JOURNAL OF METEOROLOGY VOLUME 2, NUMBER 2 JUNE 1945

# ADVECTION OF AIR AND THE FORECASTING OF PRESSURE CHANGES

By *Bernhard Haurwitz and Collaborators**

Massachusetts Institute of Technology

(Manuscript Received March 31, 1945)

## ABSTRACT

The advection method of preparing prognostic pressure charts was tested using a number of different procedures. First, it was assumed that the density change at a given level can be regarded as representative of the density change throughout a layer which includes this level. Accordingly, isopycnic lines were drawn for five levels between sea level and 14,000 meters, and forecasts of the density changes at these levels were prepared on the hypothesis that the air moves with the geostrophic wind velocity, preserving its density. The sea level pressure change is obtained by adding the density changes for all levels after making allowance for the thickness of each layer. The effects of advection above 14,000 meters were neglected. The examples selected for a test gave poor results, and a statistical check showed that, even with perfect forecasts of the density, satisfactory results cannot be expected because the density changes at a given level are not sufficiently representative of the density changes in the whole layer.

In the major part of the study the pressure forecasts were based on weight charts for four layers, from sea level to 13,000 meters. Since the weight, represented by the pressure difference between the bottom and the top of the layer, is proportional to the mean density of the layer, this method appears more satisfactory than the one studied first. To obtain prognostic weight changes, the motion of the weight lines has to be known. Three different methods for the determination of the motion of the weight lines were tested:

*a.* The motion was assumed to be geostrophic.
*b.* The trajectory of the air was found by successive approximations taking into account the variation of the pressure distribution during the forecast interval.
*c.* The trajectory of the air was found under the assumption that the absolute vorticity is conserved (Rossby method).

In all three cases the weight was considered as a conservative property of the air. The sea-level pressure changes were obtained by adding the prognosticated weight changes in all layers and the pressure change at the top level. The prognostic pressure changes thus prepared were quite unsatisfactory, and statistical checks gave correlation coefficients between the observed and prognostic pressure changes which were too small to be of forecasting significance.

It is concluded that the advection method *used by itself* cannot be recommended as a forecasting tool. In addition to advection, other factors such as divergence and vertical motions make themselves felt too. Their effects have also to be taken into account if satisfactory prognostic charts are to be constructed in a purely objective fashion.

**1. Introduction.** It has been suggested that the forecast of the future pressure field may be improved by determining for the air column above each station the changes in weight which would be caused by the horizontal advection of air. It is recognized by the proponents of this "advection method" that other phenomena also play a part in producing the day-to-day pressure changes, but it is argued that these effects are not strong enough to invalidate the prognostic chart obtained by the advection method. It is the purpose of the present paper to report on a check of the practical value of the advection method.

In applying the advection method it is necessary, strictly speaking, to know the density and wind distribution at every level in the atmosphere and to compute the weight changes due to advection for every level. In practice, only a limited number of levels or layers can be used. Under these conditions, there are two possible methods of approach. First, one may construct lines of equal density for selected heights. These isopycnic lines are then displaced with the speed indicated by the wind and pressure field at this level. In doing this it is assumed that the advective changes of mass obtained in this manner are representative not only of the changes of mass at the level under consideration, but also through a certain distance above and below this level (Section 2). The other method consists in constructing charts of the pressure difference between fixed levels (weight charts) and determining the displacement of the lines of equal pressure difference or weight through the forecast

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* The investigation reported in this paper has been carried out under the direction of B. Haurwitz and T. F. Malone. The main part of the synoptic and statistical work was done by Lt. M. A. Eaton, U.S.N.R., Mr. R. C. Staley, and Lt. A. E. Tancreto, U.S.N.R., with the liberal assistance of other staff members of the Institute's Meteorology Department.

period (Section 3). In this case, it is necessary to assume a mean motion for the whole layer under consideration but, despite this shortcoming, the latter method appears more satisfactory from a practical viewpoint than the first one. Hence, the first method and its check are discussed rather briefly here.

Even if advection is the major factor in determining the future pressure field the path of advection would still be doubtful. Three possible procedures of determining the horizontal advection have been employed in connection with the work on the weight charts. The simplest method is based on the assumption that the isobars are streamlines and that the flow pattern changes so little with time that the isobars can be regarded as the lines along which the pressure-difference lines are displaced. The second procedure uses trajectories determined by successive approximation from the isobars and from the displacement of the isobars during the forecast period (3). As a third means of determining the path of advection, the method of finding trajectories on the basis of conservation of vorticity suggested by Rossby is utilized (4).

By the selection of these three different methods of advection for a check, it is not implied that they are the only possibilities, but rather that they are the most promising ones.

It must be added here too, that neither the density of an air particle nor the mean density of an air layer as represented on the weight charts is a conservative property of the air, although either of these two quantities may occasionally remain unchanged for a given air volume. For this reason, it cannot be assumed that the lines of equal density or of equal weight move along with the velocity indicated by the trajectory of the air. Nevertheless, some such assumption seems necessary if advection is to be used in practice. An alternate method suggested by Braun and Douglis (2) would be to displace the density, or the weight lines, by the same distance and in the same direction as they moved during the time before the forecast period. However, this method appears more unsatisfactory than those employed here because its physical basis is somewhat obscure. Moreover, the study carried out at the Massachusetts Institute of Technology showed that advection is rather erratic and is, if anything, better indicated by the flow pattern than by the past motion.

2. **Density charts.** As explained in the introduction, the first attempt at a utilization of the advection method for the preparation of prognostic pressure charts was based on charts of the density distribution at different atmospheric levels. The density at the radiosonde stations (about 20–30 for each map) was obtained for certain levels (see below) by means of tables and was plotted on a map. It was then assumed that the density distribution at each level was representative of the density distribution through a certain layer. The following levels were chosen and regarded as representative for the corresponding layers:

| Level | Layer |
|---|---|
| 5,000 feet | 1–2 km |
| 10,000 feet | 2–4 km |
| 20,000 feet | 4–8 km |
| 10 km | 8–12 km |
| 13 km | 12–14 km |

Above 13 km, sufficient data for constructing a density chart usually were not available; therefore the effects of advection at higher levels were neglected. This does not mean that they were considered unimportant. But the only way to take changes at higher levels into account would have been to prepare prognostic charts of the pressure at 14 km, and it was felt that the preparation of a prognostic chart for the top level by the customary methods, based on the forecaster's experience and empirical rules, would render the check of the advection method considerably less objective and too much dependent on the skill of the forecaster. The effect of this omission on the accuracy of the forecasts is discussed below.

After the charts of the density distribution were drawn, the changes of the density during the forecast interval were determined. It was assumed that the air moves without changing its density and according to the geostrophic wind relation. This assumption implies that the temperature is conserved while the air flow is along the isobars. Thus, the density changes at each of the selected levels over each station were determined. From these density changes at representative levels in each layer the change of the pressure difference between the bottom and the top of the layer, and thus the contribution to the surface pressure change, could easily be computed. Even though the density itself varies appreciably with the altitude throughout the layer, the vertical variation of the density change with time will be smaller. Hence, it may be permissible to consider the density change at an intermediate level as representative for the whole layer. Actually, this supposition is not quite correct as will be shown at the end of this section.

The pressure changes at a given level were found by adding all the pressure-difference changes above this level. In particular, for the sea-level pressure variation, the changes in all layers above this level had to be added, except that the layer from sea level to 1000 meters was disregarded. This omission seemed advisable for two reasons. In the first place, the elevation of the ground cuts off a substantial part of this lowest layer over large parts of the United States. Secondly, the motion of the atmosphere in the lowest layer is so much affected by friction that any advection on the basis of the geostrophic wind relation would be illusory. The omission of the lowest layer in the computation of advection may falsify the results somewhat and thus give too unfavorable an impression of the results obtained with this method. However, as will be shown below, the assumption of the density change at a level being representative of the density change in the layer is so unsatisfactory that the method has to be discarded for this reason alone.

The computed pressure changes were finally added to the pressure at the start of the forecast period. In this manner a prognostic pressure chart was obtained.

This method of preparing prognostic sea-level pressure charts was used in connection with the regular map discussions held by the staff of the Meteorology Department during the period from August 31 to September 18, 1944. As the starting map the 0630Z map was used and a prognostic map was constructed, at first for 24 hours ahead, later for only 12 hours ahead because it seemed that the failure of the method to give satisfactory prognostic charts might have been due, in part at least, to the variation of the isobaric pattern during the forecast period. A forecast for only 12 hours has the disadvantage that the diurnal variation of the pressure is not eliminated, but it was felt that the shorter forecast interval should nevertheless lead to an improvement in the forecast, especially since the normal 12-hour pressure changes are generally less than one millibar in September.

During the daily map discussion the prognostic sea-level pressure chart was not only compared with the actual pressure distribution, but in addition the forecast density values were compared with those which actually occurred. In all cases the result was disappointing. In particular, the prognostic chart prepared in the customary manner by judging the displacement and deepening and filling of pressure systems by experience lead to better agreement with reality than the chart prepared with the aid of the density charts.

The failure of the method to give satisfactory prognostic charts is not necessarily attributable to the deficiency of the basic assumption of the advection method, viz., that advection is predominant in determining pressure variations as compared to other factors. The following three causes may contribute to faulty prognostic charts even though the basic principle of the advection method is sound:

i) The representative density change determined for each layer by finding the density change at a fixed level in this layer may not be truly representative.
ii) The omission of the layers above 14,000 meters may produce a considerable error.
iii) The paths selected for advection, that is the isobars, deviate too much from the actual paths to give satisfactory prognostic pressure patterns.
iv) The omission of the lowest one-kilometer layer gives rise to some error.

To check the first two points the radiosonde observations at Omaha, Nebraska, during February, 1940, 1941, and 1942 were used. These three months gave 67 sets of data. To test the first point (i) the actual surface pressure changes were correlated with the pressure changes as computed from the observed density changes plus the actual pressure changes at 14,000 meters elevation. The correlation coefficient between these two quantities was found to be

(i) 0.90

The standard error of estimate is 3.24 mb when the appropriate linear regression equation is used.

If the pressure changes at 14,000 meters are disregarded in computing the surface pressure change, the correlation coefficient becomes

(ii) 0.87

The standard error of estimate is 3.8 mb. The material on which these statistical characteristics are based is not large and refers only to winter. Nevertheless, it shows clearly that even with perfect forecasts of the representative density changes the forecasts of the sea-level pressure by no means would be perfect. Also, if the pressure changes at 14,000 meters could be forecast with complete accuracy, the forecast of the sea-level pressure would still be substantially less than perfect. Since the entire air column is considered in this test, the error arising from (iv) is eliminated. The main cause of this imperfect correlation is evidently that the so-called "representative" density changes at fixed levels are not sufficiently representative for the mean density change throughout the layer.

It follows that the application of weight charts in the advection method is much more promising than the use of density charts, because a weight chart represents the field of mean density of a layer. For this reason the third point raised above, viz. the question of the proper paths of advection, was studied only in connection with the weight charts.

**3. Weight charts.** The pressure difference between two fixed levels in the atmosphere gives directly the weight of an air column of unit cross section between these two levels. Hence the pressure difference between the two levels is directly proportional to the mean density of this air column. Thus, in applying the advection method it seems preferable to use lines of equal pressure difference between two layers rather than isopycnic lines at a level intermediate between the upper and the lower boundary of the layer. In this case, the question of the representativeness of the density does not arise. Most of the work done at M.I.T. in connection with the advection method

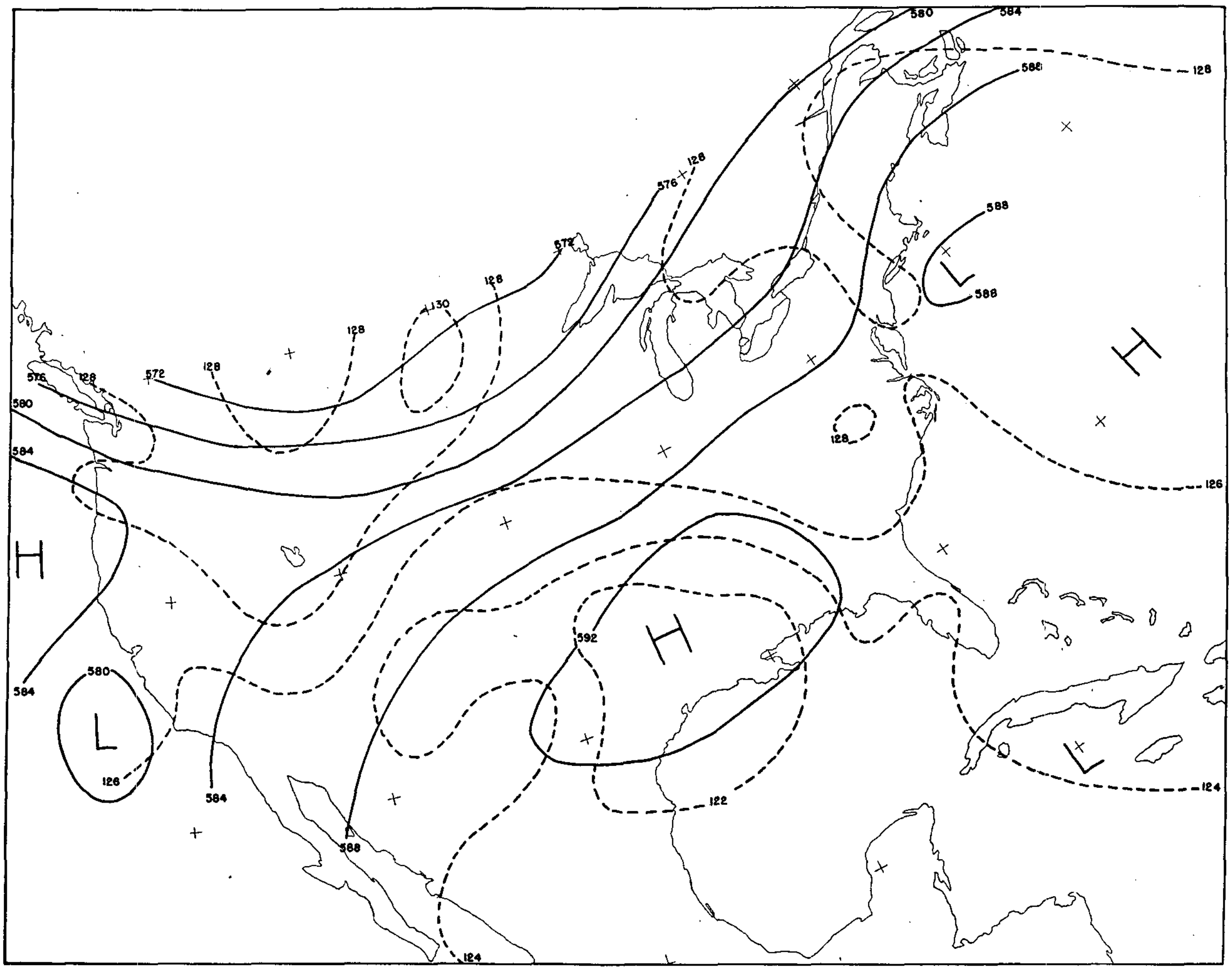

FIG. 1. Pressure difference between 10,000 feet and 20,000 feet elevation (broken curves). Mean isobars (full curves). September 20, 1944, 0400Z.

centered around the weight charts, and the density charts were considered mainly in order not to leave unexplored any possible method of applying advection.

Since pressure maps were drawn by the AAF Weather Station at M.I.T. for sea level, 10,000 ft, 20,000 ft, 10,000 m and 13,000 m, the pressure-difference or weight charts were constructed for the following layers:

Sea level to 10,000 ft (with isobars at 5,000 ft),
10,000 ft to 20,000 ft (with isobars at 15,000 ft),
20,000 ft to 10,000 m (with isobars at 20,000 ft),
10,000 m to 13,000 m (with isobars at 10,000 m).

The upper-level pressure charts are based on observations taken at 0400Z while the sea-level reports are for 0630Z. To make the sea-level reports simultaneous with the upper-air pressure data the three-hour pressure tendency was used to correct the sea-level pressures. In order to make forecasts three different methods of advection were tried as mentioned in the introduction.

### (a) *Advective motion determined by the geostrophic wind relation.*

As in the case of the density charts, it was assumed first that the air in each layer retains its weight and moves with a speed and direction given by the geostrophic wind relation. To obtain the flow pattern the isobar patterns as indicated above were used for each layer. The forecasting period was 12 hours, as in the majority of cases when the density charts were used and for the same reasons. The change of weight in each layer during the forecast period was computed by moving the weight lines with the speed and in the direction indicated by the isobars. To take into account changes above the 13,000-meter level, it was necessary to forecast the pressure changes at 13,000 meters. This forecast is based largely on rather limited experience and is admittedly not much better than a guess. The summation of all these changes for a given spot gave the pressure change at sea level which upon addition to the present pressure resulted in the prognostic pressure. This procedure was applied to the radiosonde stations, and the resulting pressures were used to draw a prognostic chart.

As an example the weight chart for the level from 10,000 feet to 20,000 feet on September 20, 1944, 0400Z is reproduced in Figure 1. Figure 2 shows the sea-level map for the same time. Figure 3 represents the prognostic sea-level pressure chart for September 20, 1944, 1600Z, obtained from the four weight charts by the advection method. Figure 4 shows the actual pressure distribution on September 20, 1944, 1830Z. The maps have only been reproduced south of 50–55° N latitude because the upper-air data farther north are too scanty to permit a reliable forecast.

At the start of the forecasting period (Fig. 2), a high is situated over the southwestern part of the United States; another one is found along the NE coast of the continent with its center over the Atlantic. These highs are separated by a weak trough. The circulation over the northwestern part of the continent is dominated by a low centered over northern Manitoba and Saskatchewan. According to the prognostic chart (Fig. 3), the high in the southwestern United States should move about 400 miles to ESE without changing its intensity appreciably. Actually the high moved about 200 miles in an almost easterly direction and, while the central pressure did not increase appreciably, the 1017-mb isobar spread considerably. The forecast position of the weak trough did not agree well with the actual position and the low which was forecast to occur as the northeastern continuation of the trough is not quite deep enough and too far to the east on the prognostic chart. The position of the high over the western North Atlantic cannot be determined accurately from the map for September 20, 1944, 1830Z (Fig. 4) because of the absence of ships' observations but the forecasted

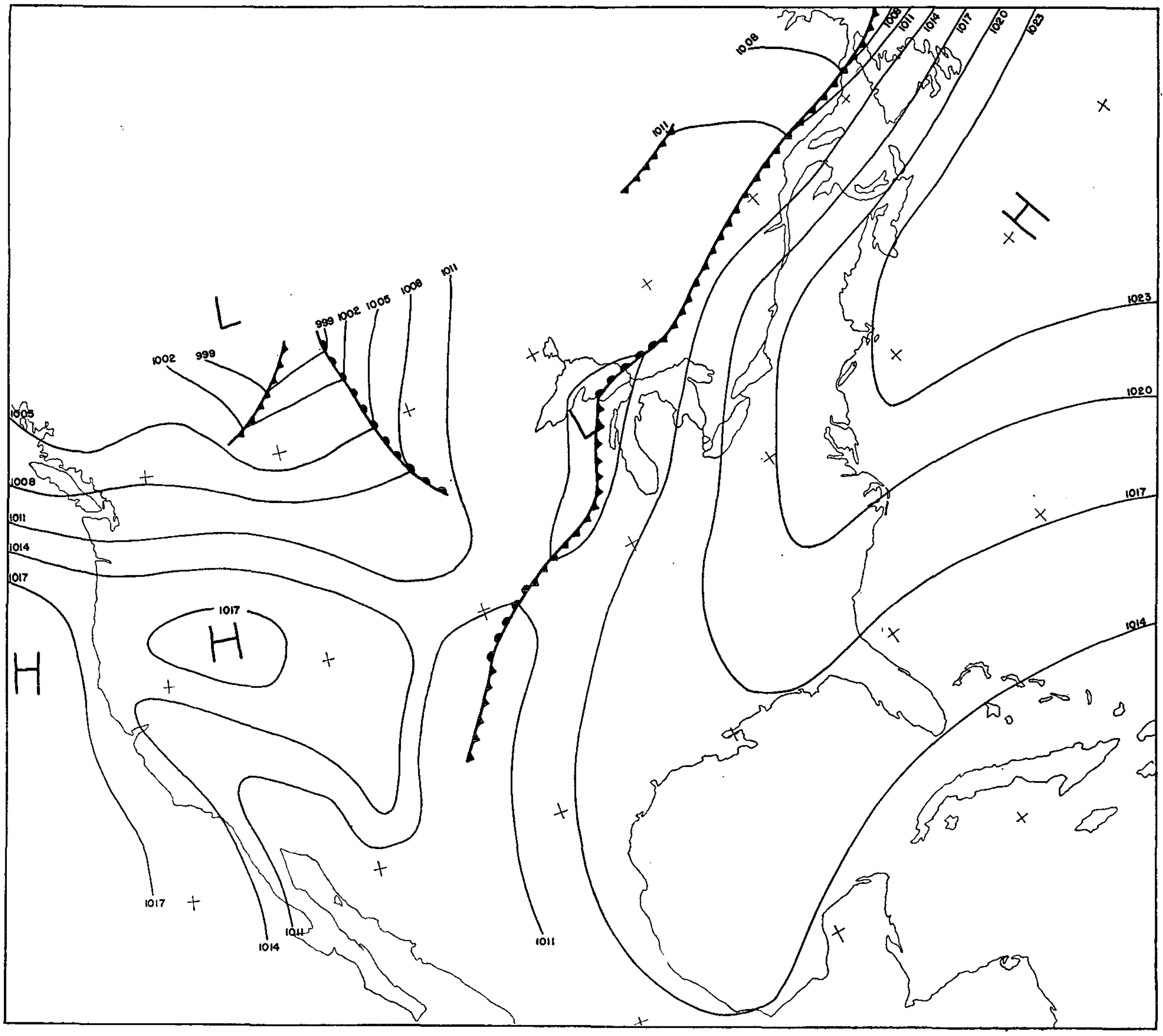

FIG. 2. Weather map for sea level. September 20, 1944, 0630Z.

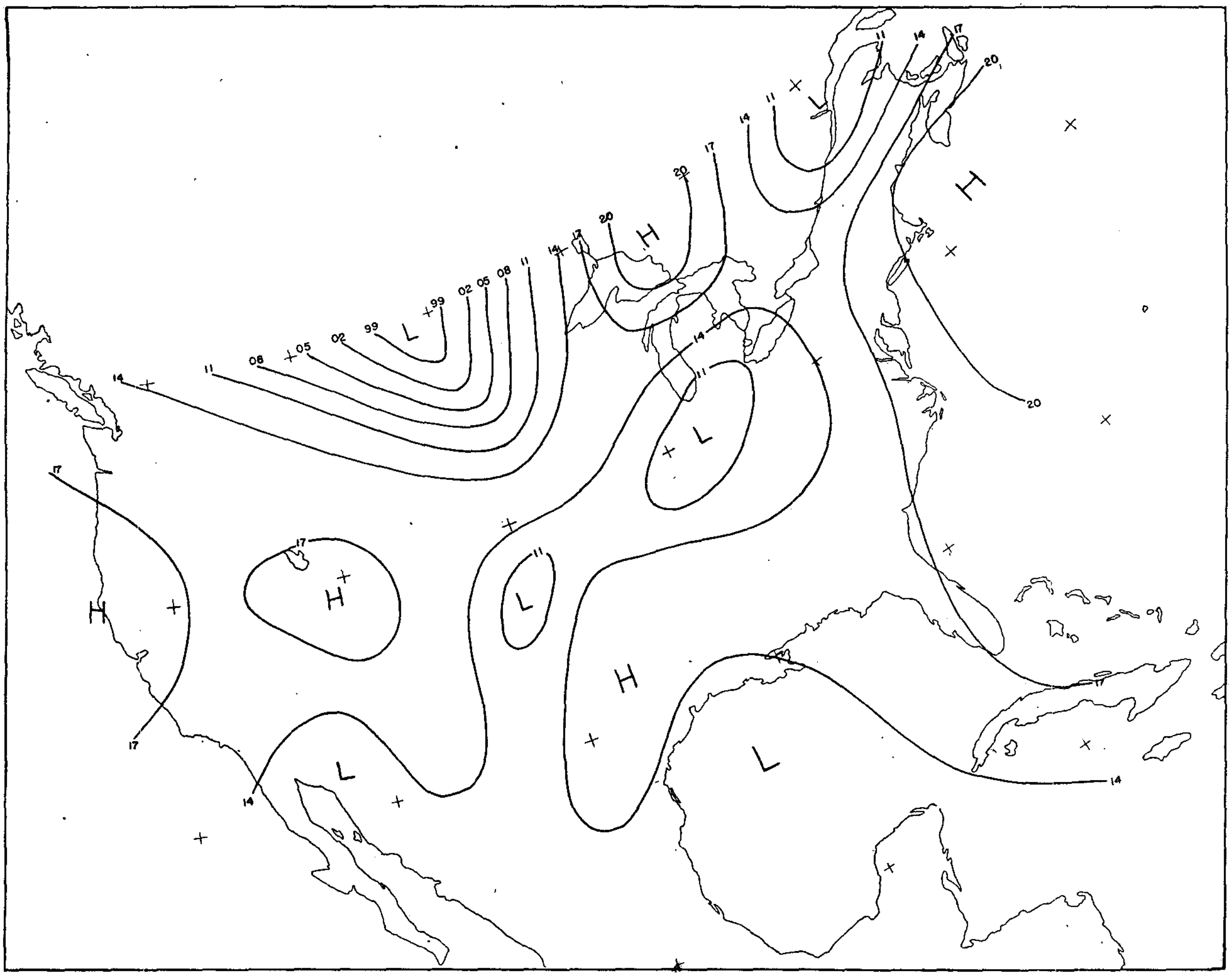

FIG. 3. Prognostic sea-level pressure chart. September 20, 1944, 1600Z.

pressures along the Atlantic coast agree fairly well with the observed pressures. This motion of the low over the Canadian prairie provinces is quite well reproduced by the prognostic chart (Fig. 3) but, while the forecast called for a strengthening of the pressure gradient, the low actually became weaker and the gradient less steep. The prognostic chart (Fig. 3) called for the formation of a high over Lake Superior extending toward James Bay, a development which was not shown by the actual map (Fig. 4). However, in this last case it must be pointed out that the failure of the advection method may be due to the inadequacy of the network of radiosonde stations in the northern part of the continent, which makes the construction of weight lines and isobars rather subjective.

On the whole, the example presented here is one of the more successful prognostic charts plotted by means of the advection method.

Such prognostic charts were drawn for about three weeks during August and September, 1944, and discussed at the regular daily map discussions. It was found that the prognostic charts constructed in this manner were certainly not superior to the prognostic charts produced by a skilled forecaster drawing on his experience.

In order to have a more objective measure of the usefulness of the advection method for the preparation of prognostic pressure charts than can be obtained from a simple comparison of the prognostic and the actual map, it is desirable to have a numerical quantity expressing the degree of similarity between the two maps. As such a quantity Braun and Douglis (2) have chosen the mean of the absolute values of the deviations of the forecast from the actual pressures, taken for a sufficiently large number of stations. However, this quantity would be smaller the smaller the variation of the pressure over the map, so that two different cases could not be compared directly. This difficulty can be overcome by dividing the mean absolute value of the deviations by the mean absolute change over the forecast period, a quantity which is called the error ratio by Braun and Douglis. However, even the error ratio does not appear to be a very suitable quantity for comparison. For instance, if the forecast were everywhere too high by the same amount the relative error as well as the mean absolute error might be quite large, even though the pressure pattern and the pressure gradient are forecast perfectly. On the other hand, both quantities might be rather small, but the pressure pattern might still be forecast rather poorly, for instance if large changes are forecast where only small changes or none occur and vice versa.

As another test of the accuracy of the forecasts, Braun and Douglis compared the signs of the forecast changes with those of the observed changes. But here again apparently good results might be indicated by high percentages of agreement while in reality the prognostic pressure pattern may diverge widely from the actual one.

Because of the absence of a satisfactory objective method of comparing prognostic and actual charts, correlation coefficients were computed between the actual and forecast pressure changes. Correlation coefficients between pressure changes rather than between the pressures themselves were computed because it was found that for the selected forecast interval high correlations, from .80 to .90, were obtained even by correlating the pressures at the beginning with those at the end of the forecast interval. Hence a high correlation between the forecast and the actual pressure would imply that the advection method gives results which are as good as the assumption that the pressure does not change at all.

All the correlation coefficients are given in Table 1. The first part of this table shows the correlation between the forecast changes of the weights of the different layers and of the sea-level pressure and the changes which actually occurred. The correlation coefficients are only between .41 and .48—too small to be of significant forecast value. The highest correlation was obtained for the forecasts of the weight of the layer between 10 and 13 km, the lowest for the layer

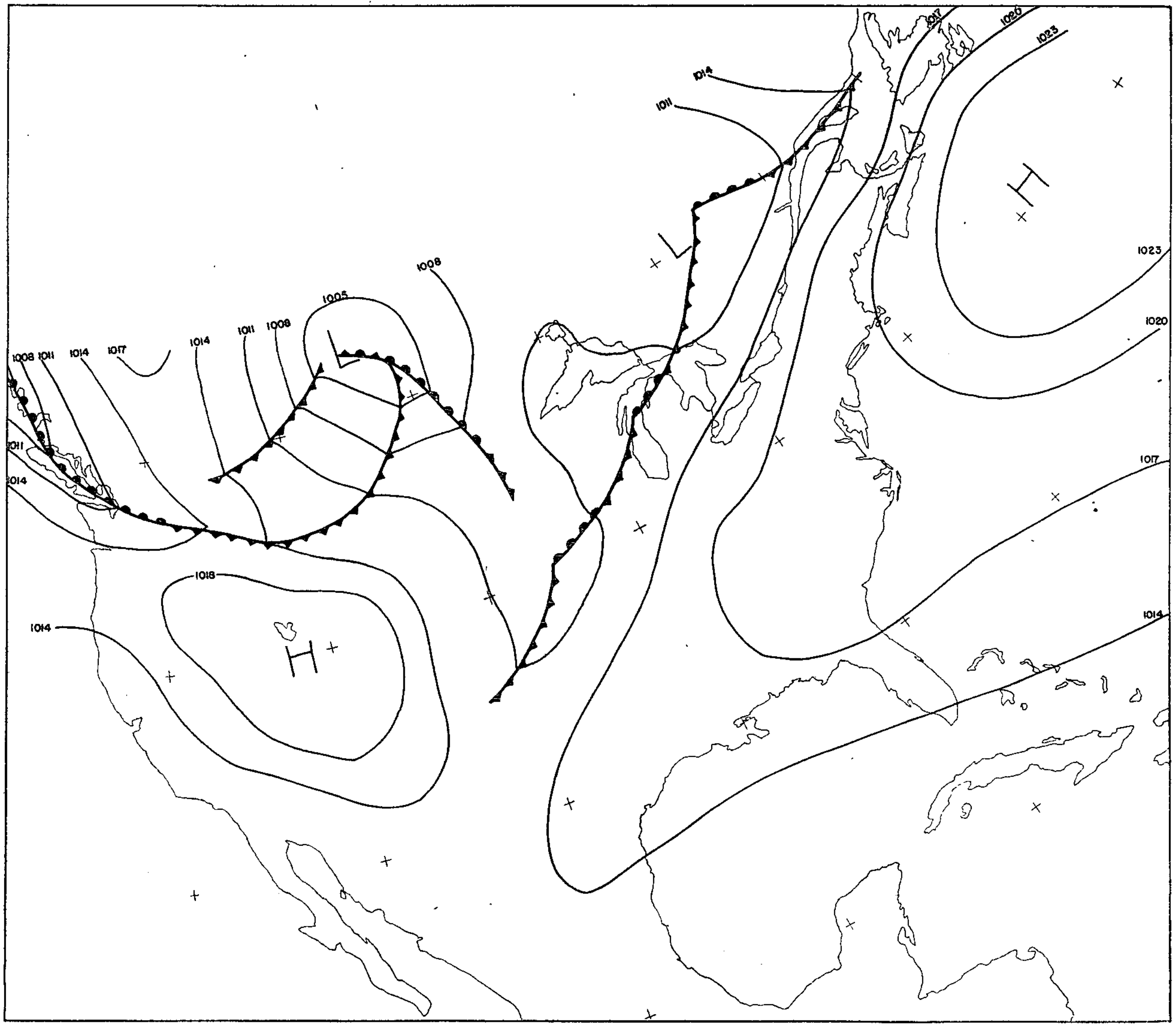

FIG. 4. Weather map for sea level. September 20, 1944, 1830Z.

TABLE 1

Statistical Evaluation of Studies in Advection
$n$ = number of cases

| | Isobars as trajectories—12 hours Sept. 18–22, 1944 | | | Standard trajectory method—12 hours Sept. 18–22, 1944 | | | Rossby trajectory method—24 hours | | |
|---|---|---|---|---|---|---|---|---|---|
| Layers and levels for which correlations of pressure changes are computed | $n$ | Correl. Coeff. | Standard Error | $n$ | Correl. Coeff. | Standard Error | $n$ | Correl. Coeff. | Standard Error |
| *A*. Layer: Sea level to 13 km. | | | | | | | 79 | +.34 | ±.10 |
| *B*. (*A*) above + observed 13-km changes | 136 | +.45 | ±.06 | 100 | +.38 | ±.09 | 79 | +.40 | ±.10 |
| *C*. Layer: 10,000 ft to 13 km | | | | | | | 78 | +.50 | ±.09 |
| *D*. (*C*) above + observed 13-km changes | | | | | | | 78 | +.61 | ±.07 |
| *E*. Layer: Sea level to 10,000 ft. | 116 | +.41 | ±.08 | 100 | +.62 | ±.06 | 78 | +.54 | ±.08 |
| F. Layer: 10,000 ft to 20,000 ft | 130 | +.43 | ±.07 | 100 | +.45 | ±.08 | 80 | +.64 | ±.07 |
| *G*. Layer: 20,000 ft. to 10 km. | 120 | +.43 | ±.07 | 100 | +.34 | ±.09 | 78 | +.64 | ±.07 |
| *H*. Layer: 10 km to 13 km. | 110 | +.48 | ±.07 | 100 | +.25 | ±.10 | 73 | +.34 | ±.10 |

between sea level and 10,000 feet, but the difference can hardly be considered significant in view of the magnitude of the standard errors of the correlation coefficients. The correlation between the forecast and the observed changes of the sea-level pressure was .45 (line B). In considering this value it should be taken into account that here the actual pressure changes at 13 km rather than forecast figures have been used so that this correlation coefficient presupposes perfect pressure forecasts at 13 km, a highly unlikely accomplishment. Assuming the existence of a linear regression equation between the actual and the forecast pressure change, the standard error of estimate of the forecast pressure was found to be 3.7 mb. This value does not compare favorably with the standard error which a reasonably skilled forecaster could attain.

An attempt was made to estimate the percentage frequency of different causes for failures of the advection method. These frequencies were obtained by judging in every case which of the following causes contributed mainly to the difference between forecast and actual weight change:

*A*. Speed of isopleths slower than speed of geostrophic wind.
*B*. Speed of isopleths faster than speed of geostrophic wind.
*C*. Lack of data (resulting in uncertainty about pattern).
*D*. Change in pressure pattern in 12 hours.
*E*. Slight movement or none.
*F*. Calculation of advective change unsatisfactory.
*G*. Reason not apparent at the present time.
*H*. Good forecast.

The percentages for the different causes are shown in Table 2. It is hardly necessary to state that they are rather subjective since the forecaster cannot be certain about the actual cause of the failure of the forecast. *G* comprises the cases where the forecaster felt definitely that other factors besides advection were active, although this may also be true in other cases even though it is not quite so obvious. In the case *H*, the forecast was considered successful by the forecaster.

### (b) *Advective motion determined by successive approximation to the trajectory.*

The assumption that the air motion follows the isobars as given at the beginning of the forecasting period is doubtless incorrect. As shown in Table 2, in a number of instances the failure of the advection method to give satisfactory results was directly attributed to this cause by the forecaster. Even if the wind always follows the isobars closely, the path of the air during the next 12 hours cannot be given by the isobars at the beginning of the period since the pressure field itself is changing. Thus, even if horizontal advection alone were determining the pressure changes, a method of advection along the isobars at the beginning of the forecast period could not give perfect results. Better agreement between prognostic and actual pressure fields could be expected if the variation of the air trajectories due to the variation in the pressure field were taken into account. This was done next in the manner outlined by Petterssen (3).

In applying Petterssen's method, it is necessary to make assumptions about the future positions of the pressure systems. Instead of forecasting a future position of the pressure systems, the trajectories have been determined from the actual positions of the pressure centers at the beginning and at the end of the forecast

TABLE 2

Sources of Error in Forecasting by the Advection Method

| Cause | 0–10,000 ft | 10,000 ft–20,000 ft | 20,000 ft–10 km | 10–13 km |
|---|---|---|---|---|
| *A* | 18% | 3% | 4% | 2% |
| *B* | 8 | 2 | 4 | 3 |
| *C* | 17 | 8 | 18 | 18 |
| *D* | 5 | 10 | 4 | 19 |
| *E* | 3 | 0 | 0 | 2 |
| *F* | 7 | 1 | 2 | 5 |
| *G* | 29 | 44 | 43 | 32 |
| *H* | 13 | 32 | 25 | 19 |

period in order to avoid any possibility of errors which are not directly due to the assumptions of the advection method. Furthermore, since the pressure at the top level, 13 km, cannot be forecast by the advection method, an error may be introduced in the prognostic pressures for which the advection method is not directly responsible. Hence, the actual 13-km pressure rather than a prognosticated 13-km pressure has been added to the forecast weight of the layer from sea level to 13 km. These two procedures require a knowledge of the position of the pressure systems and of the 13-km pressures at the end of the forecasting period. Therefore they cannot be used in actual forecasting and the results of the present check must be expected to be more favorable than they would be under actual working conditions.

The results are statistically appraised in the second part of Table 1 under the heading "standard trajectory method." Only the correlation for the layer between sea level and 10,000 ft is now appreciably larger than before. On the other hand, the correlation between actual and prognostic sea-level pressure is even smaller than before although the difference is hardly significant. The result of this comparison can be summarized by saying that this method does not yield any better results than the other method of advection. This procedure is a rigorous test of the applicability of the advection method inasmuch as the changes in flow pattern and the pressure changes at the top level were considered as known.

### (c) *Advective motion determined by Rossby's trajectory method.*

A third method of determining the horizontal flow which determines advection is found in Rossby's procedure (4) of constructing trajectories under the assumption that the vorticity of individual air particles is conserved. It is not the purpose of this paper to evaluate this method. The reason for applying it here is merely to include every procedure which might give a reasonable basis for the application of the advection method, and thus to make sure that the failure of the advection method to give better results is not caused by the use of an incorrect method of advection.

As before, maps of the pressure at sea level, 10,000 feet, 20,000 feet, 10,000 meters and 13,000 meters were chosen because these charts were constructed in connection with the daily forecasting routine. Graphical subtraction (1) of the appropriate pressure charts provided weight charts for the same layers as mentioned above, viz.

Sea level to 10,000 feet,
10,000 feet to 20,000 feet,
20,000 feet to 10,000 meters,
10,000 meters to 13,000 meters.

Graphical addition of the pressures at the top and bottom of each layer and division by two provide a mean isobar and flow pattern for the layer. The appearance of these charts is similar to the sample shown in Figure 1. From the pressure patterns the geostrophic winds were determined. The latter were regarded as the current velocities for the layers.

In the application of the Rossby trajectory method the drawing of trajectories is greatly facilitated if only certain points in the flow patterns are selected, viz.

i) Inflection points,
ii) Points of maximum curvature where the flow is from the west.

For the purpose of this part of the investigation the assumption was made that an atmospheric column between two levels moves in its layer along a path determined by the trajectory of the current in the mean flow pattern of the layer. Since the period of this motion can be determined by Rossby's method, the 24-, 48-, and 72-hour displacements of this column along its trajectory could be forecast. When a number of air columns have been treated in this manner, an area could be selected for which a prognostic chart could be drawn showing the forecast positions of the columns. Since a weight for each column was determined, the prognostic chart is actually a prognostic weight chart. When all the prognostic weight charts are added, a sea-level prognostic chart is obtained.

As in the previous section, it was assumed that a perfect forecast of the pressure at 13,000 meters could be made; and therefore, the actual pressure at 13,000 meters was simply added to the sum of the weights, a procedure which should be kept in mind when judging the merits of the advection method.

Because of the nature of the Rossby trajectory method it is impossible to secure a uniform network of points for the prognostic weight charts. The points at which the weights of different layers are determined are not in the same vertical. Hence the prognostic pressure charts are best prepared by graphical addition of the different weight charts. Furthermore, it is difficult to obtain a large enough number of starting points that satisfy the limitations set up by the assumptions, so that the distribution of the final points on the prognostic chart is as a rule rather uneven. Moreover, in many cases no values of the weights of the layers are available in the regions from which the air is coming. For example, no data could be obtained for the portion of the Pacific bordering upon the west coast of North America. The result is a restriction in the area in which verification may be made.

The series of charts selected for this part of the investigation was that of September 1–5, 1944, 0400Z. This set had an adequate network of points at the required levels so that verification charts could be

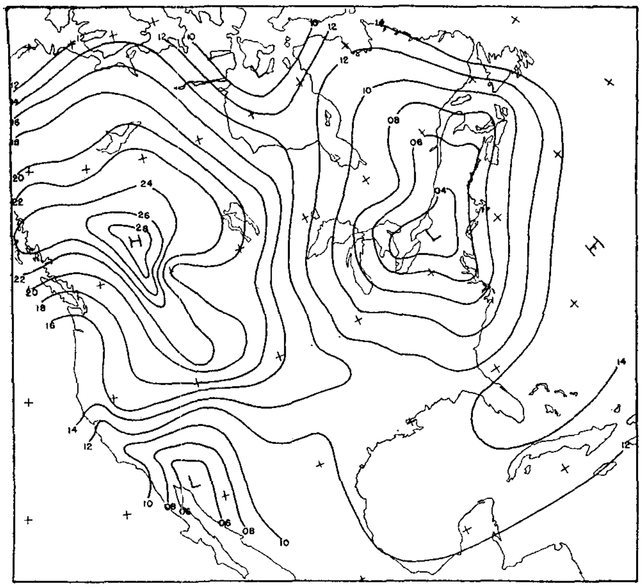

FIG. 5. Sea-level pressure chart. September 5, 1944, 0400Z.

constructed. The forecast interval was always 24 hours. Since the sea-level charts were based on the 0630Z observations while the upper-air data were obtained at 0400Z, the three-hour pressure tendency was applied as a correction to the sea-level charts.

The prognostic charts fall into two categories, weight charts for layers and constant-level pressure charts. An example of sea-level prognostic pressure charts is presented in Figure 6. Figure 5 shows the actual pressure distribution at this time. The comparison between these two charts is summarized in Table 3.

The prognosticated intensities of the systems found in Table 3 are either too low or too high and the displacement is too far eastward. In addition, the gradient of pressure is much greater on the prognostic chart than on the observed chart. A system which contributes to the intensity of the gradient on the prognostic chart is the high over the Atlantic at 40° N and 66° W. No evidence for this high can be found on the actual sea-level pressure chart because reports are lacking in that immediate area.

TABLE 3

Comparison between Observed and Forecast Sea-Level Pressure Chart
September 5, 1944, 0400Z

| Type of System | Observed Position | Forecast Position | Observed Intensity (mb) | Forecast Intensity (mb) |
|---|---|---|---|---|
| Low | New York State and Lake Ontario | Ottawa and Montreal | 1004 | 994 |
| Trough | Atlantic Coast of U.S. from Harrisburg, Pa. and southward | Atlantic Coast of U.S. from Binghampton, N. Y. southward | 1004–1014 | 994–1010 |
| Trough | St. Lawrence Valley | St. Lawrence Valley | 1004–1014 | 994–996 |
| Wedge | Kansas | High center over Milwaukee and wedge over Tennessee | 1014 | 1012–1022 |

In examining all the prognostic charts it was observed that the isobars form very definite patterns with extremely steep gradients. The magnitude of the pressure as forecast differs widely from the magnitude as observed. The difference in the magnitude of the actual and forecast pressures is more noticeable for the sea-level prognostic charts than for the 10,000-ft charts. This may be explained in part by the fact that the layer from sea level to 10,000 ft is fictitious over the portion of the continent where elevations of the surface run to great altitudes—especially over the Cordilleras. Yet this layer is displaced along the trajectory to form a prognostic weight chart which is added to the other weight charts and the 13-km observed pressure chart in order to produce the sea-level prognostic pressure map.

As brought out by the maps the geographical location of the pressure systems is not forecast satisfactorily. While the general pressure patterns have often some similarity, the errors of several hundred miles in the displacement restrict still further the forecasting value of the method. In computing the trajectory, if the speed of the current were determined by some fraction (80 to 90%) of the value of the geostrophic wind, it might be possible to secure better qualitative and quantitative results. However, it is very doubtful that a uniform reduction of the speed would lead to an over-all improvement of the results.

A further study of the results was undertaken by statistical methods, correlating forecast and observed

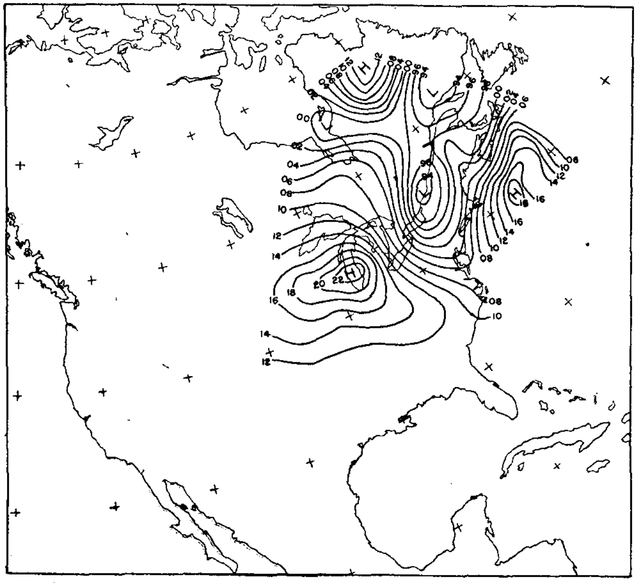

FIG. 6. Prognostic sea-level pressure chart. September 5, 1944, 0400Z.

weight and pressure changes. Because of the difficulty in finding a sufficient number of well distributed points when using Rossby's trajectory method, the correlations for each map between the prognostic and the actual values were based on only 20 points. Since there were four verification periods (September 2, 3, 4, and 5, 1944, 0400Z) there was a maximum of 80 cases for the computation of each correlation coefficient. The correlation coefficients are shown in Table 1. The Rossby trajectory method shows the lowest correlations for sea-level pressure (*B*), for the layer from sea level to 13 km (*A*), and for the layer from 10 to 12 km (*H*). The sea-level pressure forecasts are somewhat better than those of the weight of the air column from sea level to 13 km because in the former case the *actual* 13-km pressure has been added to the prognosticated weight of the air column from sea level to 13 km. The highest correlations were obtained for the weights of the layer between 10,000 ft and 20,000 ft (*F*) and the layer between 20,000 ft and 10 km (*G*). As in the case of the sea-level pressure, it will be noted that the forecasts of the 10,000-ft pressure are better than those of the weight of the air column between 10,000 ft and 13 km since the actual 13-km pressure has been added to these figures.

In comparing the correlation coefficients for the forecasts obtained by means of the Rossby trajectory method with those representing the results of the other two methods, it will be seen that in some cases the differences are quite substantial and larger than the limits set by the probable errors. A direct comparison is not possible since in the investigation on the basis of Rossby's trajectory method different material and a different forecasting interval were used. However, as far as the basic problem is concerned, namely that of constructing prognostic pressure charts, all three methods show correlation coefficients of about the same magnitude. There are no correlation coefficients in Table 1 large enough to make it appear that the application of the advection method in any of the forms tried would yield satisfactory prognostic charts.

**4. Conclusions.** From the foregoing discussion it follows that the advection method in any of the investigated forms does not yield results which recommend its application as a forecasting tool, at least by itself. To some extent its short-coming may be due to the fact that advection in each layer was based on the flow pattern at a fixed level in this layer. In general, the flow pattern changes somewhat through each layer, a fact which must of course give rise to errors. But in view of the slight variation of the flow patterns with elevation, particularly above 10,000 ft, it appears unlikely that appreciably better results would be obtained if the change of the flow pattern with the altitude were taken into account.

Some of the errors which arose in the study of the advection method at M.I.T. could have been avoided if prognosticated changes in obvious disagreement with all synoptic experience had been disregarded. If the advection method were to be used in practice such critical judgment by the forecaster should doubtless be employed. However, in doing so one of the main advantages of the advection method would be lost, namely, its objectivity; the forecaster, as heretofore, would to a large extent have to rely on his experience and on his judgment. It is not implied that experience and judgment can be eliminated from weather forecasting at the present time so that forecasting technique would become as completely mechanical as the computation of a nautical almanac. But in view of the fact that the physical basis of the advection method considers only advection and ignores other factors such as divergence and vertical motions, it appears desirable to bring a subjective element into the method only after inclusion of these other factors. If successful forecasts of the future position of the weight lines and the isobars at a top level could be made, the consideration of these other factors would be unnecessary, because in that case all the other influences would be taken into account automatically. As the present investigation has shown, this is impossible. The main reason is that the changes in weight are not due to advection in horizontal direction only, as implied by the advection method, but also due to divergence, vertical motions, and other, probably minor, causes. It would be wrong to discard advection as one of the factors determining atmospheric developments. But, since there is not just one predominant cause determining these developments, it is necessary to evaluate and combine all other important causes in order to arrive at a promising rational forecasting procedure.

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