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A QUANTITATIVE METHOD FOR 24-HOUR JET STREAM PROGNOSIS

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ABSTRACT

A formula for the rate of propagation of isotachs on a constant pressure surface is derived and a computational routine, developed during a period of experimental forecasts is described. The verification of the 24-hour forecasts made to date is described.

* * *

The wind pattern in the high troposphere fluctuates strongly from day to day. Centers of high and low wind speed situated along the axes of jet streams at 300 mb or 200 mb propagate downstream and in some measure we can set down their behavior in model form (8). But the propagation in many situations is so erratic that simple extrapolation seldom has proved satisfactory for 24 hours. It would be of practical value to develop computations that permit an objective construction of jet stream prognoses.

The problem falls in two parts:

- (a) Prognosis of the field of wind direction;
- (b) Prognosis of the field of wind speed.

F. Defant (2) has described a generally successful technique to predict the field of wind direction. Here we shall only take up the prognosis of wind speed. It is our plan to find kinematical expressions for the rate of propagation of isotachs (lines of equal wind speed) and points or lines of maximum or minimum speed. Then we shall see how these expressions can best be evaluated on synoptic charts, and what results have been obtained with prognoses made during a preliminary trial period.

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Method: The general kinematic expression for the rate of propagation (c_1) of an isotach (cf. also Petterssen (7)) can be written

$$c_1 = - \partial \phi / \partial s, \quad (1)$$

where the s -axis points along the streamlines. Since the direction of this axis is not constant in time or space, its changes must be taken into account in applying equation (1). This can be done with the "trajectory method" described by Petterssen (7).

The main problem is the evaluation of the rate of local change. We can solve it by making use of the equation of motion along the streamlines in a constant pressure surface.

$$\frac{dv}{dt} = -g \frac{\partial h}{\partial s} \rho. \quad (2)$$

Here v is the wind speed, g the acceleration of gravity, h the height of a given isobaric surface and d/dt the substantial time operator. By definition

$$\frac{d}{dt} = \frac{\partial}{\partial t} + v \frac{\partial}{\partial s}.$$

Introducing this relation and equation (1) in equation (2), we obtain

$$(v - c_1) \frac{\partial v}{\partial s} = -g \frac{\partial h}{\partial s},$$

and solving for the rate of propagation,

$$c_1 = v + g \frac{\partial h}{\partial v \partial s}. \quad (3)$$

Replacing the partial differentials by finite differences,

$$c_1 = v + g \frac{\Delta h}{\Delta v \Delta s}. \quad (4)$$

Similarly, for a point of maximum or minimum speed,

$$c_m = - \partial^2 \phi / \partial s^2.$$

Proceeding as before,

$$c_m = v + g \frac{\Delta^2 h}{\Delta v \Delta s^2}. \quad (5)$$

All further discussion will refer to equation (4) since equation (5) has not yet been tried out in practice.

Application of the mixed kinematic-dynamical equation (4) involves evaluation of the error -contour flow, and this has always been regarded

as impossible in the past. It has been asserted that the observational errors are sufficiently great and that the station density anywhere is sufficiently low that it is always possible to fit the contour direction to the winds. This is usually true, especially in the lower troposphere. Even at 700 mb, however, there are cases on record in anticyclonic situations when it is impossible to draw the contours parallel to the winds and when the analysis shows a strong flow toward higher contours.

While good observational evidence as yet is scanty, there is every indication that the gradients of wind speed along the streamlines can be very strong in the high troposphere near the jet stream axes (8). Oliver (8) has published time sections of observed winds aloft that give variations of over 100 knots/6 hours. If we can interpret these variations as indicative of changes of wind speed along a streamline rather than as lateral shifts of a whole pattern, it follows readily that the angles of cross-contour flow must be large. Further, we call attention to the paper of Neiburger et al (5) who did not find a satisfactory correlation between geostrophic or gradient and observed wind, and to that of Houghton and Austin (4) who emphatically pointed to the great magnitude of the observable accelerations aloft. J. Bjerknes (1) also bases some of his most recent deductions on deepening on observable departures from geostrophic or gradient wind in the high troposphere.

It is certainly legitimate to adopt the experimental standpoint that on many days the upper wind observations at 300 mb over the United States are sufficient to permit the drawing of separate streamline and contour fields. Two things then should show up:

- (1) The streamlines usually should point to the left of the contours where the wind speed increases downstream. They should point to the right of the contours where the wind speed decreases downstream.
- (2) Appreciable angles between contours and streamlines should be observed.

In the course of experimentation with the 300-mb charts of October to December, 1951, the first condition was always met on days when the number of winds was sufficient for the construction of streamlines. Even with perfect data, this need not have been observed of necessity. Equation (4) is not a complete one and some terms could be added, for instance a vertical motion term. The latter, of course, is zero at the surface of strongest wind which does not coincide in general with the 300-mb level. But the sign of $\frac{\partial \Delta h}{\partial t}$ turned out to be quite consistent. The term always acted in a retarding sense, i.e., the isotach patterns propagated slower than the wind. In future experiments it may be profitable to write equation (4) for an isentropic surface.

The second condition was investigated statistically by noting the angle between contours and streamlines (in degrees) in a sample of 257 cases, all evaluated within jet stream zones at points where an actual upper wind observation was available. This statistic kept track of the sign in addition to the magnitude of the angle of deflection. The sign of deflection was not systematic, as should be expected and the result, shown in figure 1, is presented without respect to sign. It is seen that the winds were parallel to the contours only in 25%, or if all angles of 10° are reckoned as an error,

in 50% of the sample. One quarter of all cases had angles greater than 20° . We see that figure 1 furnishes good indications of the existence of large accelerations aloft.

Evaluation of equation (4): Of the two quantities that determine the speed of propagation, v is immediately given since its scalar magnitude equals that of the isotach to be moved. The amount of $g \frac{\Delta h}{\Delta S}$ depends on the interval ΔS over which the term is measured. A priori there is no guide to evaluate the term, except that ΔS evidently should not extend beyond points of maximum and minimum wind. Therefore it is most suitable to choose an engineering approach. If we take a series of past maps, we can determine c_1 by comparing successive charts. We can then treat $g \frac{\Delta h}{\Delta S}$ as the dependent variable and find that interval ΔS over which $g \frac{\Delta h}{\Delta S}$ should be measured to give the best fit in equation (4).

Four choices of ΔS were tried out following this approach, illustrated in figure 2. Relative to point P, to be moved, we chose

- (1) upstream from P to the intersection of the streamline with the isotach i_0 , and the same distance downstream from P;
- (2) downstream from P to the intersection of the streamline with the next isotach i_2 , and the same distance upstream from P;
- (3) as 140 miles (2° latitude) upstream from P and the same distance downstream;
- (4) upstream from P to the point where the streamline becomes parallel to the contours, and the same distance downstream from P.

Figure 3 shows the result of the computations for the sample of 100 cases tested. Evidently the fourth method gives the best results by far and it was used in all prognoses made. Due to limited time, we did not try other possibilities. There is no cogent reason why new trials could not develop a routine that would provide still better fit.

A variation of the fourth method must be applied when the interval upstream from P becomes so great that measurement of the same interval downstream from P takes the endpoint beyond the wind maximum. In that case the sign of $\frac{\Delta h}{\Delta S}$ changes inside ΔS and this is clearly not permissible. In this case we go downstream to the maximum from P and then the same distance upstream.

Figure 4 is a nomogram that gives a graphical solution of the second term of equation (4).

Prognostic procedure: The chart material requisite for the prediction consists in

- (a) Streamline-isotach analyses at 300 mb or other chosen surface
[for techniques to prepare the isotach analysis, see (8)]
- (b) Contour analyses with 200-foot spacing drawn independently for the same surface.

Prognosis of the contour field with the method of F. Defant (2) is the first step of the routine. The prognostic contours must serve as prognostic streamlines. This is a drawback, since errors are unavoidably introduced in moving the isotachs. As yet, however, we do not know a method for prediction of the field of wind direction from wind data alone.

The question may be raised here if it would not suffice to compute the wind speeds from the prognostic contours. We have tried this and in general obtained much better results with the technique here described.

Initial contour and streamline fields are next superimposed and checked for consistency of the crossings between streamlines and contours as described earlier. Then we compute c_1 for as many points P as possible, and in the future calculations of c_m should be added. We also note the areas where streamlines are parallel to the contours over large distances. There, of course, little change should take place.

As a third and final step, we move all points P for which c_1 has been calculated and draw the prognostic isotach pattern. The following points should be noted.

(1) The isotachs are nearly always progressive. They propagate more slowly than the wind. During the tests, a few stationary cases occurred but none that were retrograde.

(2) The method allows for changes of shape of the patterns. Frequent among these are elongation (Fig. 12) and contraction (Fig. 5).

(3) The method allows for the juncture of successive maxima, discussed at the end of the paper, and for the disappearance of isotachs. If the rear end of a closed isotach moves more rapidly than the front end, the area enclosed by the isotach must diminish with time and the whole isotach disappears when the rear end catches up with the leading edge.

(4) The method is not capable of predicting the formation of new isotachs which must be done by qualitative methods in conjunction with the surface map (8). Frequently we note that the rear end of a high-speed isotach such as 150 knots moves slower than the front end leaving a broad flat area inside with strong gradients outside. In such cases it is quite safe to draw a 175-knot isotach, sometimes even a 200-knot isotach inside.

(5) The prognosis for the western border areas of the United States is hampered by lack of data over the Pacific Ocean. When the winds aloft have a strong meridional component, shortage of data outside the United States will affect the prediction in any border area.

(6) Sometimes a wind maximum was predicted to be stationary but the contour prognosis gave an eastward shift of troughs and ridges. The wind pattern then had to be moved eastward with the speed of the wave pattern.

(7) Some subjectivity remains in the method and a forecaster will need a certain amount of experience in the drawing of the final wind field. It should not be forgotten that the speed c_1 is applied to 24-hour intervals and that accelerations of c_1 are not computed.

Examples of computation of c_1 : Figures 6a-c show streamlines, isotachs and contours at 300 mb for a part of the United States on November 2, 1951, 0300Z. In practice these charts should be superimposed on a light table for computation. Here we have repeated the pertinent parts of the streamline analysis on figures 6b-c for illustration purposes.

We wish to compute c_1 at points A to E. Taking at first point A on the 125 knot isotach, we find that point upstream along the streamline passing through A where the contours and streamlines become parallel (Fig. 6a). We note that this point coincides with the point of highest wind speed along the streamline (Fig. 6b). Going the same distance downstream from A we observe that we have not passed beyond the weak minimum downstream (Fig. 6b). Thus ΔS as marked by the portion of the streamline drawn heavy should prove satisfactory.

We find that v at the upstream end of ΔS is 175 knots and about 85 knots at the downstream end (Fig. 6b). Thus $\Delta V = -90$ knots. Over the same distance $\Delta h = +350$ feet (Fig. 6a). Entering figure 4 we find $g \Delta h = -47$ knots, in round numbers -50 knots. Finally, $c_1 = 125 \text{ knots} - 50 \text{ knots} = 75 \text{ knots}$.

Proceeding in the same way at point B, we find $\Delta V = -80$ knots $\Delta h = +200$ feet. The retarding term is only -30 knots and the speed of the isotach 95 knots.

At point C, $\Delta V = -50$ knots, $\Delta h = +150$ feet. The retarding term again is 35 knots and the speed of the isotach 95 knots.

These results show that the southern end of the 125 knot isotach will move faster than the northern end, so that the shape of the pattern will change. The computed speeds are high, much higher than observed in many cases. In order to hold the propagation of the pattern to around 35 knots, a frequently observed value, the retarding term would have to amount to 90 knots, requiring $\Delta h \approx 500$ to 700 feet in view of the gradient of v present. This in turn would mean a much stronger angular departure of the streamline from the contour direction. Rapid isotach displacements do occur at times, of course. In the present case, the area of high wind elongated to somewhere in the middle of the Atlantic Ocean on the next day.

Along the northernmost streamline, we also compute the speed of the 100 knot isotach at point D and that of the 150 knot isotach at point E. At D, $\Delta V = -100$ knots, $\Delta h = +400$ feet. Thus $c_1 = 100 \text{ knots} - 45 \text{ knots} = 55 \text{ knots}$. At E, $\Delta V = -80$ knots, $\Delta h = +300$ feet. Thus $c_1 = 150 \text{ knots} - 45 \text{ knots} = 105 \text{ knots}$.

This computation tells us that the high-speed isotachs are catching up with the low speed isotachs, so that within a few hours a line of high-level wind discontinuity should be moving through the eastern United States. As yet it is a matter of hypothesis whether such discontinuities actually exist aloft. A much closer network of observations than now existent is required to investigate this hypothesis. We have some further comments on this subject at the end of the paper.

Verification: Figures 7-9 show initial pattern, prognosis and verification for December 11-12, 1951. The result was about average. Experimental daily prognoses were made for about one month.

From the prognostic charts the prescribed wind direction and speed was read for up to 25 rawinsonde stations scattered through the United States east of 110°W. These were verified against observed wind as given by rawin or 30,000-foot pibal. When the verifying wind was missing, it was interpolated from the analysis. In cases when an isotach center intensified, all stations affected were discarded since the method does not predict the formation of new isotachs.

The wind direction was verified to the nearest 10° and wind speed to the nearest 5 knots. Figures 10 and 11 show the result, again without respect to sign, since the errors were not systematic in that respect. Wind direction verified within 20° in 75% and wind speed verified within 30% in 66% of the 257 cases. The sample includes all the initial prognoses when the writers were just setting up the computations and as yet were without any experience. A new sample should show considerable improvement of skill.

It should be expected that the verification of wind speed will lag that of wind direction in practice. Over the largest part of the map, the wind direction in general changes only slowly with time, and space gradients also are weak. Wind speed, in contrast, has very strong gradients, especially along the northern rim of jet axes where speeds can drop from 200 knots to 50 knots within 200 miles. A slight error in placing the jet axis then can produce a severe error in the prognosis of wind speed. The poor forecasts recorded in figure 11 were of this kind; they do not indicate that the prediction of the whole isotach configuration failed.

Change of shape of jet centers: In the course of the prognostic work it became apparent that the centers of maximum speed along the jet axes had a definite life history that repeated with sufficient regularity to warrant setting it down in model form. Figure 12 illustrates this preliminary model.

We begin with a symmetrical distribution of isotachs along the jet axis (Fig. 12a). Subsequently we observe that in general the isotachs downstream from the maximum move faster than those to the rear. Herewith the area enclosed by the 100-knot isotach in figures 12b-c increases and the slow area along the axis between the 100-knot isotachs decreases. In addition, the high speed isotachs move faster than the slower ones. With time, they become crowded in a narrow leading edge (Fig. 12c). Then a rapid adjustment of the wind field takes place. The slow area ahead of the maximum is wiped out as the 100-knot isotach, perhaps even the 150-knot isotach, opens up to merge with the isotachs of the maximum farther downstream.

It is easy to postulate a stage, intermediate between figures 12c and 12d when an actual wind discontinuity forms the leading edge. Special observations are requisite to investigate this hypothesis, since the routine observations are too widely spaced and too infrequent for this purpose. If true, however, it becomes rational to study the jet stream dynamics with the "hydraulic jump" model, first introduced in meteorology by Freeman (3).

The reader will note that figure 12d is drawn in such a way as to permit a subsequent return to figure 12a. Such is not always the case. Speaking broadly, we can say that a jet stream as a whole has a definite life history that consists of a period of organization and a period of decay. Figures 12a-c are models of the jet stream when fully organized. Eventually, after

several days or perhaps even a week and more, figure 12c is replaced by figure 12e rather than 12d. All maxima along the current combine and wind speed along it becomes uniform. This stage presages breakdown of the current into numerous jet "fingers," and disintegration. At this time it is not possible to enlarge on this subject, except by way of hypothesis. Future studies should develop a more rigorous description of the life cycle of jet streams and the laws that govern it.

Conclusion: This report should be looked upon as an initial experiment in quantitative forecasting of the upper winds at the jet stream level. The results indicate that the method has definite promise. As we have pointed out throughout the paper, improvement should be possible in many ways as experience accumulates. One of the drawbacks is the fact that high-level winds are still scarce on many days even over the United States. We note, however, the large increase in observations aloft in recent years. If this trend continues, perhaps at an accelerated pace, then the computations outlined should provide a quick and fairly reliable method. Since no equipment is requisite that is out of the ordinary, prognoses can be made readily by mobile field units.

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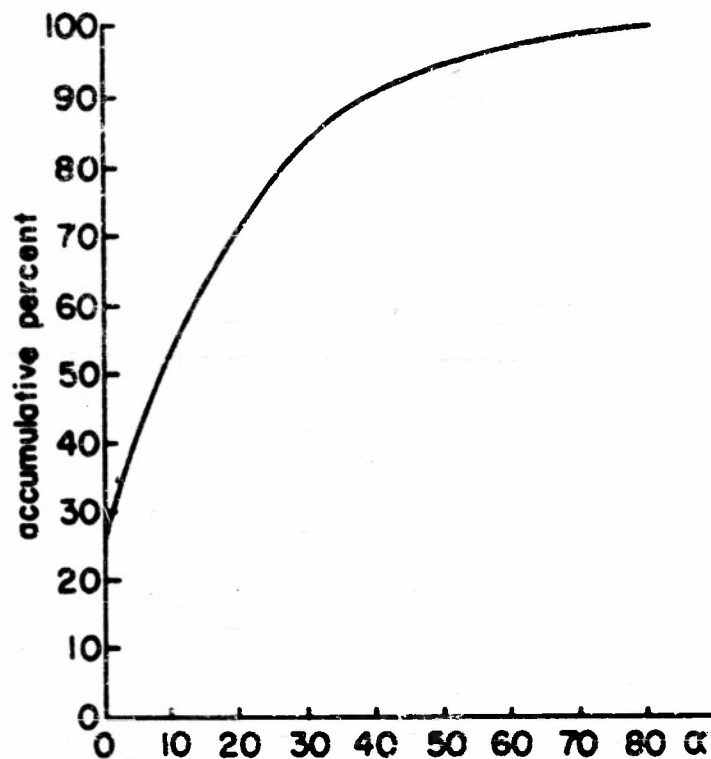


Figure 1. Accumulative percent frequency of departure of observed wind direction (without respect to sign) from the direction of the 300-mb contours (tens of degrees) in jet stream zones for a sample of 267 cases taken from the period October to December, 1951.

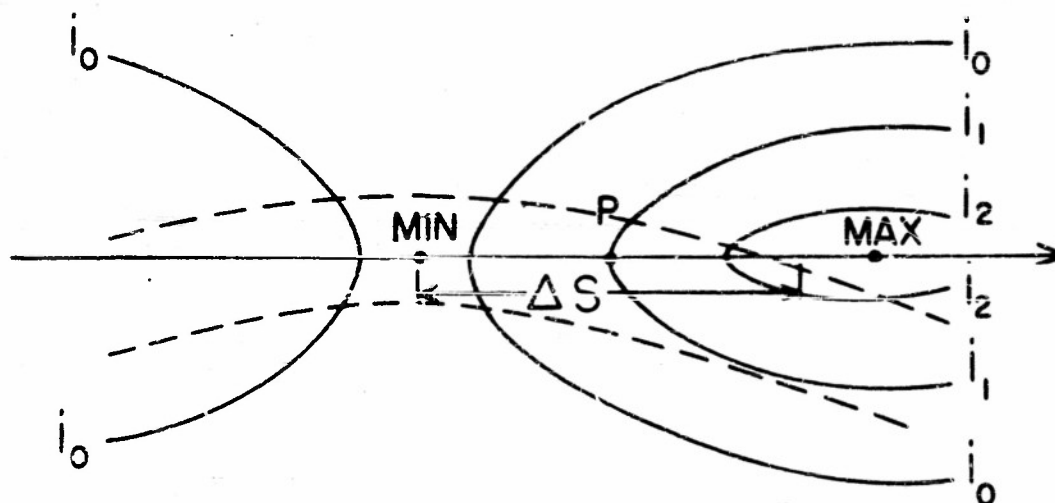


Figure 2. Illustrating determination of length interval Δs over which second term of equation (4) is to be measured.

Figure 3

Percent departure of computed from observed retarding term in equation (4), in percent of the sample of 100 cases tested. The lines correspond to the four choices of ΔS described in the text: choice 1, dotted; choice 2, dashed; choice 3, dash-dotted; choice 4, solid.

Figure 4

Nomogram for computation of retarding term in equation for propagation of isotachs. On an intersection of a ΔV and ΔH line read the amount of retardation in knots given by the sloping line.

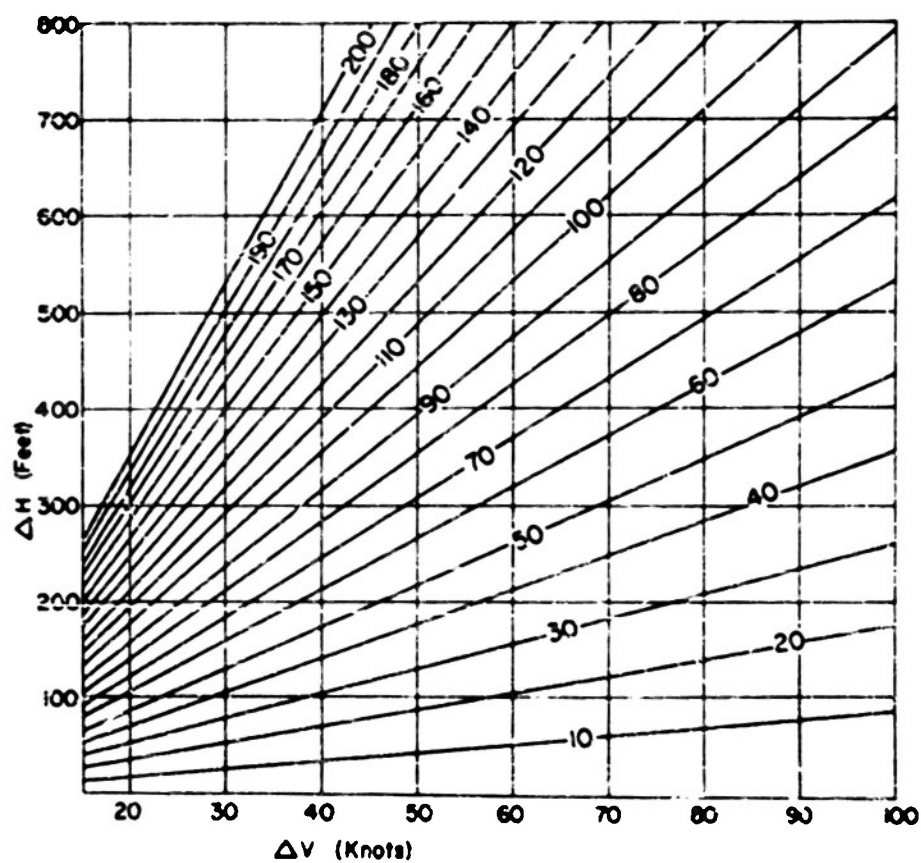
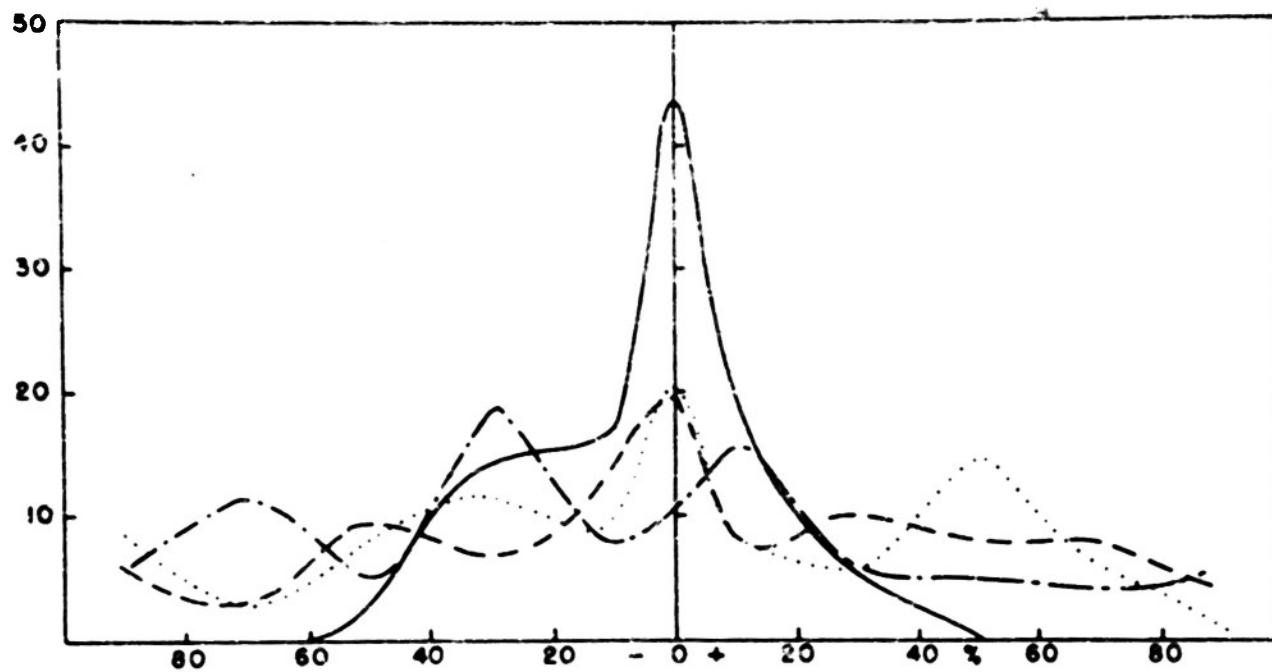


Figure 5

Model showing contraction of area enclosed by an isotach in region of converging streamlines.

Figure 6a

Streamlines at 300 mb, Nov. 2, 1951, 0400Z. Direction of observed winds shown by feathered arrows.

Figure 6b

Isotachs (knots) at 300 mb, Nov. 2, 1951, 0400Z. Text gives sample computation of the displacement of the isotachs at points A to E. Streamlines passing through these points repeated from figure 6a, extended over appropriate length interval using figure 6c.

Figure 6c

300-mb contours in 200-foot intervals (200's ft, first number omitted), Nov. 2, 1951, 0400Z. The streamlines passing through points A, B and C are again shown extended over the proper longitudinal interval to obtain ΔH .

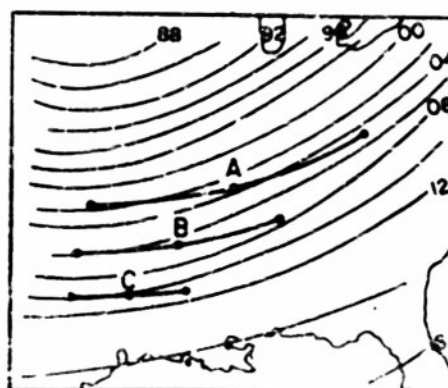
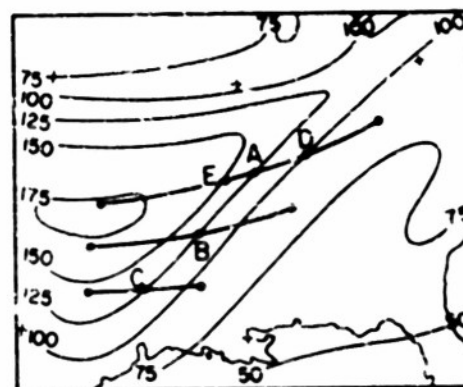
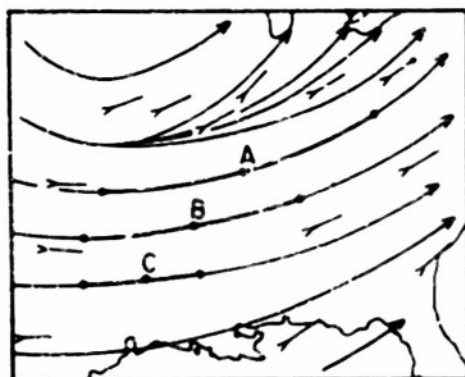
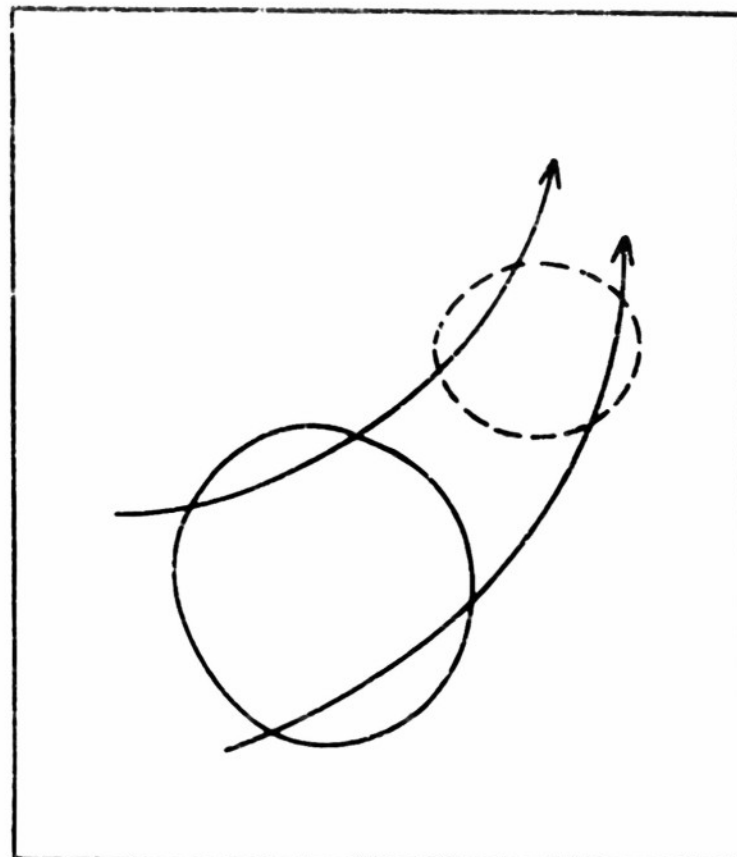


Figure 7

Streamlines (solid) and isotachs (knots, dashed) at 300 mb, December 11, 1951, 0300Z. Heavy lines mark axes of highest wind speed. "S" denotes slow areas.

Figure 8

Streamline and isotach prognosis at 300 mb for December 12, 1951, 0300Z.

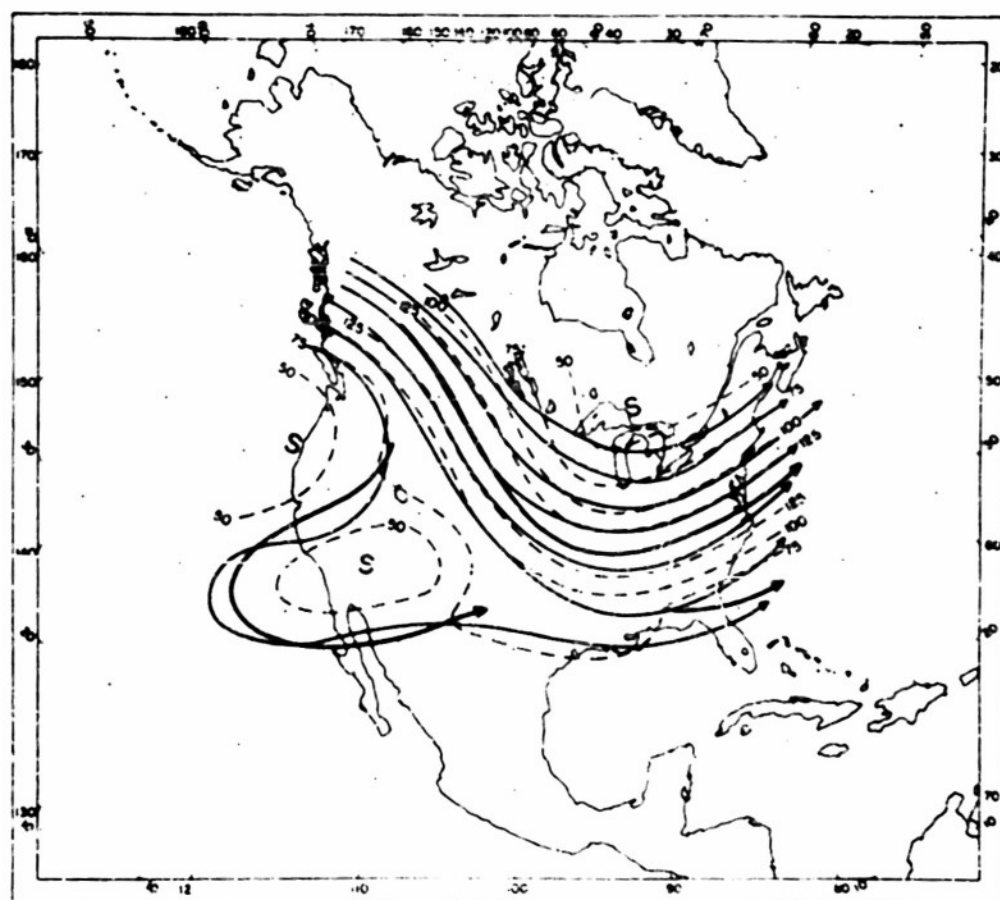
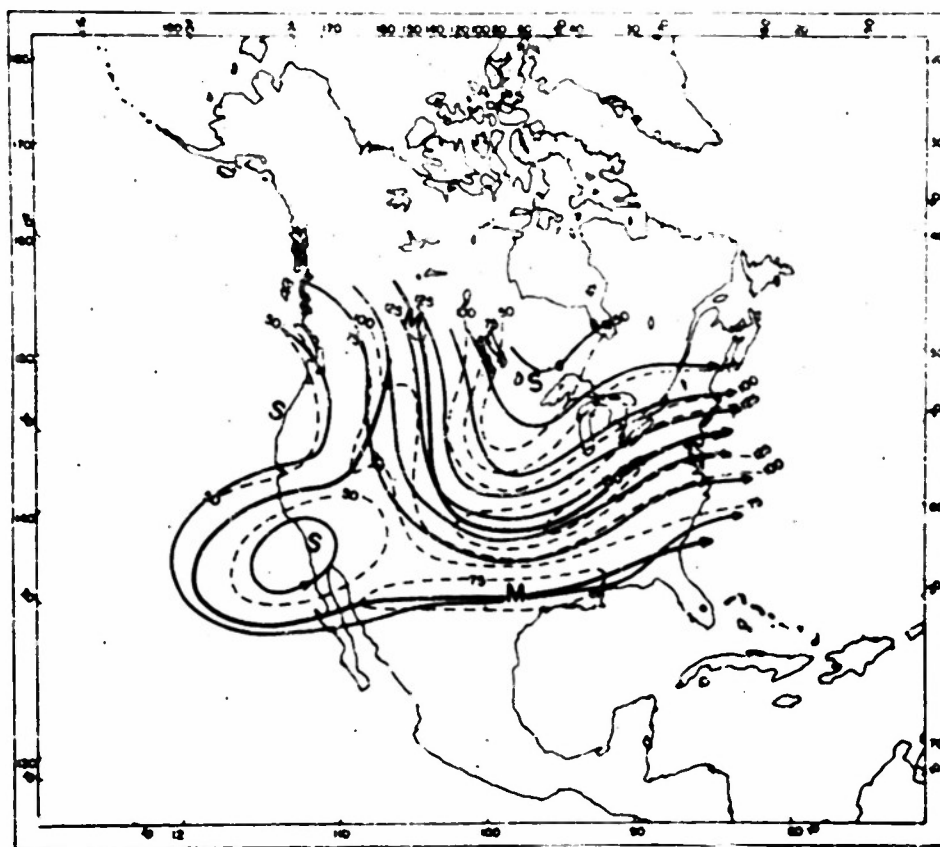


Figure 9

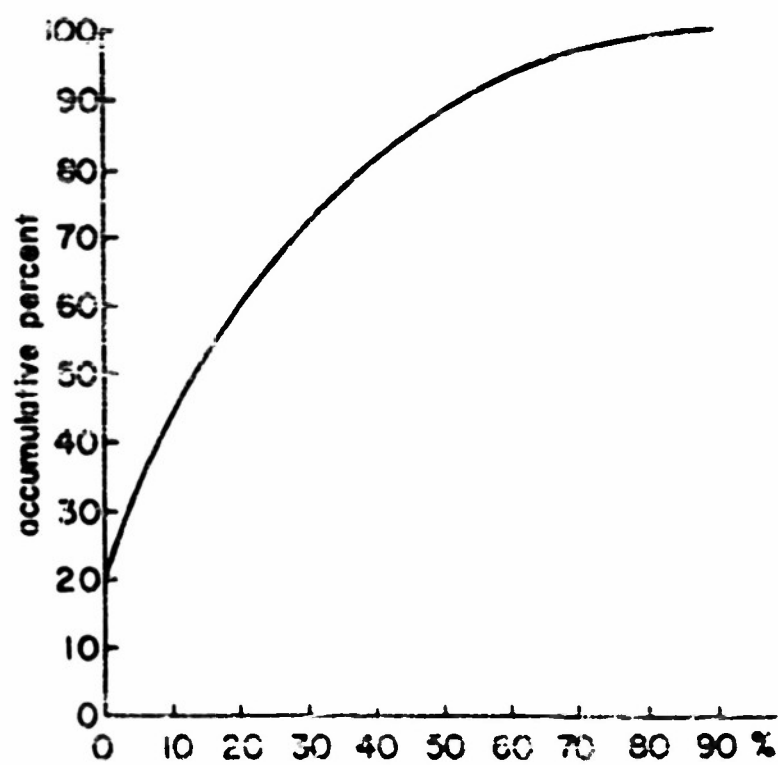
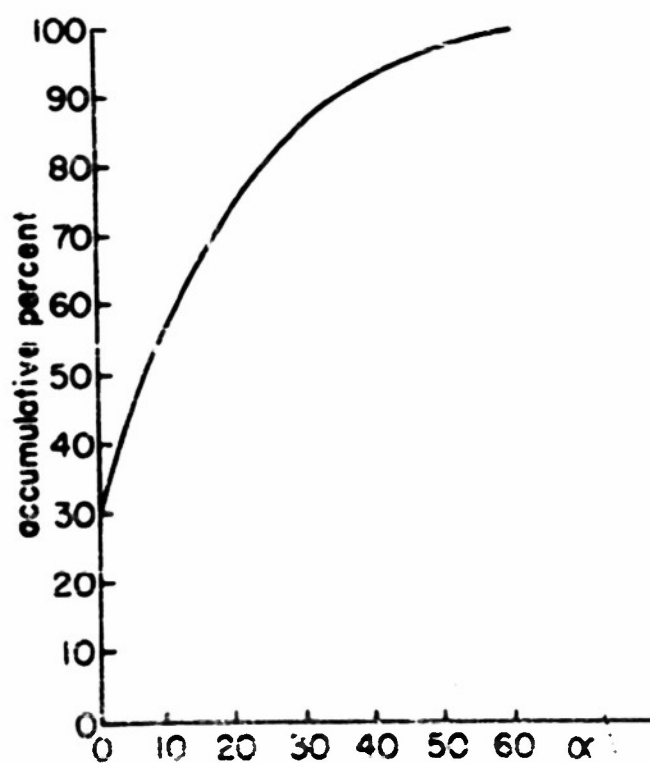
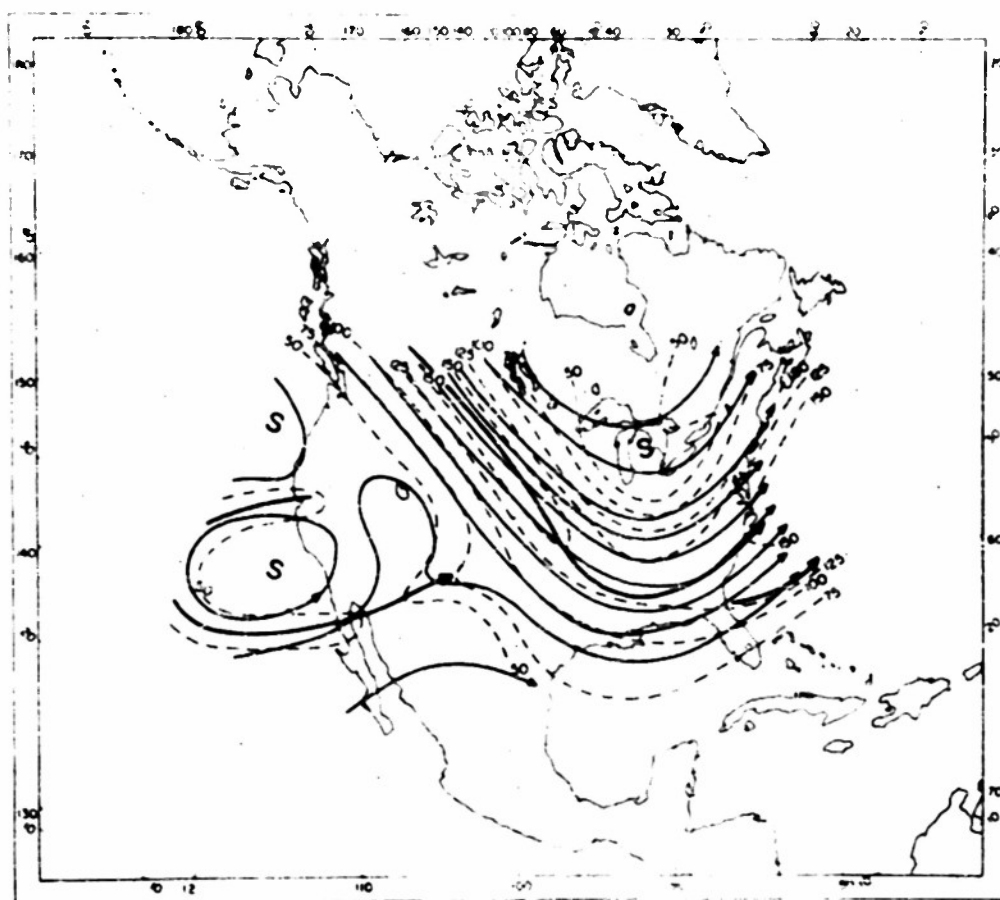
Streamlines and isotachs at 300 mb, December 12, 1961, 0300Z.

Figure 10

Accumulative percent frequency of departure of observed wind direction (without respect to sign) from predicted wind direction at 300 mb (tens of degrees) for 287 cases.

Figure 11

Accumulative percent frequency of departure of observed wind speed at 300 mb from computed wind speed (in % of observed wind speed) for 257 cases.



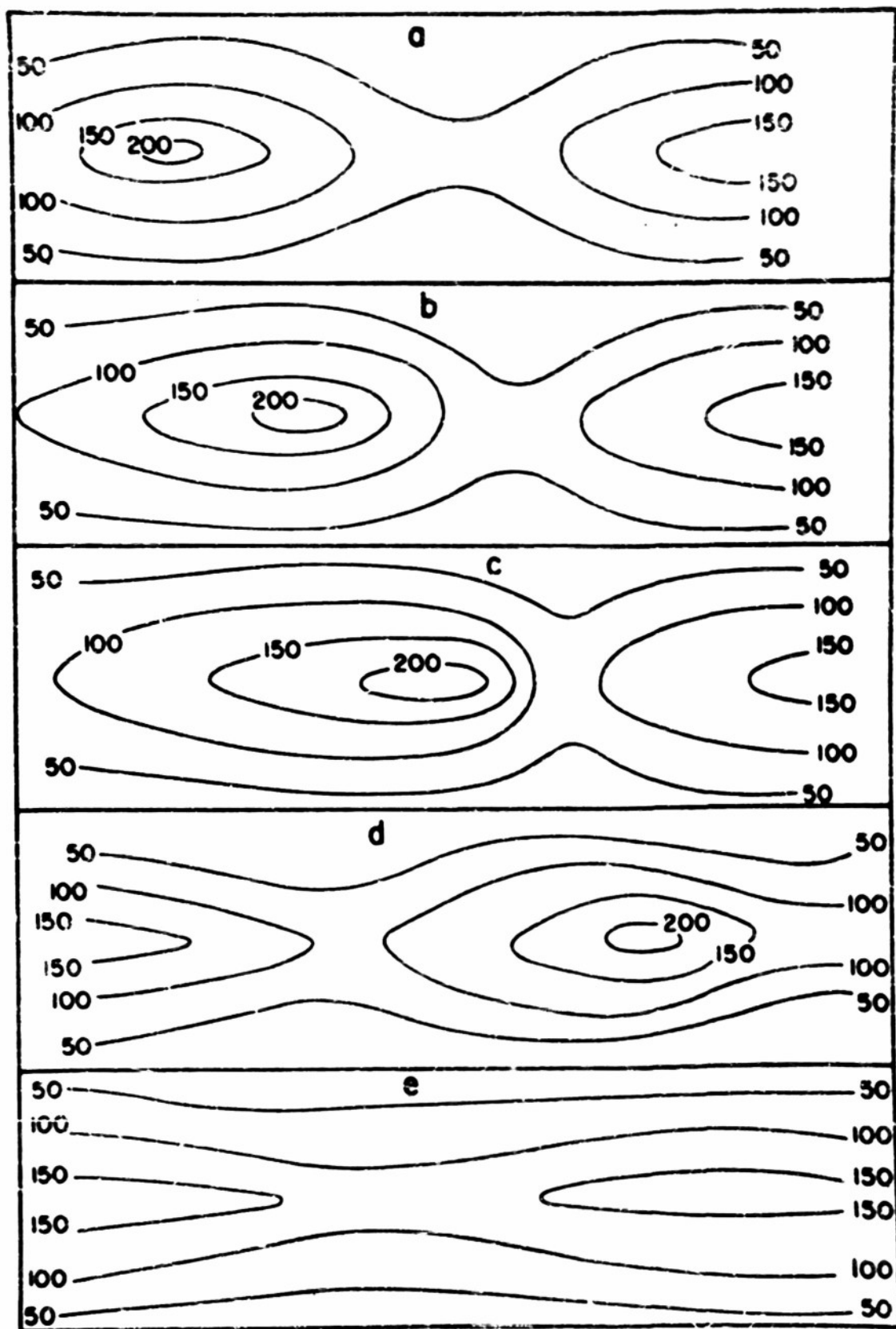


Figure 12 Five stages during eastward progression of maximum along jet stream axis. Isotechs in knots.