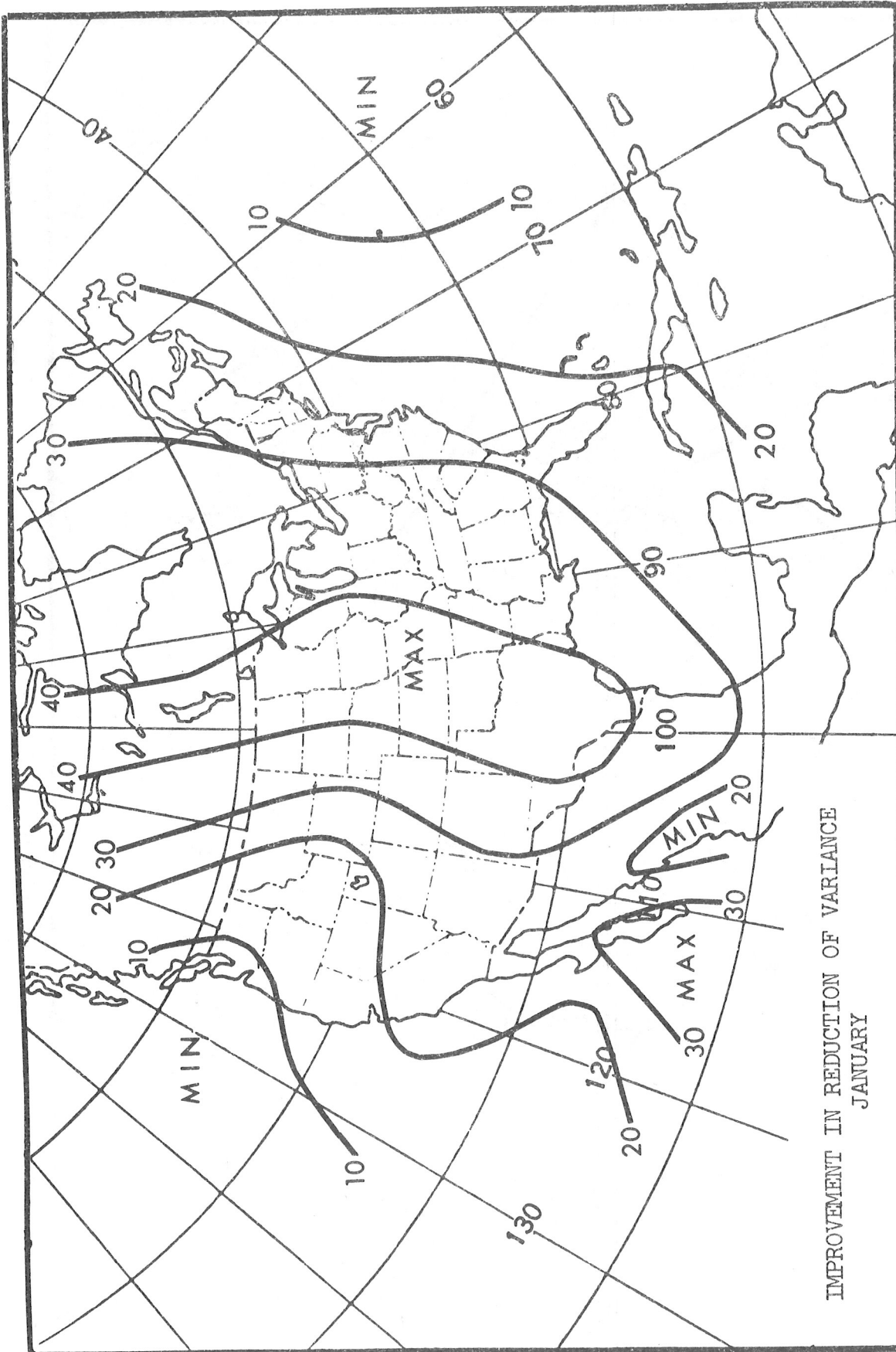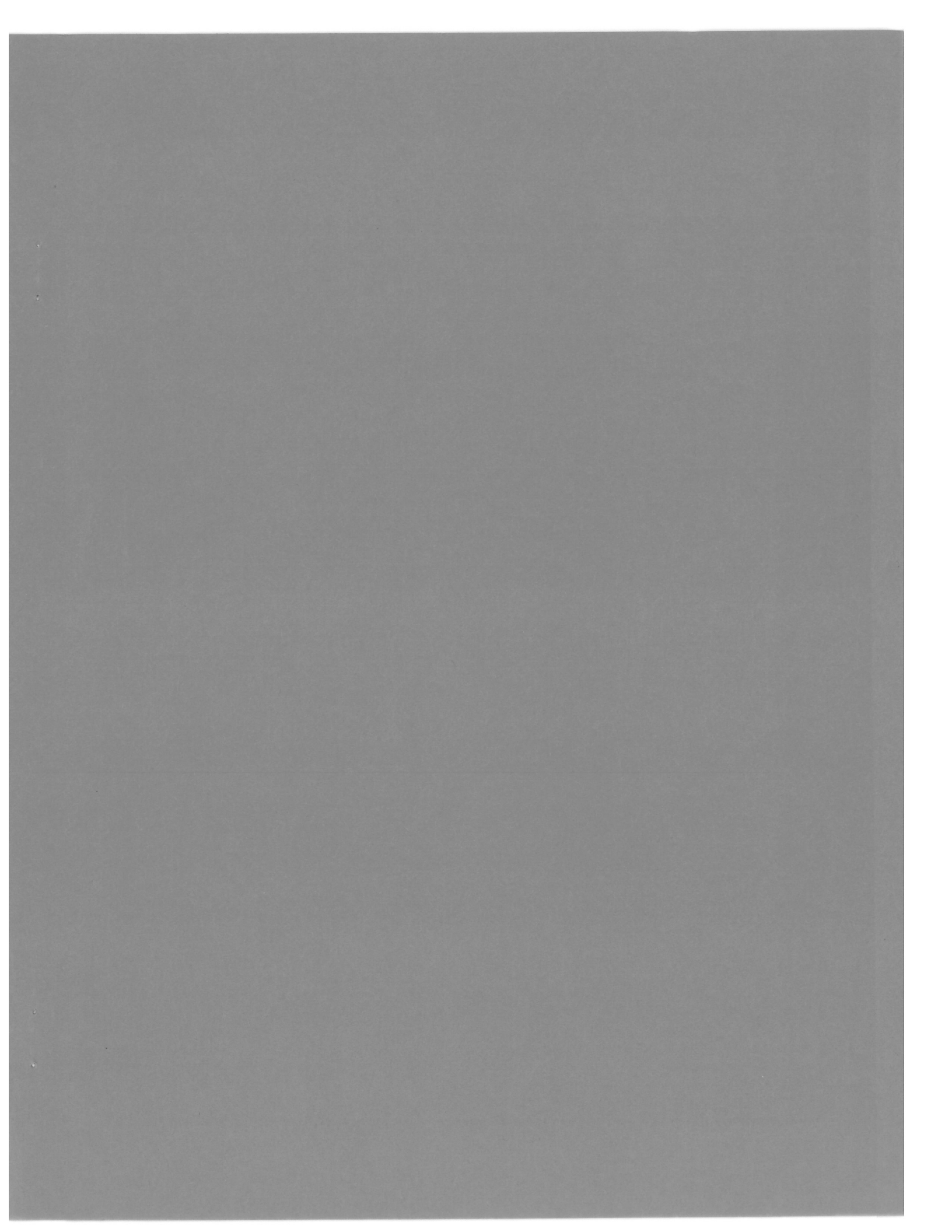Figure 15. - Same as figure 12 for January and February.

IMPROVEMENT IN REDUCTION OF VARIANCE
JANUARY

Figure 16. - Same as figure 13 for January.