REPORT OF AN EXPERIMENT IN FORECASTING OF CYCLONE DEVELOPMENT

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ABSTRACT

An experiment, aimed at forecasting the formation and intensification of extra-tropical cyclones, was conducted from 4 January 1954 to 20 March 1954. The working hypothesis to be tested was formulated as follows: *cyclonic development at sea level occurs when and where an area of positive vorticity advection in the upper troposphere becomes super-imposed upon a frontal zone at sea level.* The experiment, which was conducted in connection with the routine operation of the U. S. Weather Bureau's District Forecast Center in Chicago, resulted in 97 verifiable forecasts. The verification indicated that the working hypothesis is useful.

1. The experiment

The working hypothesis.—The theory of the processes resulting in development in the pressure field at sea level (*e.g.*, cyclogenesis, intensification, *etc.*) has been considered in an article which appears elsewhere in this issue of the JOURNAL (Petterssen, 1955). There it is shown that cyclogenesis at sea level results from an unbalance, below the level of non-divergence, between the vorticity advection and the Laplacian of certain thermal characteristics of which the temperature advection appears to be the predominant one. While the application of this and related theories to forecasting form the subject of an as yet uncompleted, detailed investigation of a few major storms, it was considered useful to arrange for a crude experiment in which the bare essentials of the theory could be tested in connection with routine forecasting.

To reduce the theoretical considerations to skeleton essentials, it is, of course, necessary to relinquish the demand for numerical accuracy, and to search for easily recognizable indicators of events or sequences which precede cyclogenesis. Recognition of such indicators about 24 hr in advance of the onset of the development would seem to be satisfactory for most types of forecasting.

Considering the vorticity of the motion, and restricting our discussion to cyclonic development of appreciable intensity, we note that development of vorticity at the 1000-mb level must result from isobaric convergence (negative divergence) at that level. Values of about 10^{-5} to 3×10^{-5} sec^{-1} have been found to be typical of cases with appreciable development.

Next, it is useful to recall that the mean divergence of an air column, extending from sea level to the top of the atmosphere, must be vanishingly small; from this it follows that the divergence must change its sign *at least once* with elevation (see fig. 1).

In the search for indications of appreciable amounts of divergence, it is natural to turn to the upper troposphere, where the vorticity systems are well-developed and the individual vorticity changes are rapid. For example, vorticity maxima in the range

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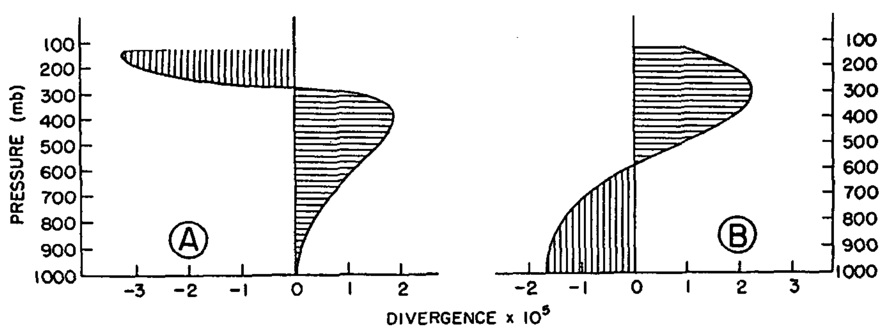

FIG. 1. Schematic distribution of divergence. A: case of non-development; B: case of development.

from 2×10^{-4} to 5×10^{-4} sec^{-1} are regularly found on the trough lines at, and to the left of, the jet stream in the upper troposphere (*e.g.*, at the 300-mb level). In these regions, the air streams through the trough and the attendant vorticity maximum with great speed. If Q is the absolute vorticity and D the divergence, we have

$$dQ/dt = \partial Q/\partial t + V\cdot\nabla Q = -DQ. \quad (1)$$

Since the air streams through the vorticity pattern at great speed, there must be large amounts of divergence in advance of the upper troughs and similar amounts of convergence in their rears. Again, since the air moves much faster than the vorticity system, it follows that the individual change in the vorticity (*i.e.*, dQ/dt) is overwhelmingly determined by the vorticity advection.

For brevity, we represent the vorticity advection at 300 mb by

$$A = -V\cdot\nabla Q. \quad (2)$$

The vorticity advection is then positive in advance of a trough and negative in its rear. Now, relinquishing the demand for numerical accuracy, we have

$$A/Q \approx \text{indicator of } D \text{ (at the 300 mb level)}. \quad (3)$$

Usually, this indicator represents an over-estimate of the amount of divergence at the 300-mb level. It should be used only in areas where the air streams through the vorticity pattern with considerable speed; outside such areas, the amounts of divergence are small and of little consequence.

Now, since the mean divergence of the whole column must be negligible against the amounts associated with developments, it follows that regions of large divergence in the upper troposphere (say, 300 mb) must be compensated for *either below or above* this level.

Experience shows that almost all cyclogenesis at sea level occurs in advance of an upper trough (*i.e.*, under an area of divergence and positive vorticity advection in the upper troposphere). Since cyclogenesis at sea level requires convergence of appreciable amounts, we may take diagram B of fig. 1 as representing the conditions typical of cyclogenesis at sea level.

While upper troughs (with divergence in advance of them) are almost always present, cyclogenesis is a relatively rare occurrence, showing that the compensation shown in diagram B does not represent the general state of affairs. In typical cases of non-development at sea level under the forward side of an upper trough, one finds conditions of the type shown in diagram A. The compensation is then established between the upper troposphere and the stratosphere.

It is now apparent that the problem of forecasting the onset of development at sea level may be reduced to that of foreseeing the conditions that will lead to a shift in the compensation, such that a state essentially of the type shown in diagram B becomes established.

The theory concerning the establishment of large amounts of convergence at sea level is discussed in the aforementioned paper. It is shown that the type of compensation depends largely upon the vorticity advection and the configuration of the temperature advection. Here, we shall not pursue the theoretical considerations, but rather follow an empirical course.

Investigation of a large number of cases of cyclogenesis has shown that *the establishment of a region of appreciable low-level convergence results when and where an area of appreciable positive vorticity advection in the middle and upper troposphere becomes superimposed upon a low-level frontal system.* Although theory supports this result, we shall be content to regard it as an empirical finding and promote it to the working hypothesis of the experiment.

If this working hypothesis should prove useful, the problem of forecasting development would be reduced largely to that of forecasting the movement of troughs and wedges at representative levels.

It should be noted that the distributions of divergence shown in fig. 1 are highly idealized. Very often, two levels of non-divergence have been found to exist. In such cases, part of the divergence in the upper troposphere may be compensated for at great heights. Complete compensation between the lower and upper troposphere is rarely attained.

Illustration of the working hypothesis.—The essence of the hypothesis may be illustrated by reference to the conditions that prevailed prior to and during the development of the so-called Thanksgiving Storm of 1952.[2] For the purpose of this article, it suffices to consider the general conditions at the 300- and the 1000-mb levels. These are shown in figs. 2–17.

Broadly, the synoptic situation under review may be divided into four periods, as follows:

1. A period of little change (figs. 2, 3, 10 and 11); the height changes at the 300-mb level indicate an eastward movement of the southern part of the trough, and some increase in the wind across the trough line; the changes at the 1000-mb level are minor;
2. A forward march of the upper trough (figs. 4, 5, 12 and 13); the height changes indicate continued eastward movement of the southern part of the trough and considerable strengthening of the wind across the trough line; although the vorticity advection in advance of the trough line is increasing rapidly, there is no appreciable change at the 1000-mb level (figs. 4 and 5);
3. A period of rapid development (figs. 6, 7, 14 and 15); the frontal wave over northeastern Texas suddenly develops into a storm of major proportions, while the upper trough (with positive vorticity advection and divergence in advance of it) continues to move eastward;
4. A period of decay (figs. 8, 9, 16 and 17); the maximum intensity was reached shortly after the time of fig. 15, whereafter a decay of the circulation set in.

[2] This storm has been investigated in considerable detail by S. Petterssen and Dorothy Bradbury. A detailed report will be published shortly.

Returning now to the 1000-mb charts (figs. 2–9), and noting the rapid increase in the vorticity between 0300 and 1500 GCT 25 November (figs. 5 and 6), we see that evidently large amounts of convergence must have set in during that period. Examination of the intermediate charts indicates that the sudden increase in the convergence set in about 0600 GCT.

In addition to the contours of the 1000-mb surface, figs. 2–9 show isopleths of the vorticity advection at the 300-mb level.

Taking this advection as a measure of amount of divergence at the 300-mb level, we note that the vertical distribution of divergence near the frontal wave prior to 0300 GCT 25 November (fig. 5) must, *essentially*, have been of the type shown in diagram A of fig. 1; after this time, and until about 0300 GCT 26 November (fig. 7), it must have been *essentially* as shown in diagram B.

Examining next the eastward movement of the area of positive vorticity advection (associated with the eastward movement of the upper trough), we see that the sudden onset of the development commenced when the area of vorticity advection became superimposed upon the frontal disturbance.

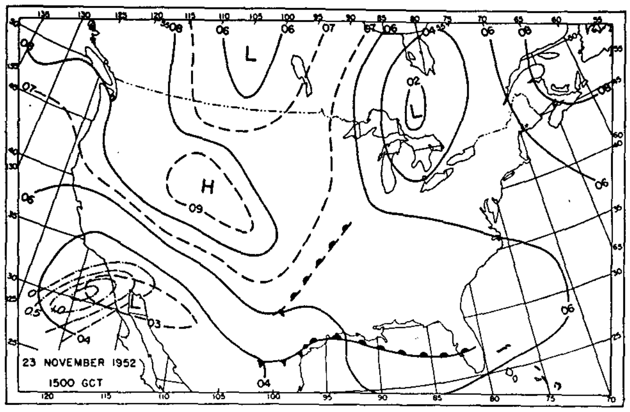

FIG. 2. Contours of 1000-mb surface and fronts, 1500 GCT 23 November 1952. Dash-dot lines indicate vorticity advection at 300-mb level (units: 10^{-8} sec^{-2}).

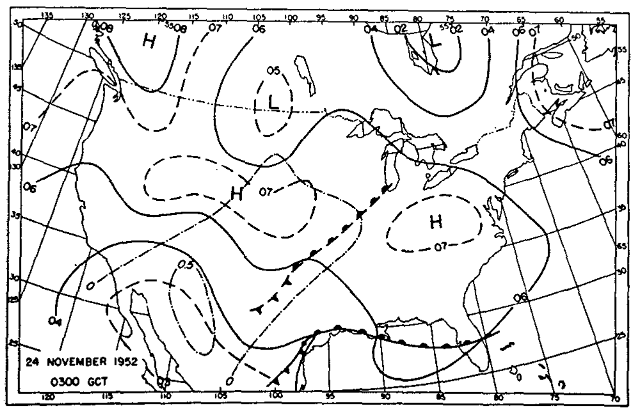

FIG. 3. Same as fig. 2, but for 0300 GCT 24 November 1952.

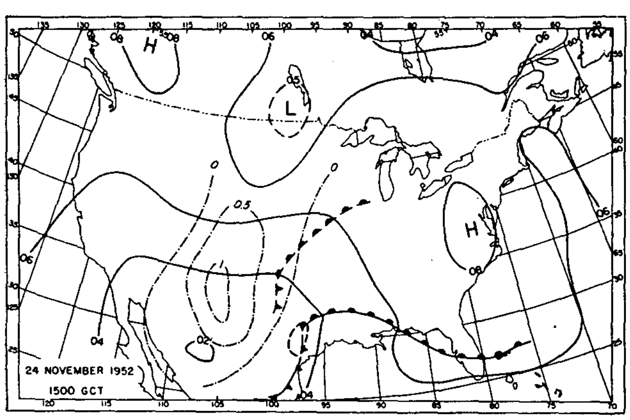

FIG. 4. Same as fig. 2, but for 1500 GCT 24 November 1952.

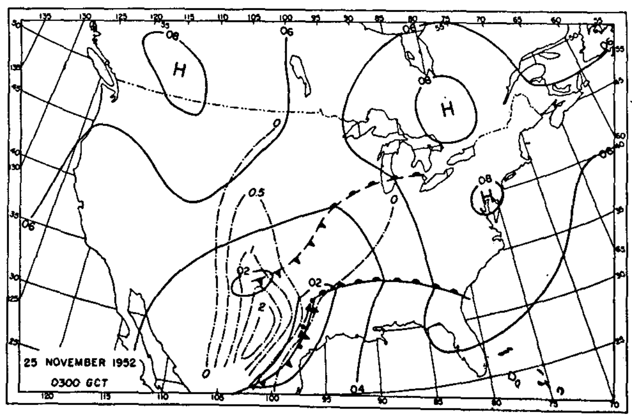

FIG. 5. Same as fig. 2, but for 0300 GCT 25 November 1952.

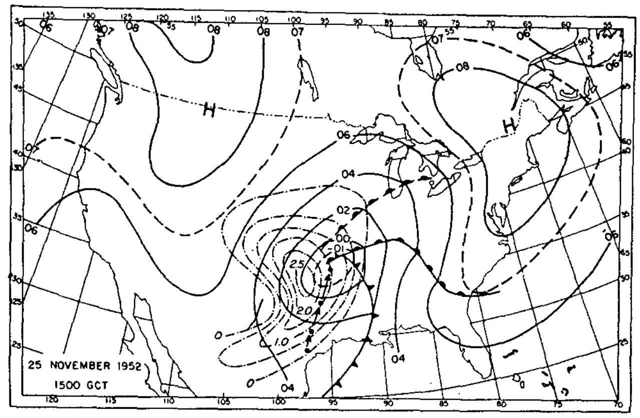

FIG. 6. Same as fig. 2, but for 1500 GCT 25 November 1952.

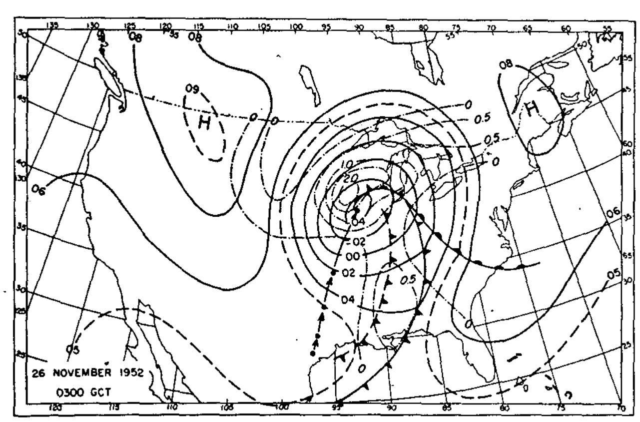

FIG. 7. Same as fig. 2, but for 0300 GCT 26 November 1952.

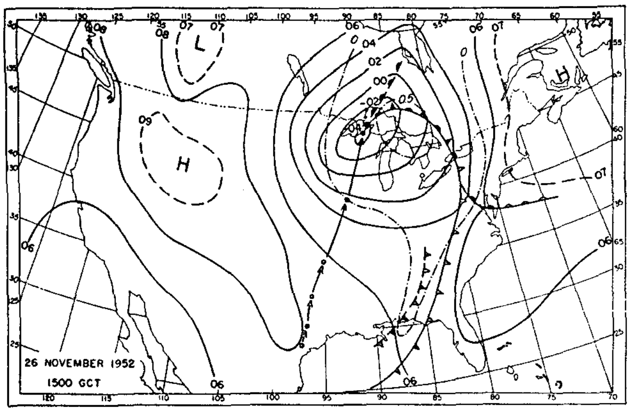

FIG. 8. Same as fig. 2, but for 1500 GCT 26 November 1952.

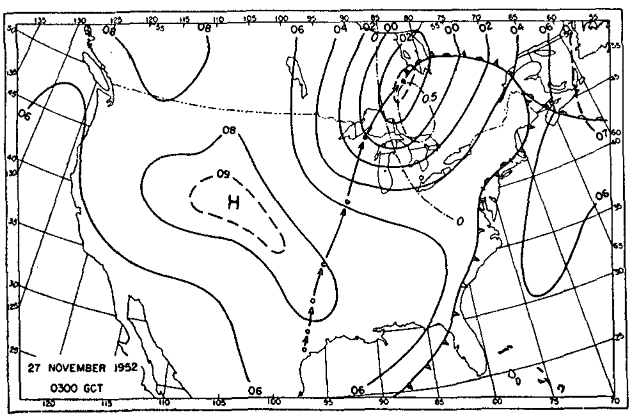

FIG. 9. Same as fig. 2, but for 0300 GCT 27 November 1952.

It will be seen, also, that the decay commenced (fig. 8) when the upper vorticity advection became insignificant.

The vorticity advection.—To evaluate the vorticity advection, it is necessary first to compute the vorticity. In this computation, it suffices to use the geostrophic vorticity,

$$Q=(9.8/fH^2)(Z_1+Z_2+Z_3+Z_4-4Z_0)+f.$$

Here, Z_1, Z_2, *etc.*, are the contour heights at significant points shown in fig. 18, and H is the grid distance.

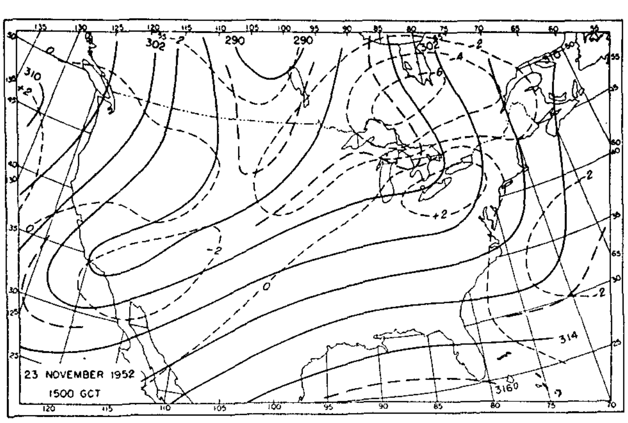

FIG. 10. Contours of 300-mb surface and 12-hr height changes (units: 100 ft), 1500 GCT 23 November 1952.

In the above formula, H and Z are expressed in meters, and the unit of Q is $\sec^{-1}$.

The vorticity thus computed should be plotted on the 300-mb contour chart, and isopleths should be drawn. An example is shown in fig. 19.

If s measures length along the contours, the vorticity advection may be written as $A=-V\,\partial Q/\partial s$, where V is the geostrophic wind. The vorticity advection is then inversely proportional to the size of the quadrilaterals formed by the contours and the vorticity isopleths. Since we are not concerned with numerical computations, it suffices to assess the vorticity

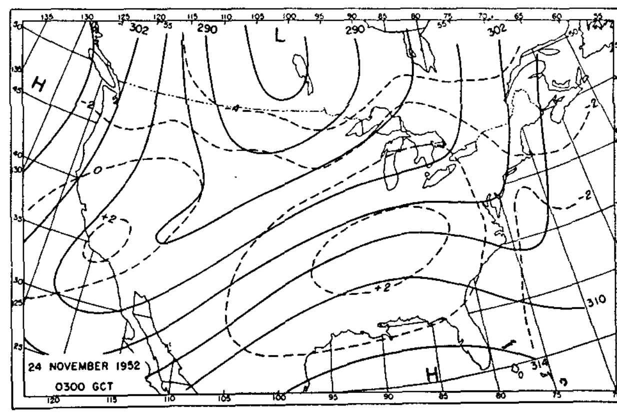

FIG. 11. Same as fig. 10, but for 0300 GCT 24 November 1952

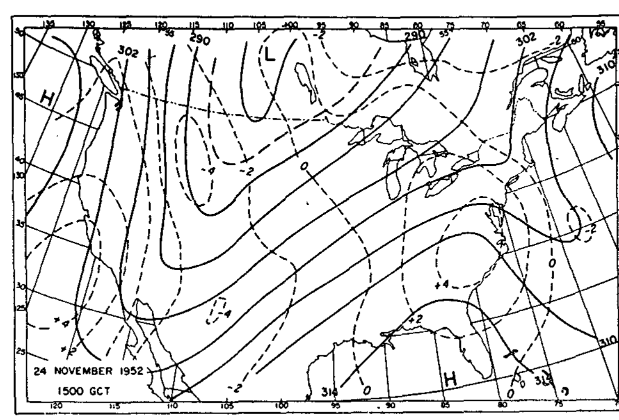

FIG. 12. Same as fig. 10, but for 1500 GCT 24 November 1952.

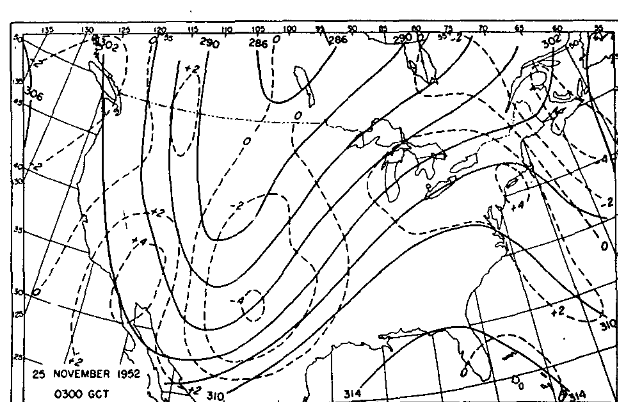

FIG. 13. Same as fig. 10, but for 0300 GCT 25 November 1952.

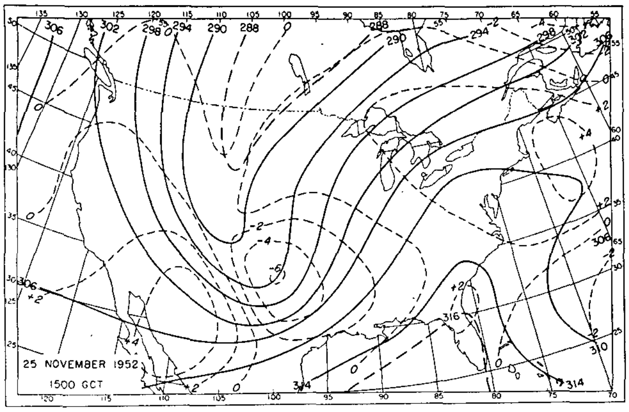

FIG. 14. Same as fig. 10, but for 1500 GCT 25 November 1952.

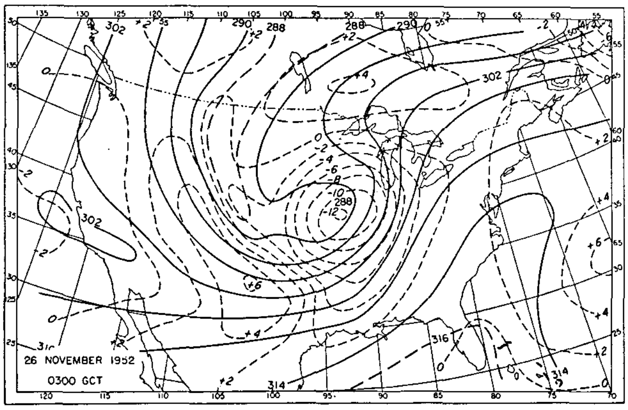

FIG. 15. Same as fig. 10, but for 0300 GCT 26 November 1952.

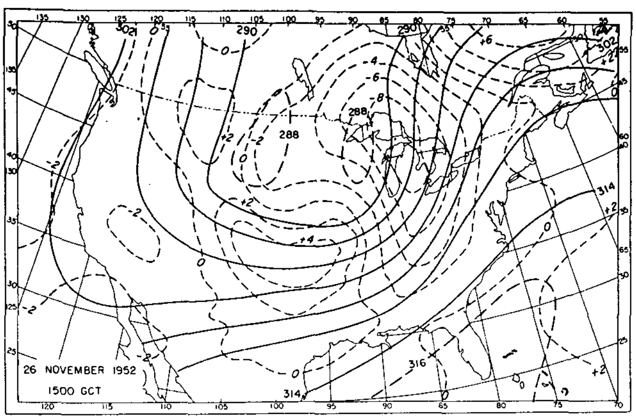

FIG. 16. Same as fig. 10, but for 1500 GCT 26 November 1952.

advection by inspection of the grid formed by the contours and the vorticity isopleths. It should be noted that the advection is positive (negative) where the wind blows from high to low (low to high) values of the vorticity.

It will be seen from fig. 19 that the areas of appreciable vorticity advection are relatively small and separated by large areas of feeble advection. This is a typical feature of the vorticity advection at high levels.

Another expression for the vorticity advection may be derived as follows. The absolute vorticity may be written as

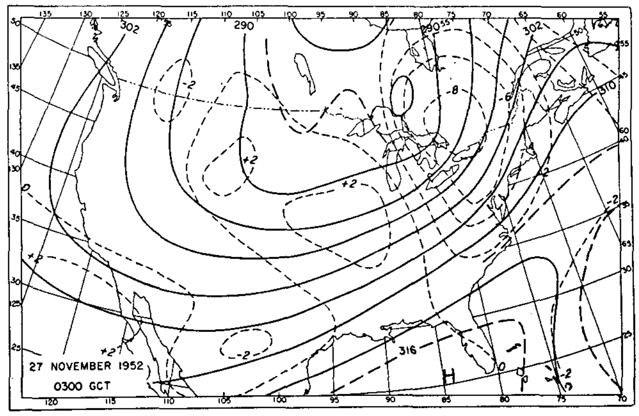

FIG. 17. Same as fig. 10, but for 0300 GCT 27 November 1952.

$$Q = VK_s - S + f,$$

where K_s is the curvature of the streamlines (or contours), S the shear of the wind, and f is the Coriolis parameter. If we choose the x-axis along the contour line, we have

$$V\frac{\partial Q}{\partial x} = V\left(\frac{\partial V}{\partial x}K_s + V\frac{\partial K}{\partial x} - \frac{\partial S}{\partial x} + \frac{\partial f}{\partial x}\right).$$

Observations show that the shear (although often large) normally varies very little along the streamlines, with the result that the term $\partial S/\partial x$ can be omitted. Similarly, the variation of the Coriolis parameter is very much smaller than $\partial Q/\partial x$. These simplifications apply to the areas where $\partial Q/\partial x$ is large, and we are here concerned only with such areas.

Now, with the above choice of x-axis, the term $\partial V/\partial x$ is a measure of the confluence. If K_n is the orthogonal curvature (*i.e.*, the curvature of curves at right angles to the contours), we have $\partial V/\partial x = K_n V$ and $K_s\,\partial V/\partial x = VK_sK_n$. The vorticity advection may now be written as

$$A = -V\frac{\partial Q}{\partial x} = -V^2\left(\frac{\partial K_s}{\partial x} + K_sK_n\right).$$

It should be noted that K_n is positive where the contours converge, and negative where they diverge. On the other hand, $\partial K_s/\partial x$ is negative in advance of the trough, and positive in its rear. It will be seen,

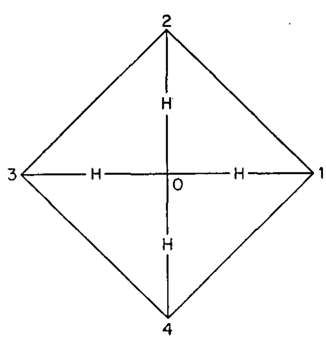

FIG. 18. Grid used for computing vorticity. In the experiment, grid length of 400 km was used.

therefore, that the conditions favorable for large positive vorticity advection are: (a) rapid decrease in curvature of the contours ahead of the trough line, (b) rapidly diverging (fanning) contours ahead of the trough line, and (c) strong winds.

In the case shown in fig. 19, the confluence effect (K_n) is very small, and almost all of the vorticity advection is due to the change in curvature. In the case shown in fig. 6, the orthogonal curvature contributes substantially to the vorticity advection. It should be noted that the vorticity advection is proportional to the square of the wind speed. This emphasizes the importance of the jet stream in creating large amounts of high-level divergence in areas where the configuration of the contours undergoes rapid spatial changes.

The experiment.—It should be emphasized that the experiment was planned to be a crude one. On account of other duties of the members of the research group, it was possible to analyze only one 300-mb chart a day. Sketchy computations of the vorticity were made, and the field was analyzed. The daily map conference of the U. S. Weather Bureau's District Forecast Center in Chicago commenced at 1730 GCT, and the vorticity computation and analysis became available at, or shortly after, that time. By comparison of the vorticity-advection chart (an example is shown in fig. 19) with the sea-level analysis and, assessment of the movement of the upper troughs and wedges, 24-hr forecasts of cyclogenesis and intensification of existing cyclonic systems were produced during the conference, which usually lasted 45 min. The amounts of foreseen developments were indicated in such terms as *strong*, *moderate*, *slight*, *none*, or *negative*. Although no numerical equivalents were assigned to these terms, it was understood that a *strong development* would mean one that resulted in a major storm, that a *moderate development* would be one that resulted in a storm of average intensity, and so on, while *none* would indicate little or no change in intensity.

All forecasts were placed on record. In all, about 150 forecasts were produced. Of these, 97 were found to be verifiable in the sense that the resulting intensity could be evaluated with reasonable confidence.

The forecasts were made by University of Chicago personnel, and the verifications by personnel of the U. S. Weather Bureau.

An example.—To illustrate the application of the working hypothesis, we shall consider briefly the sequence of events that led to the development of a major storm on 12–13 January, 1954.

In figs. 20–23 are shown four stages of the development at sea level, at intervals of 24 hr. In the early hours (GCT) of 10 January, a slight frontal wave formed in the vicinity of the point marked A on fig. 20. January 10th having been a Sunday, no experimental forecast was issued until 1730 GCT 11 January. The synoptic situation at sea level was then as shown in fig. 24. It will be seen that the isallobars do not indicate any deepening at this time.

In fig. 25 are shown three sections of the contours of the 300-mb surface, and the corresponding vorticities. On 9 January, a trough was situated over the western Rockies and Southern California. The vorticity associated with the trough was relatively weak (maximum value about 1.7×10^{-4} sec^{-1}). The trough moved rapidly towards the east, while the sea level frontal system moved slowly towards the southeast. On 10 January (middle section of fig. 25), the current across the trough line and the vorticity have increased. The vorticity advection at this time is, however, slight, as is evidenced by the grid formed by the contours and the vorticity isopleths. The area of positive vorticity advection is now becoming super-imposed upon the sea-level frontal system, and a wave begins to form near A in fig. 20. Some slight

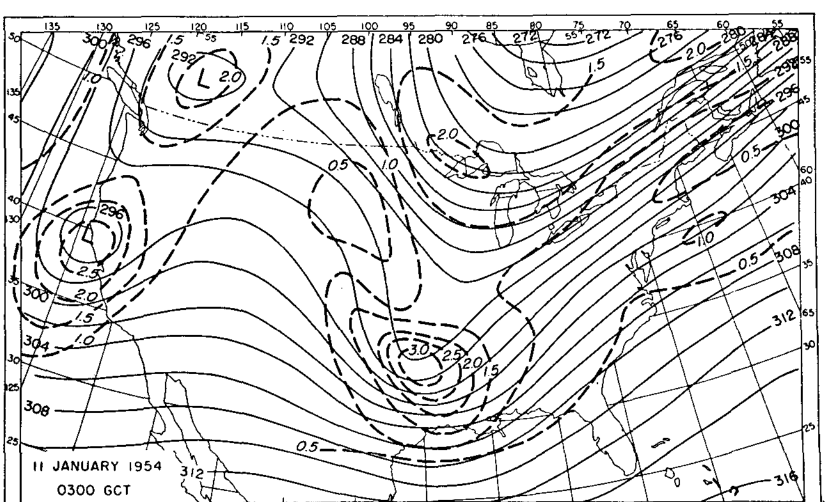

FIG. 19. Contours of 300-mb surface (units: 100 ft) and vorticity at 300-mb level (units: 10^{-4} sec^{-1}), 0300 GCT 11 January 1954.

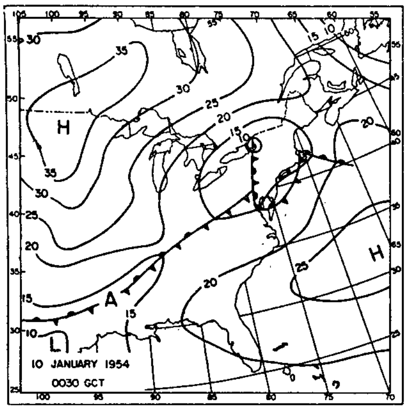

FIG. 20. Sea-level synoptic situation, 0300 GCT 10 January 1954.

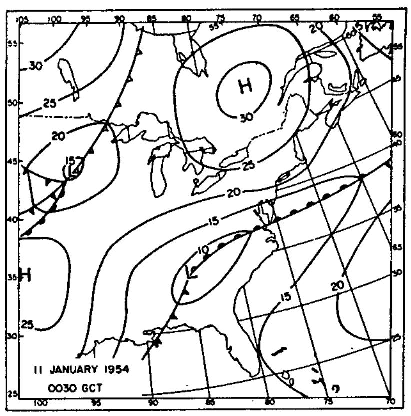

FIG. 21. Same as fig. 20, but for 0300 GCT 11 January 1954.

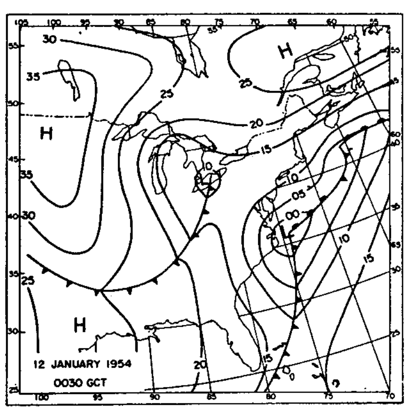

FIG. 22. Same as fig. 20, but for 0300 GCT 12 January 1954.

increase in the circulation results, as is shown by fig. 21.

At 0030 GCT 11 January (right-hand section in fig. 25), the wind across the upper trough has increased appreciably, and so has the vorticity. The complete 300-mb chart for this time is shown in fig. 19.

The movement of the upper trough was obtained by applying the senior author's wave formula (Petterssen, 1952) to the 500-mb chart. Since the speed of troughs and wedges is almost constant above the 600-mb level, the speed thus computed can be taken to apply to the 300-mb level. In addition, the speed was assessed by the aid of past trends, with

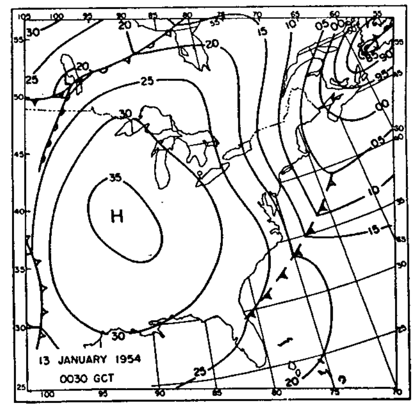

FIG. 23. Same as fig. 20, but for 0300 GCT 13 January 1954.

use of the 12-hr height tendencies. This indicated a further increase of the vorticity advection over the wave disturbance shown in fig. 24. In view of the 9-hr difference between the latest available sea-level chart (fig. 24) and the latest available 300-mb chart

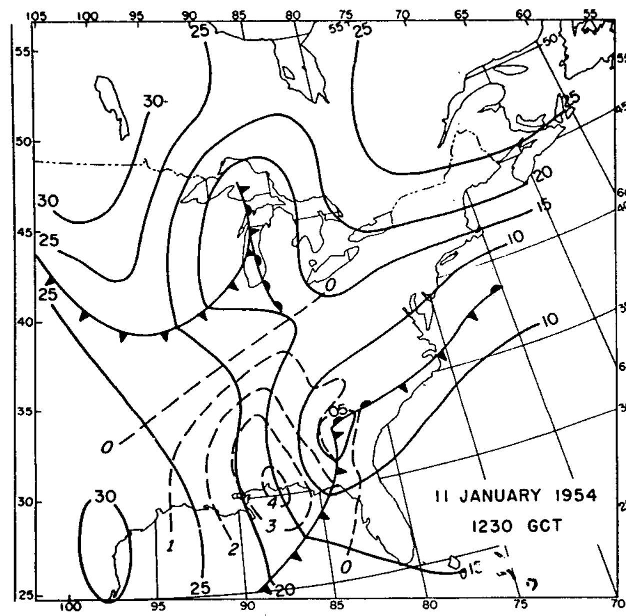

FIG. 24. Latest sea-level chart available at time prognosis was made. Broken lines are isallobars.

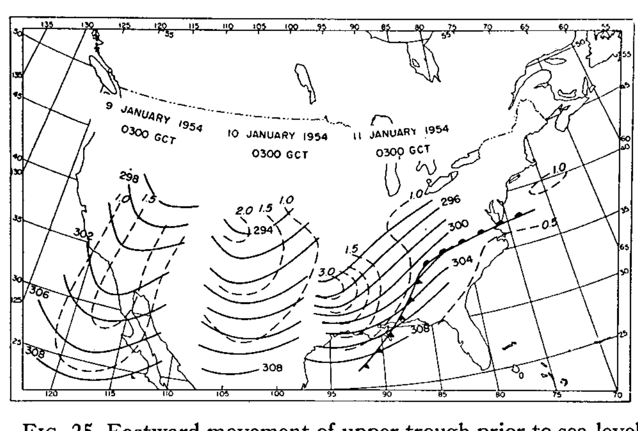

FIG. 25. Eastward movement of upper trough prior to sea-level development. Full lines: contours of 300-mb surface (units: 100 ft); Broken lines: absolute vorticity (units: 10^{-4} sec^{-1}).

(fig. 19), the position of the upper trough was extrapolated forward 9 hr. The following synopses and forecasts were then made:

1. "The 300-mb chart shows a fairly large and intense area of positive vorticity advection, which at 1230 GCT should be centered over the border between Mississippi and Alabama. During the preceding 24 hr, the frontal system has produced nothing but small waves. At 1230 GCT, there is no indication of development (no falling pressure in the vicinity of the wave). However, as the 300-mb trough (the movement of which is assessed to about 12 deg long per day) approaches the frontal system, rapid cyclone development should occur. This development is imminent, and is expected to take place near Cape Hatteras and move northeastward with considerable speed (in view of the strong steering current)."

2. "The low-pressure center near Chicago is not associated with any high-level divergence. Decreasing, rather than increasing, circulation around the center is indicated. This center is likely to be absorbed in the circulation created by the Cape Hatteras development within about 18 to 24 hr."

3. "The vorticity maximum over the California coast shows only a weak area of high-level vorticity advection.[3] Since this area is not associated with, or anywhere near, a frontal zone, not much development can be expected within the coming 24 hr."

4. "There is a small vorticity center in the northwest, near the Canadian border. At the present time, the indications of high-level divergence are very weak. In view of the presence of a frontal zone in this area, the situation should be watched carefully. There is, however, no reason to expect any appreciable development within the near future."

Figures 22 and 23 show the synoptic situation 7 and 31 hr after preparation of the forecast. It will be seen that the resulting development attained considerable intensity. On 13 January, the storm began to move on a more easterly path, while it continued to intensify and expand.

Some interesting cases.—The case illustrated in figs. 19–25 is a relatively simple one. Some interesting and more intricate cases are listed below, together with the forecasts and pertinent remarks.[4]

Case 1, 5 January 1954. The following forecast, which verified, refers to a case of appreciable intensification of an already existing low:

"An intense area of high-level divergence is centered over the southern Appalachians. Appreciable low-level cyclonic development is almost imminent to the east of the southern Appalachians."

Case 2, 25 February 1954. The following forecast, which verified, refers to an exceedingly complex situation:

"There is a moderately large and moderately intense area of high-level divergence connected with a short-wave trough from North Dakota to Colorado. The thickness pattern indicates a fair amount of baroclinicity. Moderate to strong development in the pressure field is expected. This development should result in a collapse of the ridge separating the mid-west low from the low over western Canada. The ultimate result would be some sort of a trough to the east of the Rockies. It is doubtful whether this development will influence the intensity of the mid-west low to any appreciable extent."

Case 3, 7 January 1954. Although the following forecast verified, it is doubtful whether the working hypothesis could account for all the wide-spread development that took place:

"The West Coast trough has a vorticity and divergence distribution similar to the East Coast trough. Cyclogenesis, probably of medium intensity, is expected near eastern Colorado and western Oklahoma tomorrow, when the upper trough approaches the frontogenetical zone in the said area."

Case 4, 26 January 1954. The forecast below was classified as a failure. Although cyclogenesis occurred in the region indicated, the resulting circulation became "moderate to strong" at the end of the 24-hr period. The development illustrated by this case is typical of the frequent cyclogenesis on trailing fronts (not disturbances arriving from the Pacific) in the Texas-Oklahoma region:

"There is quite a good grid indicating upper-level divergence to the east of the trough over Arizona. Since this trough is calculated to move east with considerable speed, development associated with the front over Texas appears likely."

Case 5, 10 February 1954. The forecast quoted below became a failure. A *post-mortem* indicated that, in the area of positive vorticity advection, the trough moved approximately with the speed of the wind (a rare occurrence), with the result that $\partial Q/\partial t$ was comparable with $\boldsymbol{V}\cdot\nabla Q$. The vorticity advection was therefore inadequate as an indication of high-level divergence:

"There is an area of high-level divergence centered over the Oklahoma Panhandle. The trough aloft should move eastward with a speed of about 10 to 15 deg long per day. Moderate development is expected over Oklahoma and northern Texas."

Case 6, 11 January 1954. Forecast (3), in the example discussed in detail above, was classified as a failure. This was due partly to the erroneous analysis,[4] but mainly to the circumstance that the standard method of verification (see section 2, below) was difficult to apply. Actually, the low in question deepened by about 10 mb, while the circulation in the vicinity of the center remained weak.

Post-mortem.—The results of the verification are shown in table 2. It will be seen that, out of eleven forecasts of *strong* or *moderate to strong* development, eight verified while three were off more than one category. In addition, four cases of *strong* or *moderate to strong* development occurred (lower left corner of table 2) without being forecast. These latter cases are the major failures. Three of these cases have been accounted for as cases 4, 5 and 6, above. A *post-mortem* on the fourth case showed that the failure was due

[3] Later analysis (see fig. 19) showed that the vorticity advection was appreciable.

[4] Interested readers should consult the pertinent synoptic charts (not reproduced here).

to an error in the vorticity computation which eliminated an area of vorticity advection.

Other notable failures are the eight cases in the upper right portion of table 2. The *post-mortem* on these cases failed to divulge any particular cause except, perhaps, bad judgment. Some of these failures may well be due to weaknesses inherent in the working hypothesis.

It should be noted that, in the application of any qualitative or semi-qualitative technique, personal skill remains a prominent element. The writer does not wish to convey the impression that there is a strict one-to-one correspondence between the intensity of the vorticity advection at the 300-mb level and the resulting development at sea level. Apparently much depends upon other factors (such as the intensity and slope of the front, orographic influences, *etc.*), which have not been explored. Nevertheless, it appears that the working hypothesis is useful and may be improved upon as further experience is gained.

2. The verification

The system of verification.—Only those forecasts were used which could be verified. The surface charts prepared in Chicago extend only a short distance over the Atlantic; consequently, a considerable number of forecasts in connection with coastal storms could not be verified. Similarly, the basic data from northern Canada were often inadequate for forecasting and verifying developments in that region. No satisfactory method was found for handling the break-away lows from the extensive and deep low-pressure system usually present in the Gulf of Alaska. Forecasts of such break-away lows were therefore excluded.

Although no standard nomenclature was used in describing the forecast developments, it was possible to reduce the expressions to the following equivalents: (1) filling or no significant development, (2) slight to moderate, (3) moderate, (4) moderate to strong, and (5) strong. While some subjectivity is involved in this reduction, it is believed that no bias resulted.

Since the 24-hr change in central pressure of the low frequently does not adequately describe the change in intensity of the circulation about the low center, an attempt was made to measure the circulation values, although this was possible only to a rough approximation. Since the circulation is equal to the line integral of the velocity component along a closed circuit, the method[5] used consists of evaluating the wind components at regular intervals around the circumference of a circle and adding these components, considering them to have been multiplied by unit distances. The wind components were estimated by assuming geostrophic balance, taking pressure differences over finite intervals of 100 naut mi normal to the circumference of the circle at the standard points. Three concentric circles were used for computation purposes, and the largest sum of pressure differences from any of the three circles was used as the circulation measure. This was done since, as a low intensifies and expands, the zone of strongest circulation usually appears at greater distances from the center. The innermost circle had a radius of 250 naut mi, and eight points were taken around its circumference. The second circle had a radius of 375 naut mi and 21 points at which pressure differences were read; and the third circle had a radius of 500 naut mi and 16 points. By use of this technique, a rough estimate of the maximum circulation around a given low is quickly obtained. It should be noted that there are limitations to the strictly objective use of this circulation measure. A strong anticyclone on one side of the low occasionally made an excessive contribution to the total value (see, for example, case 6, above). This was especially true just east of the Rockies, where the sea-level pressure gradients sometimes are fictitious. Also, it was found that by varying the orientation of the overlay for measuring the circulation, the values might vary by as much as 10 to 20 per cent.

In addition to consideration of the circulation around the circumference of circles, it was found useful to consider the changes in the central pressure of the lows. By comparison of the 24-hr changes in the circulation measure with the corresponding change in the central pressure, a classification table (table 1) was developed. On occasions, it was found that the forecast would verify relative to circulation change but not in regard to central pressure, or *vice versa.* In such cases, that verification was preferred which appeared to be based on the most reliable data. It will be seen from table 1 that some lee-way exists

[5] The method was developed with the assistance of Mr. J. E. Hovde.

TABLE 1. Development classification.

Descriptive term	Circulation change	Decrease in central pressure (mb)
Strong	30 or more	15 or more
Moderate to strong	20 to 29	9 to 15
Moderate	10 to 19	5 to 12
Slight to moderate	6 to 9	3 to 8
Filling or none	5 or less	less than 5 or any increase

TABLE 2. Results of verification of forecasts.

	Observed				
Forecast	Strong	Moderate to strong	Moderate	Slight to moderate	None or decreasing intensity
Strong	3	0	1	0	0
Moderate to strong	0	5	0	2	0
Moderate	0	1	14	0	5
Slight to moderate	1	0	1	13	3
None or decreasing intensity	2	1	0	1	44

in the central pressure changes as compared with the circulation changes. A forecast was verified as correct if its descriptive value corresponded to a subsequently measured value in the same category as given in table 1. In five cases, the forecast was considered correct although the descriptive term was somewhat indefinite and could have verified in either of two adjacent categories.

The results.—The results of the verification of the forecasts of intensification are given in table 2. It will be seen that 79 of the 97 verifiable forecasts were in the proper categories. There were six near-misses, and 12 cases in which the forecast was missed by more than one category. These results are considered to be very good, since it is apparent that a chi-square or other contingency measure would show a considerable improvement over what chance alone might give for similar marginal distributions.

It is concluded, therefore, that the working hypothesis is a useful forecasting tool.

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