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An Objective Method of Forecasting Five-Day Precipitation for the Tennessee Valley

By
WILLIAM H. KLEIN

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AN OBJECTIVE METHOD OF FORECASTING FIVE-DAY PRECIPITATION FOR THE TENNESSEE VALLEY

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AN OBJECTIVE METHOD OF FORECASTING FIVE-DAY PRECIPITATION FOR THE TENNESSEE VALLEY

William H. Klein

INTRODUCTION

Long-range weather forecasting as practiced by the Extended Forecast Section of the U. S. Weather Bureau consists of two main steps. The first step is the forecast of the general circulation, expressed by the prognostic mean maps and indices at sea level and 700 mb. The second step is the interpretation of the prognostic circulation patterns in terms of actual weather, expressed as mean temperature and precipitation anomalies. Most of the research conducted in the Section since its inception 8 years ago has dealt with the first phase, the general circulation, primarily because it is the basic and most important problem of extended forecasting, and, secondarily, because of specific wartime requirements of the Armed Forces. At the present time, however, there is reason to believe that one of the best ways of improving the forecasts in the immediate future lies in more detailed study of the second problem, namely, the temperature and precipitation anomalies associated with coexisting circulation patterns. The importance of this type of study was stressed by Norton, Brier, and Allen [1] in an experiment which demonstrated that anomaly forecasts based on the same observed mean maps varied with different forecasters and in all cases left considerable room for improvement.

The investigation to be described in full in this report[1] was started as a pilot project in July 1946, in an effort to improve and render more objective the precipitation anomaly estimates based on prognostic circulation patterns. Precipitation rather than temperature was investigated, because forecast verification scores had been consistently lower on precipitation than on temperature forecasts [1]. The Tennessee Valley was selected for study because accurate records from a dense network of stations within a homogeneous area were available[2]. Because of the irregular distribution of precipitation, measurements at such a

[1] A condensed account of this work may be found in the Bulletin of the American Meteorological Society [2].

[2] Tennessee Valley Authority, Hydraulic Data Division, Precipitation in the Tennessee River Basin, published quarterly.

network of stations are a more representative index of large-scale atmospheric processes than measurements at a single station. Precipitation frequency and intensity were not studied separately because, in the Tennessee Valley, as Solot [3] showed, they are positively correlated (0.61) and directly proportional. Instead, only the amount of precipitation was considered.

I. PROCEDURE

Figure 1 locates the area used in the investigation, the east-central section of the Tennessee River drainage basin. It is primarily a valley, 12,000 square miles in area, bounded by ranges of mountains 3,000 to 4,000 feet high. The city of Knoxville, at 36° N. lat., 84° W. long., is situated in approximately the center of the valley and was used as the reference point from which all parameters developed during the investigation were measured.

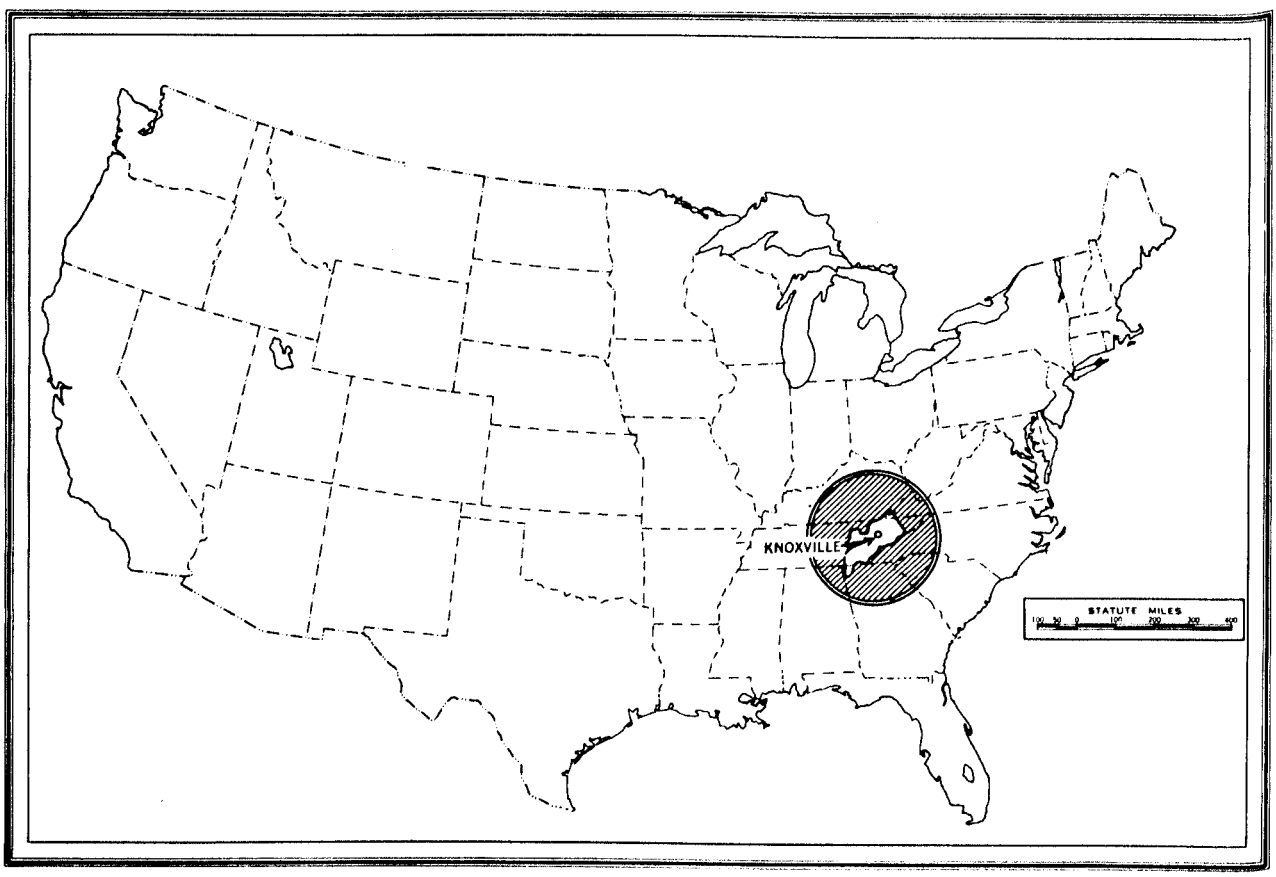


Figure 1.--Location of the east-central section (clear area within hatched circle) of the Tennessee Valley.

Average daily precipitation amounts for 30 stations within the area for the three winter months of December, January, and February, for the period from December 1939 to February 1946, had been tabulated by Brier [4]. Twice-weekly overlapping 5-day mean maps were also available for the same winter months from December 1940 onward (186 maps, 18 months in all). The average daily amounts of precipitation were combined into 5-day totals, corresponding as closely as possible to the periods covered by the 5-day mean maps, and then studied in relation to the observed mean circulation patterns at the 10,000-foot level, or 700-mb. constant pressure surface[3]. This level rather than sea level was selected because, as Namias [5] explains, in current extended forecast practice the 700-mb. map is the fundamental prognosis. The mean sea level forecast is largely derived from the 700-mb. prognostic map and is generally less reliable than it; also the 700-mb. map has smoother and more conservative patterns, which simplify the definition and measurement of various parameters.

Initially, the explanation of quantitative precipitation amounts was attempted in terms of a few basic parameters applied with equal weight to all cases. It was soon concluded, however, that better results could be obtained by stratifying the 10,000-foot mean maps into four general classes. This was accomplished by first deciding whether Knoxville was located within 5 longitudinal degrees on either side of a trough or ridge line in the circulation pattern. If not, the next step was to determine whether Knoxville was in the zone of southwesterly flow ahead (east) of a trough, or in the zone of northwesterly flow in the rear (west) of a trough (see Figure 2). Trough and ridge lines were located, in accordance with extended forecast practice, at the longitudes where the isobars reached their minimum or maximum latitude, regardless of where the area of greatest isobaric curvature was found.

In addition the average 5-day precipitation amounts were grouped into three classes of "heavy," "moderate," and "light," the classes used in precipitation forecasts issued by the Extended Forecast Section of the Weather Bureau. Because of the short period of record involved, there was no distinction made between any of the three winter months. The

[3] The isobars on the 10,000-foot constant level map are nearly equivalent to the contour lines on the 700-mb. constant pressure map, and a pressure difference of 2 mb. on the former is approximately equal to a height difference of 75 feet on the latter. Since most of the period investigated antedates May 1945, the time of transition from 10,000-foot to 700-mb. maps, all results will be presented in terms of the former and all references to current procedure given in terms of the latter.

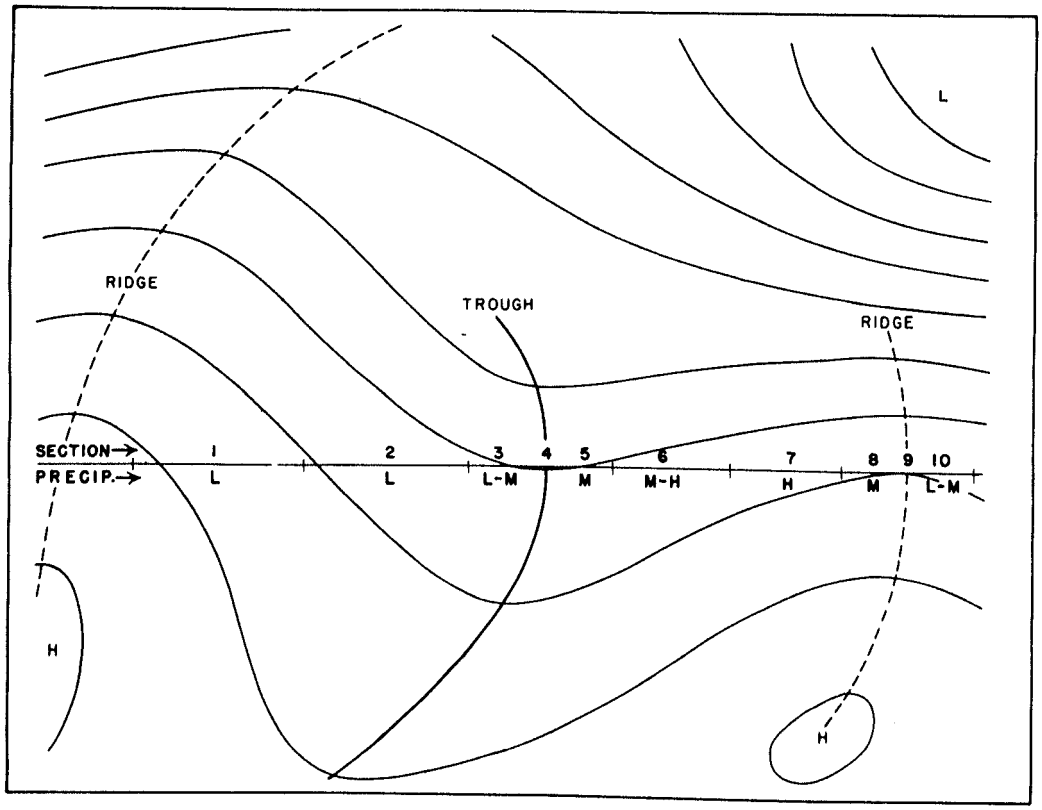


Figure 2.--Schematic 700-mb. contour pattern, showing precipitation anomaly distribution for numbered sections (see Table 1).

Table 1.--Distribution of 5-day precipitation observed in the Tennessee Valley during the winter months of 1940-1946, according to precipitation and map classes.

Location of Knoxville on mean 700-mb. map	Section	No. of cases observed L	M	H	Total	Percent in each class L	M	H	Index H/(L+H)
									%
Part I. General Zones									
a. Rear of trough		31	21	6	58	54	36	10	16
b. Near trough		13	13	10	36	36	36	28	44
c. Ahead of trough		3	18	36	57	5	32	63	92
d. Near ridge		13	9	13	35	37	26	37	50
Part II. Subdivisions of Zones									
a. 6° ahead of ridge to 14° from trough	1	16	12	2	30	53	40	7	11
a. 13°-6° in rear of trough	2	15	9	4	28	54	32	14	21
b. 5°-1° in rear of trough	3	9	7	5	21	43	33	24	36
b. On trough line	4	1	1	1	3	33	33	33	50
b. 1°-5° ahead of trough	5	3	5	4	12	25	42	33	57
c. 6°-11° ahead of trough	6	3	13	10	26	12	50	38	77
c. 12° ahead of trough to 6° from ridge	7	0	5	26	31	0	16	84	100
d. 5°-1° in rear of ridge	8	7	5	8	20	35	25	40	53
d. On ridge line	9	0	1	2	3	0	33	66	100
d. 1°-5° ahead of ridge	10	6	3	3	12	50	25	25	33
Part III. Weighted averages									
a. Rear of trough						54	36	10	16
b. Near trough						34	37	29	46
c. Ahead of trough						6	33	61	91
d. Near ridge						39	26	35	47
Part IV. All Zones		60	61	65	186	32	33	35	52

class limits were determined from the original precipitation data (213 cases based on 21 months) in such a way that each class occurred one-third of the time. Total precipitation of more than 0.73 inch during a 5-day period was designated "heavy" (H); less than 0.22 inch, "light" (L); and intermediate amounts, "moderate" (M). These designations will be followed throughout this report.

II. AVERAGE PRECIPITATION BY 700-MB. ZONE

Results obtained by grouping the data into these precipitation and map classes are summarized in Table 1. It should be noted that the figures given in this table are based on one parameter only, the position of Knoxville with respect to the 700-mb. trough-ridge system.

The most striking feature of the table is the sharp distinction between precipitation ahead of and behind the trough line, or essentially, between southwesterly and northwesterly flow aloft. This is illustrated by cases a and c under Part I, "General Zones," which show that only 5 percent of the 57 cases when Knoxville was situated ahead of the trough were in the L category, while 63 percent were in class H. On the other hand, only 10 percent of the 58 cases when Knoxville was in the rear of the trough were H, while 54 percent were L. In terms of a single quantitative index of precipitation, given in the last column of the table as the ratio of the number of H cases to the number of H plus L cases, the comparison is even more striking, since this single index had a value of 92 percent in the zone ahead of the trough but only 16 percent in the rear of the trough. The second interesting feature of the table is the approximate equality of the precipitation occurring near the trough and near the ridge. This equality is illustrated by the single index values of 44 percent near the trough and 50 percent near the ridge, and is indicative of a poor correlation between precipitation and either absolute pressure or isobaric curvature at 10,000 feet, since troughs by definition have lower pressure and more cyclonic curvature than ridges.

Part II of Table 1 gives the results obtained by subdividing each of the four main zones into two approximately equal sections. These sections are numbered from 1 to 10 in Table 1 and in Figure 2. Underneath each section in the diagram is indicated its prevailing precipitation anomaly. In the rear of the trough, for example, L precipitation occurred with almost equal frequency in both subdivisions. In the other three zones, however, exact position was of greater consequence. Near the trough, there was less precipitation in the 5-degree (longitude) section of northwesterly

flow behind the trough line than in the 5-degree strip of southwesterly flow ahead of the trough line. Section 6 (from 6 to 11 degrees ahead of the trough) was characterized by less precipitation than Section 7, which extended from a point 12 degrees ahead of the trough to a point 6 degrees west of the ridge. Near the ridge, southwesterly flow in the 5-degree strip behind the ridge line was accompanied by more precipitation than northwesterly flow in the 5-degree section ahead of the ridge line. The three cases exactly on the trough and ridge lines were too few to give reliable averages.

It is apparent from the preceding discussion that the average precipitation in the two sections of any one zone was not equal. Since the number of cases within each section was also unequal (as shown by column 4, Part II, of the table), the original summary by general zones (Part I of the table) gave undue weight to the sections having the greatest number of cases. To correct this bias, the weighted averages (Part III of the table) were obtained by averaging the percentage values of precipitation which occurred in each section (columns 5, 6, and 7, Part II), regardless of the number of cases, separately for each 700-mb. zone and each precipitation class. The weighted averages are, therefore, more representative of each of the four main zones taken as a whole. Comparison shows that for the zones ahead of and behind the trough, the weighted averages are very similar to the unweighted averages (Part I). In the other two zones, however, considerable change is effected by introducing the weighted averages, and the equality of precipitation near trough and ridge is emphasized. The weighted averages show that heavy precipitation occurred more than half the time in the zone ahead of the trough while light precipitation occurred more than half the time in the zone behind the trough. The frequency of heavy and light precipitation near both trough and ridge was about equal; about one-third of the cases in each of the four zones had moderate precipitation.

Results, to be presented in Part V, conclusively demonstrate that flow with a southerly component in advance of a 10,000-foot trough is intimately associated with copious 5-day precipitation in the Tennessee Valley in winter. This conclusion is consistent with observed correlations between (a) heavy 5-day winter precipitation in southeastern United States, and (b) subnormal 600-mb. temperatures at El Paso, Tex., both a few days earlier, determined by Namias [6], and contemporaneously, determined by Allen, et al [7], since cold air aloft at El Paso implies the existence of a trough somewhere in the center of the country. This conclusion is also in good agreement with results of studies of daily precipitation in the eastern half of the United States. The consistent appearance of deep troughs aloft to the west of flood-producing

storms has been noted by Showalter [8], Holzman and Showalter [9], Showalter and Solot [10], and Vederman [11]; while daily precipitation amount has been connected with surface and 10,000-foot southerly wind components by Showalter [12], Brier [4], and Miller [13]. The meridional wind component has also been successfully correlated with 5-day precipitation by Winston [14]. Finally, the present results are consistent with graphs presented by Tannehill [15], demonstrating an inverse relationship between monthly and annual rainfall over the nation and the station pressure at three cities in the western part of the United States, since low pressure in the West implies southerly flow in most of the country.

Several explanations may be offered to account for the close connection which apparently exists between southerly flow in advance of a trough and precipitation amount, whether measured on a daily, 5-day, monthly, or annual basis. Important factors are probably the abundant moisture supply and convective instability which characterize maritime tropical air advected from the Gulf of Mexico and Caribbean regions by southerly winds, as suggested by Willett [16]. Another important factor is the effect of horizontal convergence in southerly flow, as expressed by the latitude term in the equations for the divergence of either the gradient wind, used by Petterssen [17], or of the true wind computed by Namias and Clapp [18]. Horizontal convergence can also be expected in southerly flow ahead of the trough, because, as Bjerknes and Holmboe [19], and Haurwitz [20] have pointed out, trough speed usually exceeds mean zonal wind speed in the layers below 10,000 feet. Finally, the tendency for cold air masses in winter to persist in the lower layers, due to stability and snow cover, leads to over-running (both frontal and non-frontal) rather than displacement by warmer air transported by southerly winds, with convergence, upward vertical motion, and precipitation as a consequence. The results shown in Table 1 can also be explained by the fact that sea level troughs in the eastern United States in winter are generally displaced about 10 degrees to the east of their corresponding 10,000-foot troughs, because of the normal east-to-west temperature gradient in these troughs. Consequently, the 10,000-foot trough is filled with dry, cold, polar air, while the warm, moist, tropical air from which most of the precipitation falls is east of the 10,000-foot trough in the sea level trough.

III. PARAMETERS TESTED

The relationships discussed in the preceding section suggest that some success can be attained by always forecasting heavy precipitation ahead of the trough, light in the rear of the trough, and moderate near both trough and ridge. For more accurate forecasts, however, it is necessary to derive a specific forecasting technique for each of these four zones. Accomplishment of this goal constituted the purpose of the greater part of this investigation.

In the course of this study some two dozen independent variables, suggested either by theory or experience as significant for precipitation forecasting, were measured objectively on most of the 5-day mean maps and were then related to concurrent 5-day precipitation amounts. Although there is considerable interrelation among these parameters, they have been grouped into six main classes. The classification and discussion of each parameter follows:

A. Measures of Position

The use of the position factor was immediately suggested by the figures in Table 1. It was measured in the three following ways:

1. Distance from the trough line, defined as the number of degrees longitude from Knoxville to the first point of minimum pressure at the same latitude (36° N.), upstream for cases ahead of the trough and near the ridge, and downstream for cases in the rear of the trough. For cases near the trough, the distance was considered positive for troughs east of Knoxville, negative for troughs west of Knoxville.

2. Distance from the ridge line, defined as the number of degrees of longitude from Knoxville to the first point of maximum pressure at the same latitude (36° N.), upstream for cases near and in the rear of the trough, and downstream for cases ahead of the trough. For cases near the ridge, the distance was considered positive for ridges east of Knoxville, negative for ridges west of Knoxville.

3. Relative position, a parameter introduced as a refinement of the first two to equalize the effects of different wave lengths, and defined as the ratio of the distance of Knoxville from the trough line to the distance from trough to ridge lines (one-half wave length). It varied in value from 0, when Knoxville was on the trough line, to 1.0 when Knoxville was on the ridge line.

B. Measures of Trajectory

It is apparent that the origin and properties of the air reaching the Tennessee Valley are instrumental in determining the precipitation. Assuming stationary circulation patterns and geostrophic flow, so that isobars, streamlines, and trajectories coincide, the two simplest expressions of air trajectory were these:

1. Wind direction, measured from 0° to 360° (with a west wind as 270°) by applying a protractor to the tangent line constructed at Knoxville parallel to the isobar passing through Knoxville. When no regularly drawn isobar passed through Knoxville, an appropriate intermediate isobar was constructed.

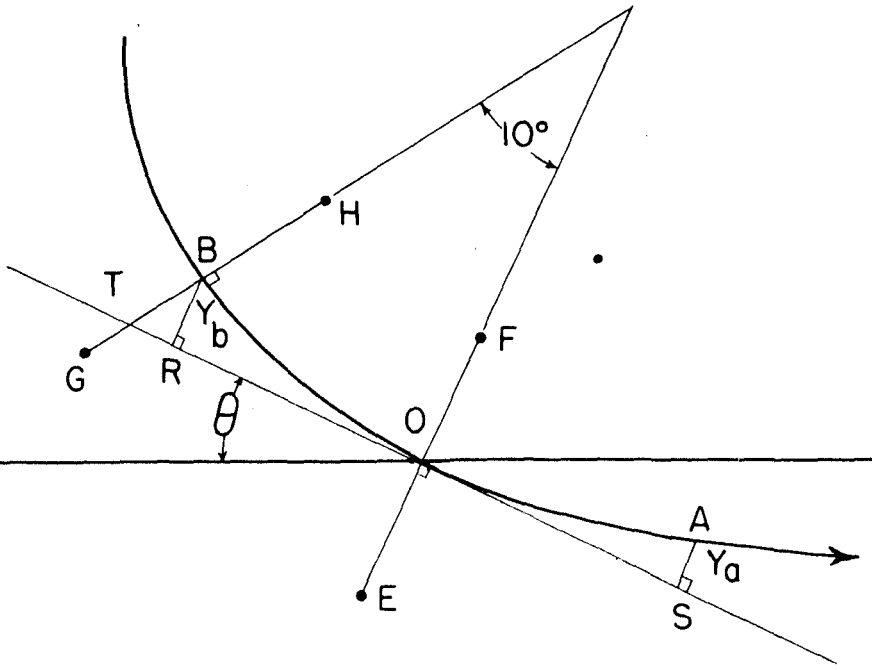
2. Amplitude, defined as the difference in latitude between Knoxville and the point of intersection of the isobar through Knoxville with the first trough line upstream (for cases ahead of the trough and near the ridge) or with the first ridge line upstream (for cases behind and near the trough).

   A closer approximation to the air trajectory was obtained by following the isobar through Knoxville upstream a distance equal to the geostrophic wind speed multiplied by an arbitrary time interval. Time intervals of 24 and 36 hours were selected as giving trajectories most representative of prevailing air flow during the 5-day period. Since isobaric spacing, and consequently wind speed, generally vary along the path of the trajectory, the wind speed at a point 10 degrees upstream, as well as the speed at Knoxville, was used in computing the point of origin of the trajectory. The trajectory origin was also determined, neglecting the speed factor, by tracing it upstream; first, a fixed distance of 15 degrees of latitude (equal to the average distance of the 24-hour trajectory); and second, a varying distance to the first trough or ridge line. For each of these trajectory origins, the following parameters were tabulated:

3. Latitude of the point of origin.

4. Longitude of the point of origin.

5. Trajectory direction, defined as the ratio of the difference in latitude between the origin of the trajectory and Knoxville to the difference in longitude between the origin and Knoxville. This ratio is approximately equal to the tangent of the angle made with an east-west line by a line drawn from the point of origin to Knoxville.



Arc BOA, curved isobar passing through Knoxville.	Point O, Knoxville. Point A, 10° (latitude) downstream. Point B, 10° (latitude) upstream.
$\overline{EOF}$, normal to the isobar at 0.	Point E, 5° (latitude) to the right, facing downstream. Point F, 5° (latitude) to the left, facing downstream.
$\overline{GTBH}$, normal to the isobar at B.	Points G and H, 5 degrees to the right and left, respectively.

Angle θ, angle between tangent line $\overline{TROS}$ and latitude parallel ϕ (considered positive for southerly winds, negative for northerly winds).

$\overline{AS}$ and $\overline{BR}$, perpendicular to tangent line $\overline{TROS}$.

Figure 3.--Schematic isobar drawn through Knoxville, with tangent and normal lines.

6. Mixing ratio at the origin, interpolated among isopleths of normal January mixing ratio at 3 km., prepared from data of Ratner [21].

C. Measures of Convergence

It is well known that precipitation is closely related to ascent and adiabatic cooling of air columns and consequently, to horizontal velocity convergence in the lower troposphere. Several expressions of convergence at 10,000 feet were therefore tested in relation to precipitation.

1. Isobar curvature. It can be shown from either the vorticity theorem of Rossby [22], or the divergence of the gradient wind theorem of Petterssen [17], that cyclonic curvature is conducive to convergence. Smith [23] obtained significant coefficients of association between isobaric curvature on 5-day mean maps and the 5-day precipitation in most of the United States, while Namias [24] found similar results relative to monthly mean maps. In the present study, isobaric curvature at Knoxville was obtained both qualitatively (classified as cyclonic, anticyclonic, or neutral) and quantitatively (taken as the reciprocal of the radius of curvature, measured in degrees of latitude; considered positive for cyclonic curvature and negative for anticyclonic curvature).

2. Horizontal wind shear. Cyclonic vorticity may occasionally be more apparent from cyclonic shear than from cyclonic curvature. To allow for this, the horizontal shear of the geostrophic wind at Knoxville was estimated from the isobar spacing. Qualititatively, it was designated as cyclonic, anticyclonic, or neutral. Quantitatively, it was computed by taking the pressure difference between Knoxville and a point 5 degrees of latitude to the left of it (facing downstream), and subtracting from this the pressure difference between a point 5 degrees to the right and Knoxville. In Figure 3,

$$\text{Shear} = (p_O - p_F) - (p_E - p_O), \qquad (1)$$

the subscripts denoting the points at which the pressure (p) was read.

3. Change of curvature. The importance of trajectories with increasing cyclonic curvature in producing convergence and heavy precipitation on a daily basis has been stressed by Austin [25], Gilman [26], Showwalter [12], and Shands [27]. In this study, the average change of isobar curvature in the Knoxville vicinity was estimated by a slight modification of a method proposed by Namias and Clapp [18]. Y_a is here defined as the perpendicular distance in degrees of latitude

from the isobar, at a point 10 degrees of latitude downstream from Knoxville, to the tangent line constructed at Knoxville; and Y_b is the same factor for a point 10 degrees upstream. The quantity $(Y_a - Y_b)$ was taken as the change of curvature[4] and considered positive for increasing cyclonic curvature and negative for increasing anticyclonic curvature. In Figure 3

$$Y_a = \overline{AS} \text{ and } Y_b = \overline{BR}, \tag{2}$$

and the quantity $(Y_a - Y_b)$ is negative because the curvature at 0 is becoming less cyclonic.

4. Divergence formula. Namias and Clapp [18] derived the following equation for divergence from Rossby's vorticity theorem.

$$-\mathrm{div}_2 V = \frac{2.29 \times 10^{-7}}{f + (9V/10^6 R)} \times [V \sin\theta\,(10^{-4} \cos\phi) + 1.06 \times 10^{-6} V^2 (Y_a - Y_b)] \tag{3}$$

This formula expresses the horizontal divergence of the velocity vector, V, at a given latitude, ϕ, as a function of the meridional wind component, $V \sin\theta$[5], and the rate of change of curvature along the air trajectory multiplied by the wind speed, given by the term $V^2 (Y_a - Y_b)$. When measuring divergence at a fixed point such as Knoxville, the Coriolis parameter, f, and latitude ϕ are constant. The equation then reduces to:

$$-\mathrm{div}_2 \times 10^7 = 2.67\,[\,0.81\,V \sin\theta + 0.01\,V^2 (Y_a - Y_b)\,] \tag{4}$$

The term containing the radius of curvature, R, has been dropped as negligible as compared to the Coriolis parameter, f. The equation in this form was used to measure divergence for cases behind and ahead of a trough. Near troughs and ridges the wind is always due west by definition, and $\sin\theta$ is therefore 0. The formula was there used in its simplest form:

$$-\mathrm{div}_2 V \times 10^7 = 0.029\,V^2 (Y_a - Y_b). \tag{5}$$

Positive values derived from the above equations indicate convergence; negative values indicate divergence.

---

[4] The average change of curvature per unit distance over the 20-degree arc is actually $0.003\,(Y_a - Y_b)^\circ$ latitude^{-2}.

[5] In Figure 3, θ is considered positive for southerly winds and negative for northerly ones.

5. Local pressure change. This term was introduced as a crude indication of the extent of isallobaric convergence, the significance of which had been first pointed out by Brunt and Douglas [28]. It was obtained by taking the difference between the pressure at Knoxville on the current mean map and its pressure on the mean map a half-week earlier.

6. Trough speed. Petterssen [17] has shown that horizontal convergence depends on the velocity of propagation of the pressure system. Half-week trough displacement in the east-west direction was therefore measured by subtracting the longitude of the trough or ridge line nearest Knoxville on the current mean map from its longitude on the mean map observed a half-week earlier.

D. Indicators of Storm Path

It is commonly observed that the heaviest 5-day precipitation occurs along the mean storm path which prevailed during the 5-day period. It is extremely difficult, however, to define and measure this parameter objectively, especially in the absence of a mean sea level map. The following three approximate indicators of storm path were tested:

1. Confluence ratio. Confluence is a term introduced by Namias [29, p. 19] to describe the process in which air streams of different origin and properties approach each other and flow side by side. Confluence occurs most frequently when a stream of warm air from the south curves anticyclonically alongside a cold cyclonically-curved stream from the north, as shown on the right-hand side of Figure 4. Although confluence is associated with convergent isobars, it does not imply either velocity or mass convergence.

   The importance of confluence in accelerating the zonal westerlies has recently been stressed by Namias [5]. It now appears that confluence is also an important factor contributing to precipitation, primarily because it indicates a region of frontogenesis and one where storm paths tend to concentrate. The close connection between confluence and the prevailing storm path is illustrated on the right-hand side of Figure 4, where the storms converge in a region of marked confluence. The effect of confluence on precipitation can also be explained by Scherhag's divergence theorem, presented by Baum [30], which calls for mass convergence in an area where isobars converge. A more satisfactory explanation is offered by Sutcliffe's [31] analysis of the effect of an increasing temperature gradient on the wind field.

Since confluence usually increases the meridional temperature gradient, it increases the thermal wind vector from west to east and therefore produces an accelerated west wind aloft or an accelerated east wind at sea level. The equations of motion require a non-geostrophic component of the wind at right angles and to the left of the acceleration vector; hence, a circulation is set up such that there is a surface flow of cold air towards warm, with resulting convergence and precipitation, and a reverse flow aloft.

Several measures of confluence were devised. The most satisfactory was obtained by measuring the pressure difference between points five degrees of latitude on either side of Knoxville, measured at right angles to the isobar direction and then repeating this process at a point ten degrees upstream. The ratio of the pressure difference at the station to that upstream was called the confluence ratio. In Figure 3

$$\text{confluence ratio} = \frac{(p_E - p_F)}{(p_G - p_H)} \tag{6}$$

Confluence is indicated with a ratio greater than 1; negative confluence, or diffluence, with a ratio less than 1. Measured in this way, the confluence ratio represents the change of geostrophic wind speed along the path of an air particle. Acceleration means confluence; deceleration, diffluence.

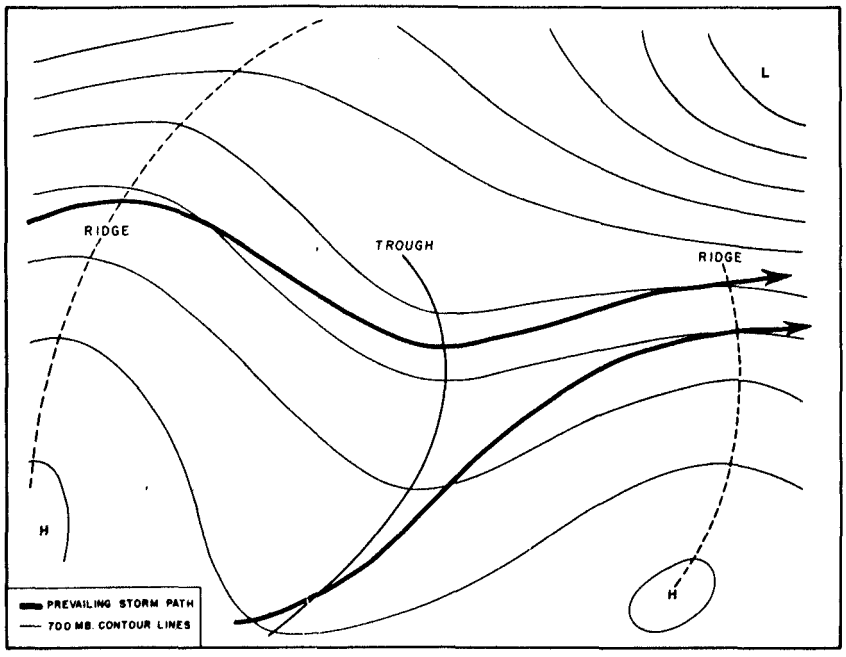


Figure 4.--Schematic 700-mb. contour pattern with principal storm paths.

2. Trough tilt. The horizontal slope or east-west orientation of the trough line was called the trough tilt. For example, the lower portion of the trough line in Figure 4 is oriented from northeast to southwest, whereas the upper portion is oriented from northwest to southeast. Because of the normal west-to-east motion of pressure systems, storms are more likely to move up a trough with the first type of orientation than to move up one with the second type. (This relation of trough tilt to prevailing storm paths is indicated in Figure 4.) The trough tilt was measured by subtracting the longitude where the trough line intersected 36° N. lat. (the latitude of Knoxville) from the longitude where the same trough line intersected 30° N. lat., so that positive trough tilt denoted NE-SW orientation (and H precipitation), and negative tilt indicated NW-SE orientation (and L precipitation).

E. Measures of Local Index

High zonal index is typically characterized, according to results of Namias' investigations [5, 29], by light 5-day precipitation throughout the country, while low zonal index is generally associated with considerable heavy precipitation. This relationship is in agreement with the observation of Kincer [32] that heavy 10-year precipitation in the eastern two-thirds of the United States occurs with relatively high pressures in the north, low pressures in the south, and with the finding of Brier [4] that heaviest Tennessee daily precipitation occurs with surface easterly winds. The meridional, as well as the zonal, index is related to precipitation, as implied in the discussion of the effect of a southerly wind component (earlier in this paper). Several local indices were therefore measured as follows:

1. Wind speed, measured in meters per second by applying a geostrophic wind scale to the map at Knoxville and at a point 10 degrees of latitude upstream; the average of these two speeds was also tested.

2. Perpendicular pressure difference, defined as the pressure difference between points 5 degrees on either side of Knoxville, measured in a direction perpendicular to the isobar passing through Knoxville, and, as such, is exactly equal to the numerator of the confluence ratio described above.

3. Meridional pressure difference, an estimate of the local zonal index, obtained by subtracting the pressure at 40° N. lat. from the pressure at 30° N. lat. Pressures were read at 85° W. long. for cases ahead of and behind the trough; at the trough line for cases near the trough; and at the ridge line for cases near the ridge. If the ridge (or trough) did not exist at both 30° N. and 40° N. lat., the 85° W. long. meridian was substituted for the ridge (or trough) line at the parallel where the ridge (or trough) was missing.

4. Meridional wind component, a measure of the local meridional index, computed by multiplying the geostrophic wind speed at Knoxville by the sine of the angle made with a west-east line by the isobar passing through Knoxville (V sin θ, in Figure 3). Southerly winds were considered positive and northerly winds negative.

F. Measures of Intensity

In daily weather, deep or intense storms usually produce more precipitation than weak systems. Although deep troughs usually have large amplitude, the relation is by no means perfect; hence the relative intensity of storms was here measured solely in terms of pressure by means of two parameters;

1. Absolute pressure, simply read from the map at Knoxville.

2. Relative intensity, measured by subtracting the pressure in millibars at Knoxville from the pressure at the same latitude on the trough line and then dividing by the distance in degrees of longitude between Knoxville and the trough line.

G. Measures of Stability

It is well known that steep lapse rates are favorable for the occurrence of convective showers. Smith [23] points out that the close association between steep lapse rates and cyclonic curvature probably contributes to the correlation between curvature and precipitation. In addition, convective instability has been shown to be an important precipitation-producing factor on a daily basis by Hewson [33], and on a 5-day basis by Namias [6]. Although an evaluation of both absolute and convective stability was therefore desirable, such an evaluation was not possible in this investigation because the requisite knowledge of the temperature and moisture fields could not be obtained from the 10,000-foot map alone, and once information about the temperature field is admitted, the sea level map is automatically defined. In this investigation it was decided to concentrate exclusively upon the mean 10,000-foot map and to reserve the mean sea level map for a later study.

IV. EVALUATION OF PARAMETERS

The relation between precipitation and each of the parameters discussed in the preceding section was studied by the method of graphical correlation. This method, originally introduced by Bean [34] and modified for meteorological application by Brier [4], demonstrates graphically the relation between the dependent variable and two independent variables. For example, in Figure 13, for each of the 35 cases of precipitation near the ridge, distances from the ridge are plotted against pressure differences along the ridge. Dots, circles, or crosses correspond to the H, M, or L type precipitation, respectively, observed in each case. Two curves were drawn to separate as many as possible of the H from the M cases (upper curve) and of the L from the M cases (lower curve). The success with which this segregation can be accomplished is a measure of the importance of the variables plotted as coordinates for precipitation forecasting. Another index of the relative importance of the independent variables is the slope of the curves of separation. When the curves are almost horizontal, and when the range of points along the two axes is approximately equal, as in Figures 11 and 13, the variable plotted as ordinate is more important than the variable plotted as abscissa; the opposite is true when the curves are vertical.

Each of the parameters discussed in the previous sections of this paper was tested and evaluated in this fashion. Dozens of graphs, testing many combinations of parameters, were plotted, but only those few embodying useful or significant relationships have been reproduced in this report. Because of the small number of cases within any one of the four main zones, the drawing of the curves of separation was necessarily somewhat subjective. Within the limits of the data, however, the curves were drawn as smoothly as possible, parallel to one another within any one graph and are believed to represent relationships consistent with physical reasoning. The addition of new data will probably result in slight modification of both the ranking of the independent variables tested and the shape and location of the curves of separation drawn on the graphs.

As an additional aid in evaluating the contribution of each parameter to precipitation, the analysis of variance technique described by Snedecor [35] was used, with slight modification. For each zone, the mean value and standard deviation of every one of the measured parameters were computed for each of the three classes of precipitation, L, M, and H. The variance ratio, F, defined here as the ratio of the variability between the means of the precipitation classes to the variability within the classes, was then used to test the significance of the difference between these means.

Table 2.--Arithmetic means[1] and variance ratios (F) for each precipitation class for each parameter[2] in each zone.

Parameter	Ahead of trough				Rear of trough				Near trough				Near ridge			
	L	M	H	F	L	M	H	F	L	M	H	F	L	M	H	F
A. Measures of position																
1. Distance from trough	7.0	12.4	16.7	2.46+	14.3	15.1	13.5	0.21	0.38	0.54	0.60	0.06	24.9	20.8	27.2	0.95
2. Distance from ridge					30.0	30.0	26.3	0.64	30.8	32.7	34.9	0.61	0.4	1.8	1.2	0.39
3. Relative position	0.24	0.37	0.58	3.30+	0.35	0.32	0.32	0.23								
B. Measures of trajectory																
1. Wind direction	264	258	253	2.70+	290	285	285	1.70+								
2. Amplitude	0.7	2.9	5.8	3.52δ	-13.2	-11.7	-6.5	2.46+	-15.7	-16.8	-11.7	1.37	8.6	8.6	7.7	0.13
5. Direction (24-hr.)					-0.45	-0.33	-0.33	2.71+	-0.40	-0.46	-0.38	0.23	0.44	0.31	0.21	0.83
5. Direction (t-r)	0.10	0.19	0.30	5.62δ	-0.43	-0.37	-0.25	2.87+	-0.44	-0.47	-0.36	0.87	0.30	0.38	0.26	3.09+
6. Origin mixing ratio					1.7	1.8	1.8	1.23	1.7	1.7	1.8	0.16				
C. Measures of convergence																
1. Isobar curvature	0.11	0.11	-0.01	2.51+	0.53	0.31	0.35	2.08+	0.83	0.65	1.07	1.60	-0.71	-0.35	-0.35	2.80+
2. Wind shear	2.0	1.8	1.5	0.15									2.5	1.2	3.0	2.43+
3. Change of curvature	-0.6	-1.4	-1.4	0.13	0.3	0.5	0.7	0.38	-1.3	-1.6	-1.2	0.14	-0.1	0.2	0.3	0.26
4. Divergence formula	-5.8	0.16	3.3	1.04	-10.3	-5.9	-5.6	1.73+	-8.9	-10.1	-6.3	0.30	-4.6	2.3	2.7	2.23+
5. Local pressure change									-2.4	-3.3	-4.2	0.38				
6. Trough speed	-4.0	-2.2	-1.0	0.67									5.6	3.5	1.3	0.30
D. Indicators of storm path																
1. Confluence ratio	1.31	1.31	1.33	0.04	1.15	1.17	1.32	0.57	0.95	1.10	1.03	1.79+	1.17	1.16	1.34	3.73δ
2. Trough tilt	8.5	7.0	6.4	0.11					1.5	2.5	7.7	3.21+				
E. Measures of local index																
1. Wind speed	20.0	18.5	17.5	0.88	19.3	17.4	17.3	1.34	18.2	16.7	17.8	0.20	13.7	14.3	16.5	1.96+
2. Pressure difference (perpendicular)	17.0	14.8	14.3	0.98	14.2	13.6	13.0	0.36	14.5	13.8	14.7	0.20	10.7	10.9	14.4	4.57δ
3. Pressure difference (meridional)	17.0	14.0	13.2	1.39	13.6	13.5	13.3	0.05	14.7	13.8	14.2	0.08	9.8	9.7	13.0	3.96δ
4. Wind component (meridional)	2.1	3.8	4.9	2.30+	-6.2	-4.6	-3.9	2.16+								
F. Measures of intensity																
1. Absolute pressure	699	700	702	1.42									705	704	704	0.30
2. Relative intensity	0.19	0.23	0.27	1.03					0.5	0.4	0.3	0.42				

[1] Means have units appropriate to each parameter.

[2] Parameters are numbered in accordance with numbered sections of Part III of the text.

+ Variance ratio in excess of the 20 percent probability level.

δ Variance ratio in excess of the 5 percent probability level.

The results are presented in Table 2. An asterisk next to an F value denotes that there exist less than 20 chances in 100 that the observed difference between the mean values of the three precipitation classes, for the particular parameter and zone for which that F had been computed, would be obtained as a result of random sampling from a homogeneous population. A double asterisk indicates less than 5 chances in 100 of the same occurrence. Since the number of cases and degrees of freedom were similar in most cases, the F values can be compared directly for an easy, though approximate, rating of the relative importance of each parameter. The F test, however, evaluates only the contribution of each parameter taken singly, while the method of graphical correlation takes account of the joint effect of several parameters in combination and eliminates duplication by parameters which correlate highly with each other. The graphical method was therefore relied upon more heavily in evaluating the independent variables.

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V. RESULTS OF THE EVALUATION

Ahead of the Trough

Results obtained from the graphs drawn for cases in this zone agreed with the figures in Table 2 in showing that the most important group of independent variables was the measures of trajectory, and the second most important, the measures of position. The best measure of trajectory and the most effective single parameter of all those tested was the direction ratio from Knoxville to the point on the trough line with the same pressure (the trajectory direction, parameter B. 5. in Table 2). This parameter had the highest variance ratio of any parameter in any zone and one which exceeded the 1 percent probability level. The best measure of position was the ratio of distance from the trough line to half-wave length, termed the relative position (parameter A. 3. in Table 2).

When trajectory direction and relative position were combined by the method of graphical correlation, the results, while superior to those obtained from either parameter alone, were not appreciably better than the results obtained by graphically combining the other measures of trajectory and position. The simplest measures were therefore used in the graph to be applied in the forecasting routine. In Figure 5, trajectory is expressed by amplitude (parameter B. 2.) and position by the distance from the trough (parameter A. 1.). Ninety-one percent of the cases lying above the curve fell into the H precipitation class, while 71 percent of the cases below the curve were in the M class. Most of the incorrect cases (H below the curve and M above the curve) lie in the lower left-hand corner of the graph, at points close to flat troughs of small amplitude, where determination of exact amplitude is difficult and experimental errors become important. Similarly, all the cases of L precipitation occurred in troughs of small amplitude. Because there were only three L cases in the entire zone ahead of the trough and because these cases occurred in regions where amplitude measurement is inaccurate, no curve of separation was drawn between M and L.

As might be expected from the method of measurement, the two parameters of amplitude and distance are correlated, larger amplitude going with greater distance. The correlation is not perfect, however, and each parameter contributes to precipitation, although both the slope of the curve in Figure 5 and the values of F in Table 2 indicate that the amplitude parameter is more important than the distance factor in governing precipitation. The curve of separation also indicates that, for any given distance from the trough line, there is a certain critical amplitude which

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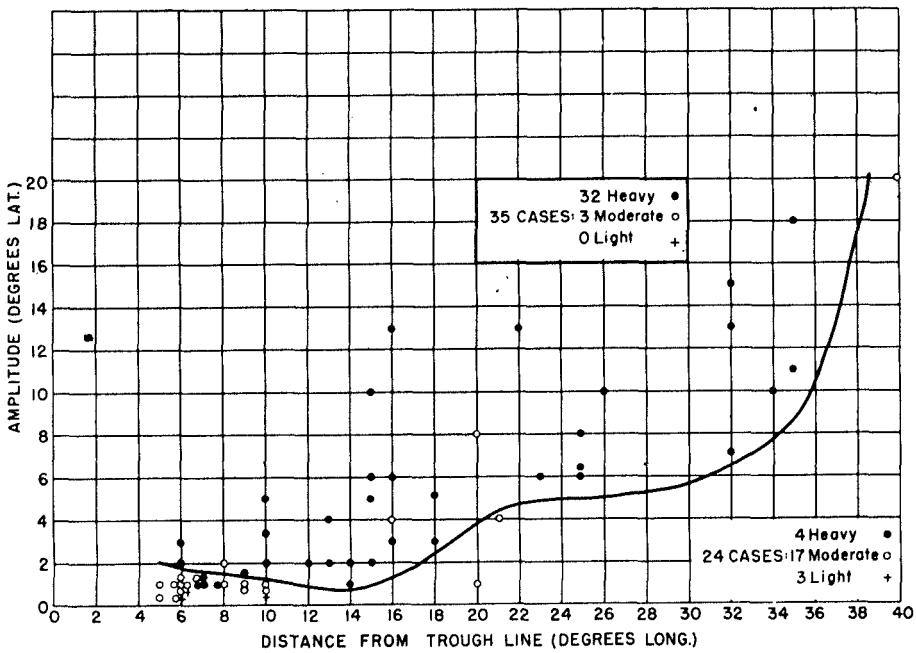

Figure 5.--Precipitation anomaly observed ahead of the trough for given amplitude and distance.

must be exceeded to give heavy precipitation. This critical amplitude appears to be least at a distance of approximately 14 degrees from the trough, where the curve dips to its minimum point. This optimum distance for precipitation is just about half way between the trough and ridge lines for average wave lengths in the eastern United States, or nearly at the point of inflection on the 700-mb. map. It is about 4 degrees ahead of the sea level trough if an average vertical displacement of 10 degrees between the sea level and the 700-mb. trough be assumed.

Other parameters with variance ratios exceeding the 20 percent probability level were isobar curvature (parameter C. 1.) and meridional wind component (E. 4.), but neither of these was used in the forecast procedure. The curvature criterion indicated that more precipitation was associated with anticyclonic than with cyclonic curvature, a result opposite to that expected on the basis of theory, experience, and the results of previous investigators. This was not too surprising, however, because Smith [23] obtained significant coefficients of association between precipitation and curvature at sea level, but not at 10,000 feet, for the entire eastern half of the United States in winter. The meridional wind component followed expected lines, with precipitation amount directly proportional to southerly wind component, but it failed to improve the forecasts prepared from Figure 5, implying that the effect of the meridional wind component is largely one of wind direction--and therefore highly correlated with amplitude--and only slightly one of wind speed.

A few parameters appeared to be somewhat related to precipitation, as shown by scatter diagrams and fairly high variance ratios, but proved of no value in improving the forecasts prepared from Figure 5. Chief among these were the measures of local index, all of which showed a tendency for more precipitation with weaker west winds (low zonal index), in agreement with the findings of Kincer [32], Namias [29], and Brier [4]. The best measure of convergence was obtained by application of the divergence formula (parameter C. 4.); as expected, heavy precipitation was associated with convergence and light, with divergence. It is interesting to note that the full divergence formula (equation 3) tested much better than one of its components, the change of curvature term (parameter C. 3.), but no better than its other component, the meridional wind component (parameter E. 4.). It was concluded that the latter exercises the dominant role within the formula. The relative intensity (parameter F. 2.) tested as expected, with more precipitation associated with deeper troughs, but made no independent contribution because of the high correlation which exists between intensity and amplitude. The absolute pressure (parameter F. 1.), like isobaric curvature, tested oppositely to what had been expected. Cases of high pressure and anticyclonic curvature were characterized by more precipitation than cases of low pressure and cyclonic curvature. This anomalous result may be due to the dominant effect of the Bermuda High and its attendant moist maritime tropical air upon precipitation in the southeastern United States. In general, then, none of these additional parameters improved the forecasts because their effects had already been included in the basic graph. Figure 5 was, therefore, used as the final forecasting graph for cases ahead of a trough, with heavy precipitation forecast for a point falling above the curve and moderate for a point below the curve.

Rear of the Trough

In this zone, as in the zone ahead of the trough, both the graphical and variance tests indicated that the most important variable was trajectory. Unlike the zone ahead of the trough, however, no measure of position showed any consistent relation with precipitation. Instead, the second most significant general parameter for precipitation occurring in the rear of the trough turned out to be the local index. No single parameter within these groups was particularly outstanding, and not one parameter of all those tested for the rear of the trough had a variance ratio in excess of the 5 percent probability level. Various measures of trajectory and local index were combined by the method of graphical correlation, but the results were very similar for all combinations. It was therefore decided to express trajectory simply as wind direction (parameter B. 1.), and local index simply as wind speed (parameter E.1.).

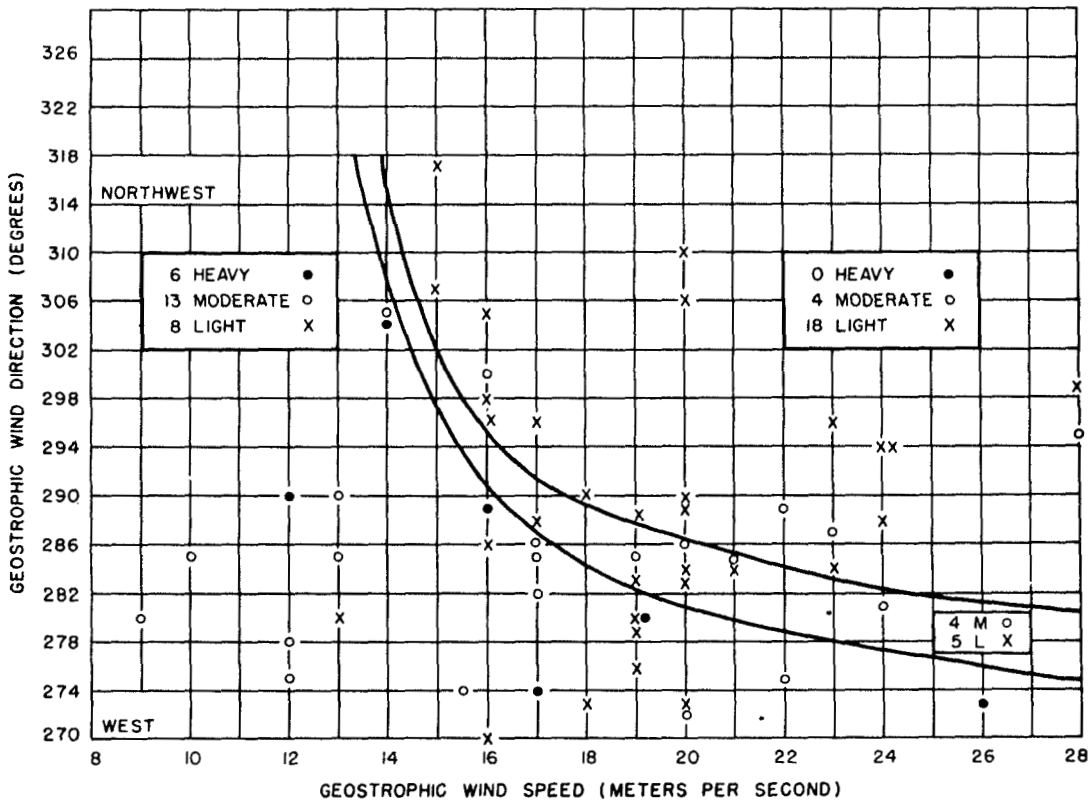

Figure 6.--Precipitation anomaly observed behind the trough for given wind speed and direction.

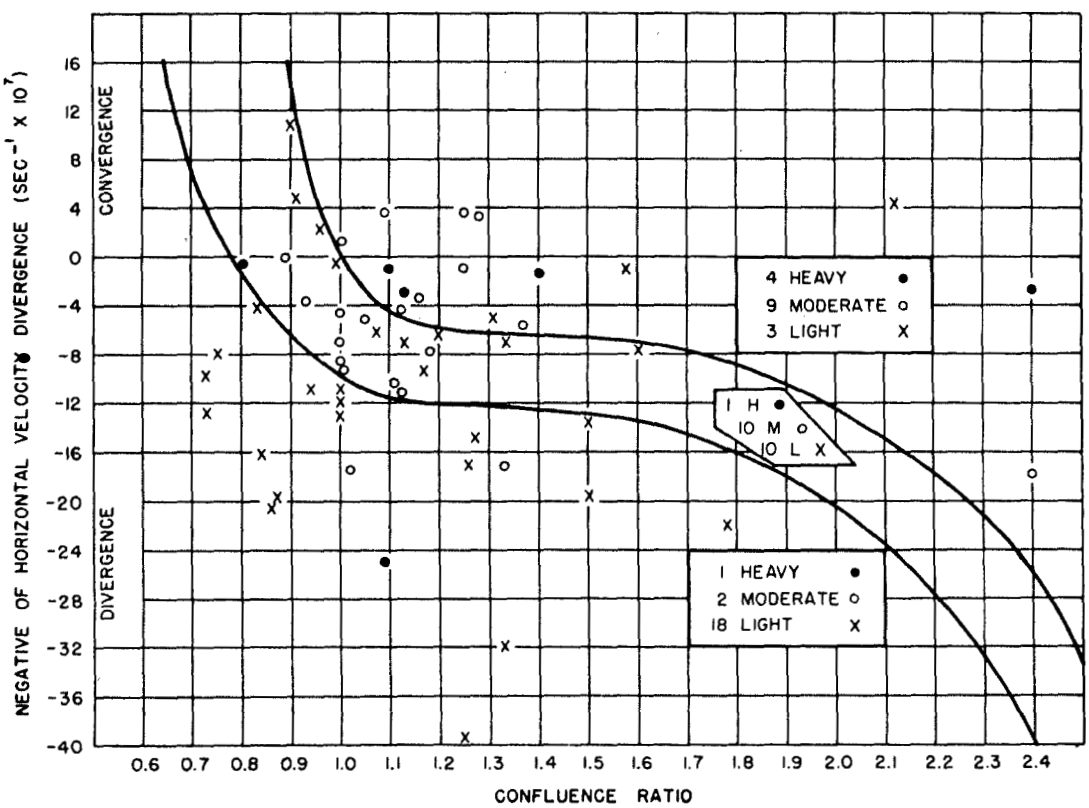

Figure 7.--Precipitation anomaly observed behind the trough for given confluence and divergence.

These factors are combined in Figure 6. The anticipated results associated light precipitation with strong winds (high zonal index) and northerly flow (dryness and divergence). Eighty-two percent of the cases lying above the top curve were in class L, while 48 percent of the cases falling below the bottom curve were M. L and M classes occurred with about equal frequency in the narrow transition zone between the two curves. This was therefore designated as a doubtful zone in which either L or M should be forecast. Neither in this graph nor in any other for the rear of the trough was it possible to separate the six observed H cases from the M cases. It was therefore decided that no forecast of H would be made in the rear of the trough, since it occurred there only about 10 percent of the time.

After trajectory and local index, the next most valuable independent variables in the rear of the trough were convergence, as measured by the divergence formula (parameter C. 4.) and confluence (parameter D. 1.). Figure 7 shows a tendency for H and M precipitation to occur with convergence and confluence, and for L precipitation to occur with divergence and diffluence. Eighty-six percent of the cases below the lower curve in this figure were L, and 56 percent of the cases above the upper curve were M, but a large number of cases (36 percent) fell into the doubtful zone between the two curves. The shape of the curves showed the confluence ratio to be important only in cases of extreme confluence or diffluence. For average values the lines are almost horizontal and confluence contributes very little to precipitation. A similar conclusion is suggested by the variance ratios given in Table 2.

Figures 6 and 7 are combined in Figure 8, which shows that the joint results are superior to those produced by either graph alone. Eighty-five percent of the cases below the lower line were L; 60 percent of the cases above the upper line were M; and only 10 percent of all cases were left in the doubtful zone. Figures 6, 7, and 8 can therefore be used for objective precipitation forecasts in the rear of the trough.

Application of the divergence formula, however, involves some tedious calculation and also some duplication of parameters, since the meridional wind component, $V \sin \theta$, is included in the divergence formula as well as in the wind speed-direction graph (Figure 6). The change of curvature term alone (parameter C. 3.) was therefore tried in place of the computed divergence in Figure 7. The results of this substitution, shown in Figure 9, are considerably poorer than those obtained from the full divergence formula; but they do show a tendency for more precipitation to occur with change of curvature in the cyclonic sense, in accordance with theory. The slope of the curves in Figure 9 indicates that confluence and change of curvature have approximately equal impor-

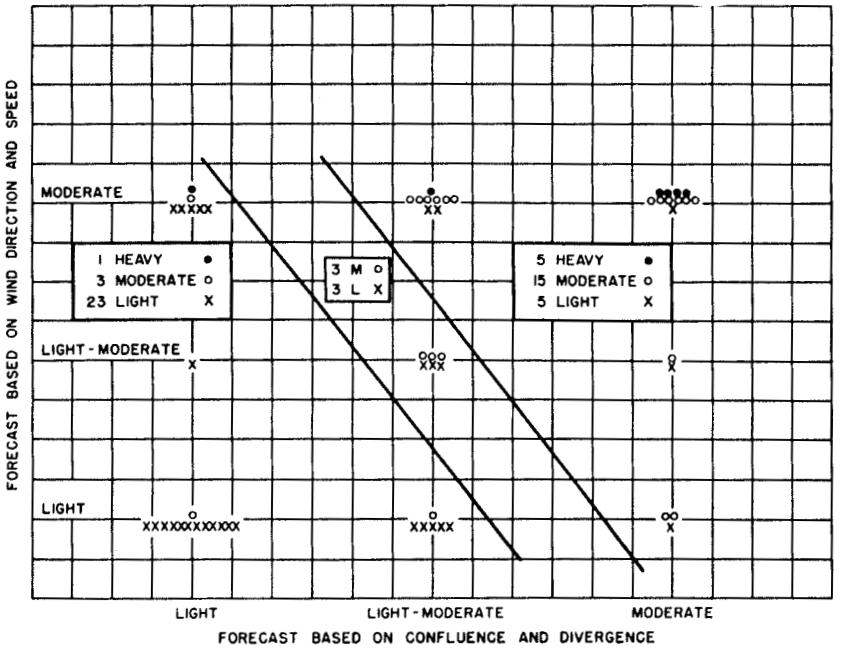

Figure 8.--Result of combining forecasts based on wind speed and direction (Figure 6) with forecasts based on confluence and divergence (Figure 7).

tance in the rear of the trough. Comparison with Figure 6, furthermore, reveals that these factors contribute considerably less to precipitation than either wind direction or wind speed.

Forecasts based on Figure 9 were next combined with forecasts based on Figure 6, with results shown in Figure 10. A marked improvement is apparent. In fact, the distribution of cases in Figure 10 is almost identical with that of Figure 8, making it possible to substitute Figures 6, 9, and 10 for Figures 6, 7, and 8 without loss of forecast accuracy. Since the change of curvature term by itself is easier to handle than the full divergence formula, it is recommended that the former be used in practice.

Several measures of position, trajectory, and intensity, based on the trough downstream from Knoxville, were tested by graphical means, but none were able to improve the forecasts and none tested as well as their analogues based on the ridge upstream. Furthermore, in the rear of the trough, as in the region ahead of the trough, the isobaric curvature term (parameter C. 1.) had a variance ratio greater than the 20 percent probability level, but absolute values were opposed to those expected from physical theory.

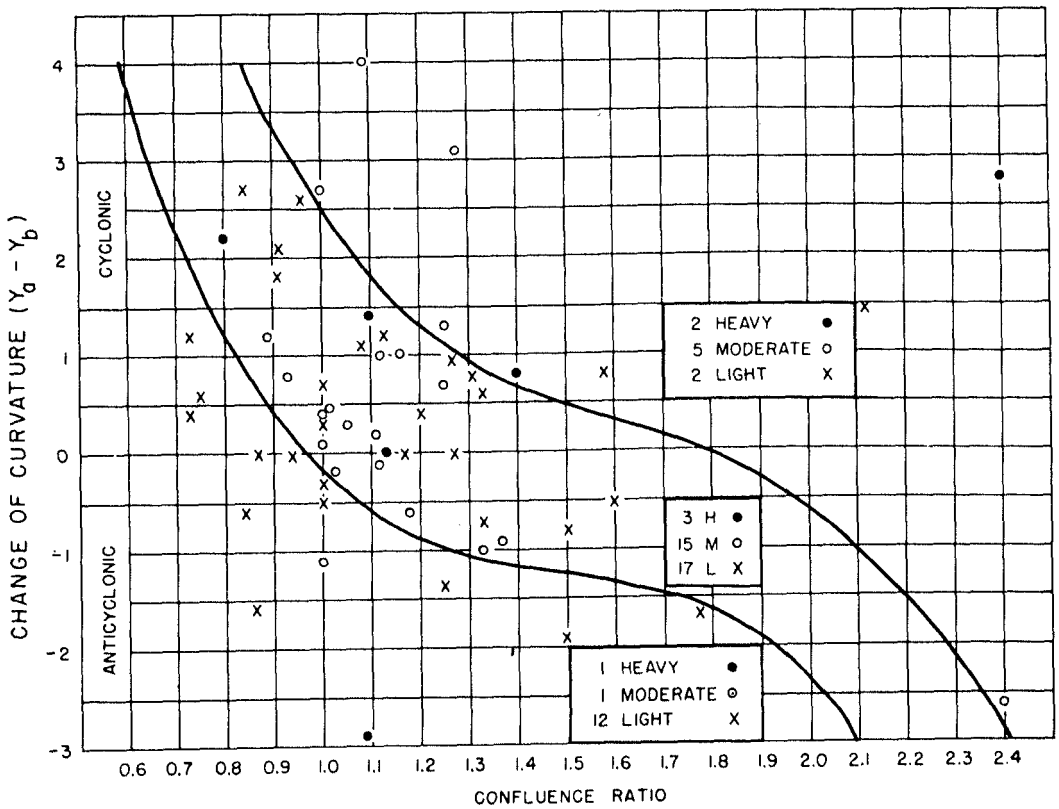

Figure 9.--Precipitation anomaly observed behind the trough for given confluence and change of curvature.

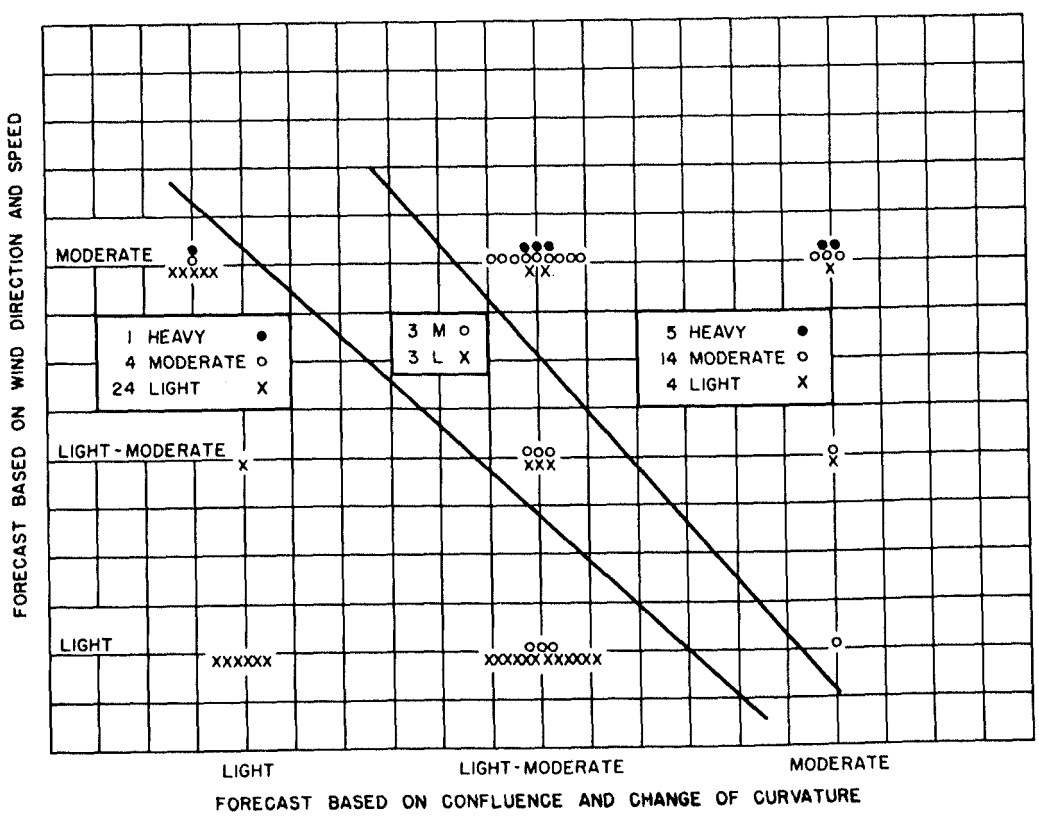

Figure 10.--Result of combining forecasts based on wind speed and direction (Figure 6) with forecasts based on confluence and change of curvature (Figure 9).

Near the Trough

Of all the independent variables tested in this zone, only the indicators of storm path had variance ratios in excess of the 20 percent probability level. The two parameters within this group, confluence ratio (D. 1.) and trough tilt (D. 2.), were too highly correlated with each other to permit them to be combined effectively. The reason for this correlation is evident from an inspection of Figure 4, which shows confluence with positive trough tilt (northeast to southwest) and diffluence with negative trough tilt (northwest to southeast).

All graphical and variance tests pointed to trough tilt as the most outstanding single parameter in cases of precipitation near the trough. Trough tilt was so dominant that it proved very difficult to find any additional variables which would appreciably better forecasts made from it alone. Slight improvement was effected by adding the distance from the trough line (A. 1.), the isobar curvature (C. 1.), and some of the measures of trajectory (Group B parameters). Each of these parameters tested in accordance with theoretical expectations, with more precipitation observed ahead of than behind the trough line, more precipitation with trajectory from a more northerly direction. The graphs, however, offered little basis for a choice among these independent variables.

Figure 11 shows the results obtained by combining distance from the trough line and trough tilt. The fact that the lines are almost horizontal emphasizes the dominant effect of the trough tilt. Seventy-one percent of the cases above the upper curve were of the H class; 72 percent of the cases below the lower curve were L; and 60 percent of the cases in the intermediate zone were M. Forecasts prepared from Figure 11 were improved most notably by combining them with the trajectory direction parameter (B. 5.) based on the ridge upstream. The results of this are given in Figure 12. One hundred percent of the cases falling below the lower line were then H; 79 percent of the cases above the upper line were L; and 67 percent of the cases between the lines were M. Forecasts based on Figure 12 were not appreciably bettered by combining them with the isobaric curvature parameter. Since this factor is also rather difficult to measure accurately, it was not included in the final forecast method, which is based only on Figures 11 and 12 for cases near the trough.

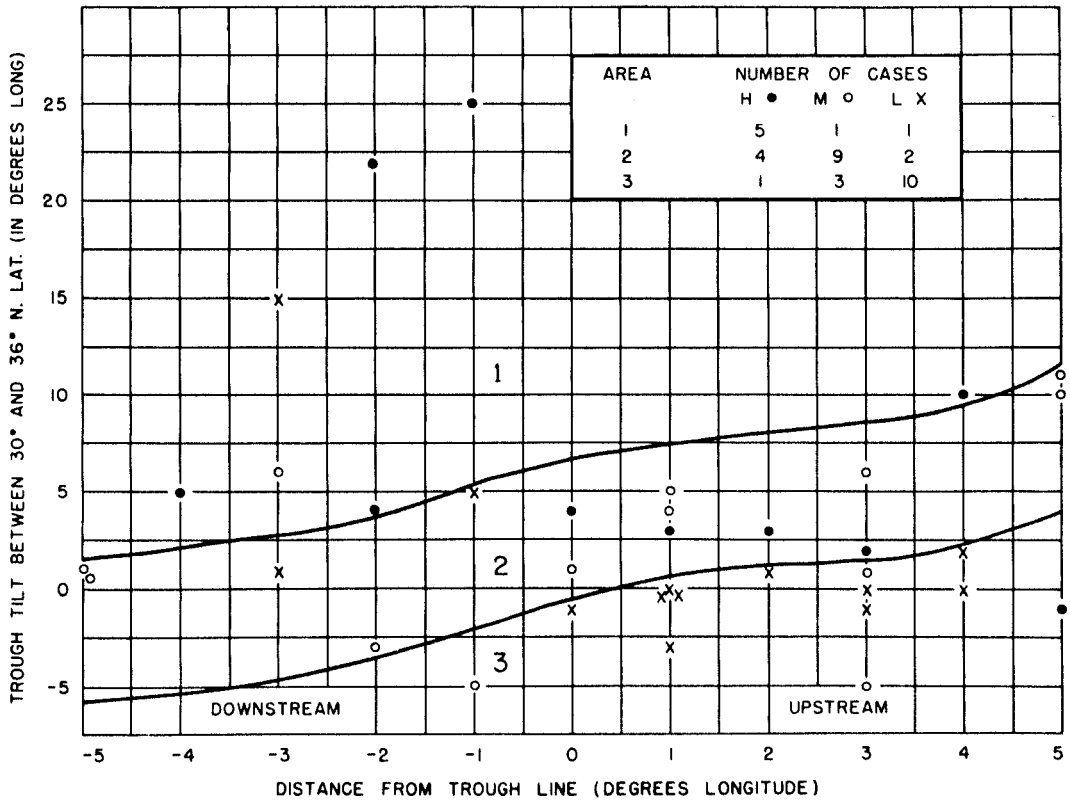

Figure 11.--Precipitation anomaly observed near the trough for given trough tilt and distance from trough line.

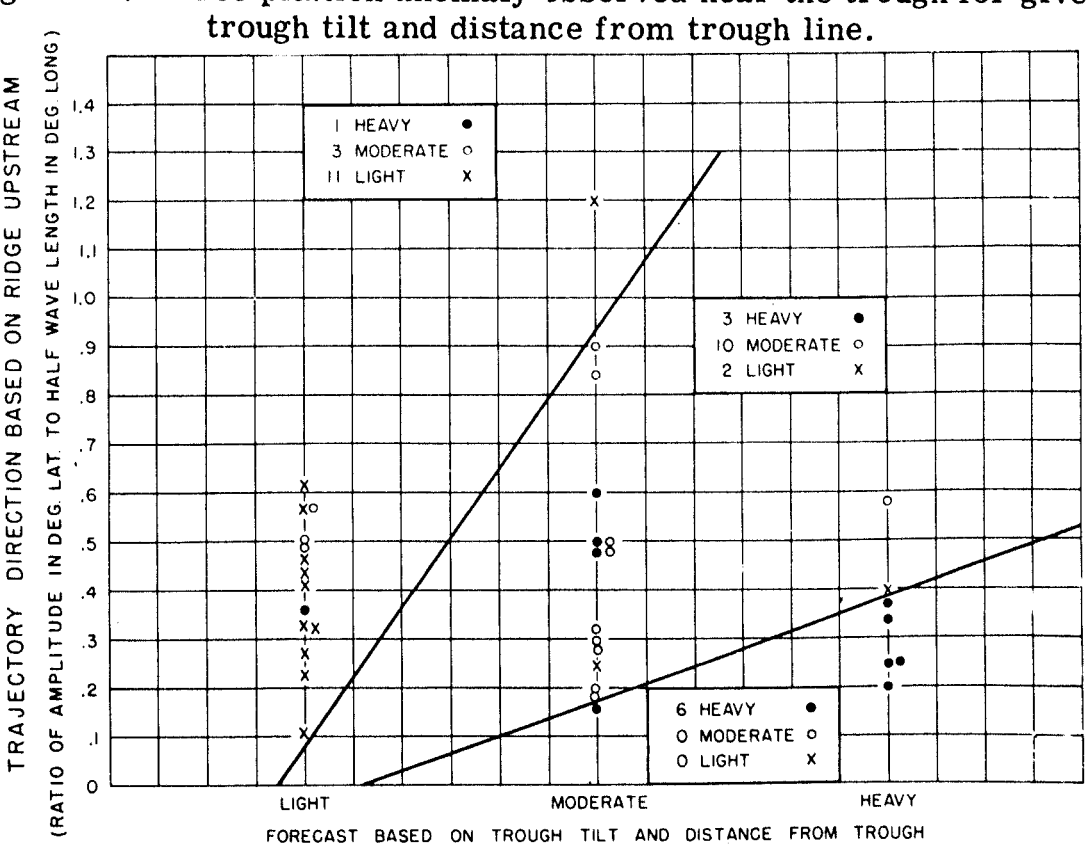

Figure 12.--Result of combining forecasts based on trough tilt and distance (Figure 11) with the trajectory direction parameter.

Near the Ridge

The most important group of parameters in the zone near the ridge was the measures of local index (Group E in Table 2). All these factors, when tested--(1) wind speed, (2) perpendicular pressure gradient, and (3) meridional pressure difference--had variance ratios above the 20 percent probability level, while the last two exceeded the 5 percent level. The fourth measure of local index, the meridional wind component (parameter E. 4.) was not tested because it is approximately zero for all cases near the ridge or trough line (the angle θ is zero for a due west wind).

Table 2 shows that the mean value of each of these measures applied near the ridge was greater (indicating stronger west winds) for H than for L precipitation. In each of the other three basic zones, however, there was a slight tendency for more precipitation to occur with weaker west winds, in agreement with the findings of other authors. The anomalous behavior of the local index term near the ridge is a result of the close relationship existing between local index and the prevailing storm path in the ridge zone. With high local index, strong west winds carry cyclonic activity and moisture all the way across from trough to ridge; whereas a low local index is indicative of an extended ridge or closed high, with a minimum storminess and precipitation, Figure 4 illustrates the approach of storm paths to flat ridges, in the upper portion of the diagram, and the absence of storms in pronounced ridges, in the lower portion.

Little difference was noticeable among the results obtained from the various measures of local index because they are highly correlated with each other near the ridge or trough, where isobars are almost due west-east. The parameter most conveniently measured, the meridional pressure difference (E. 3.), was therefore used for the first forecasting graph, Figure 13, in which is also plotted the distance from the ridge line (parameter A. 2.). Although this latter parameter had a very low variance ratio, it gave useful results when combined graphically with the pressure difference term. Figure 13 clearly shows the dominant effect of the meridional pressure difference, since the curves of separation are almost horizontal. It also indicates, however, that a slight tendency exists for more precipitation to occur west than east of the ridge. Seventy-seven percent of the cases above the upper curve had H precipitation; 100 percent of the cases below the lower curve were L; and 60 percent of the cases in the intermediate area were M.

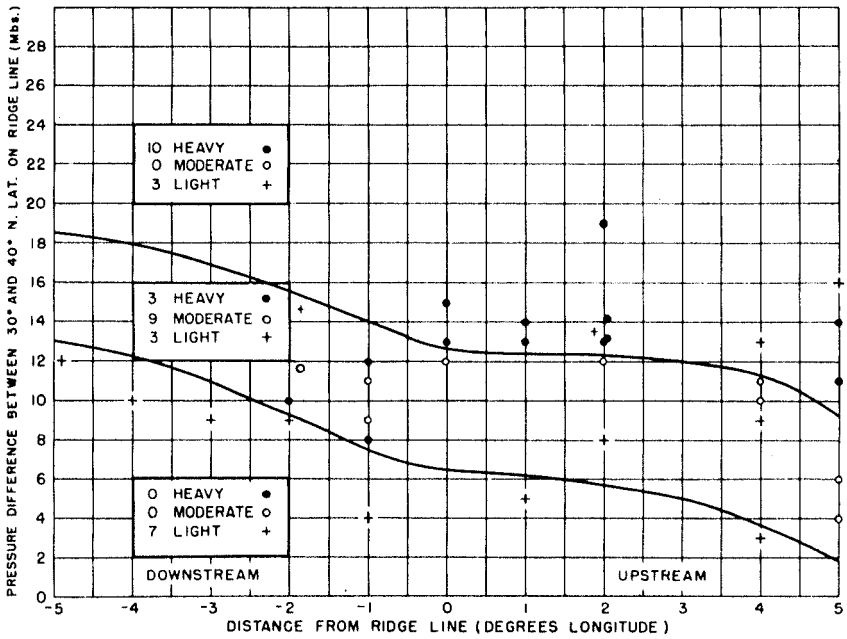

Figure 13.--Precipitation anomaly observed near the ridge for given meridional pressure difference and distance from the ridge line.

The second best parameter for use near the ridge was the confluence ratio (D. 1.). Table 2 shows this parameter to have a variance ratio in excess of the 5 percent probability level and mean values in agreement with theoretical expectations (H with strong confluence, L with weak confluence and diffluence).

After the confluence ratio, the trajectory direction (parameter B. 5.), based on the trough upstream, had the next highest variance ratio. Its absolute values, however, showed less precipitation when the trajectory came from a more southerly direction, just the opposite of the results obtained in the other three basic zones and by other investigators. This exceptional result is probably due to the same factors responsible for the anomalous behavior of the local index term near the ridge, since trajectory direction and local index are closely related in this zone, as can be seen from an inspection of Figure 4.

The only other parameters with variance ratios in excess of the 20 percent level were various measures of convergence. As in each of the other zones considered, the full divergence formula (parameter C. 4.) gave considerably better results than the change of curvature term alone (parameter C. 3.). Because of its wind velocity term (V^2), however, the divergence formula was too closely related to the local index to be of much forecast utility. The value of the wind shear (C. 2.) was

impaired by the fact that more precipitation occurred with anticyclonic than with cyclonic shear, in opposition to theory. The most useful measure of convergence proved to be the isobar curvature (parameter C. 1.). With strong anticyclonic curvature the prevailing precipitation class was L; with weak anticyclonic curvature, H. It is interesting to note that in zones of homogeneous curvature, near the trough as well as near the ridge, the curvature term behaved in accordance with theory and gave fairly good results. No usable results could be obtained, however, when the curvature was considered qualitatively only, i. e., as cyclonic or anticyclonic, or when it was measured in the zones behind or ahead of the trough, where it could be either cyclonic or anticyclonic.

Figure 14 combines the second and third most useful parameters near the ridge--the confluence ratio and the radius of curvature. It is apparent that the curves of separation in this figure do not separate the cases of H, M, and L as effectively as did the first forecasting graph for the ridge zone, Figure 13. Forecasts based on Figure 13 were therefore plotted against forecasts based on Figure 14, with improved results illustrated in Figure 15. Eighty percent of the cases above the upper line fell into the H class, 100 percent of the cases below the lower line into L, and 73 percent of the intermediate cases into M. Since no additional parameter was able to improve the results obtained from Figure 15, it was taken as the final forecasting graph in the ridge zone. In practice, Figure 15 can be replaced by two simple rules, as follows: (1) when the same precipitation class is forecast from both Figures 13 and 14, that class should be the final forecast; (2) when a forecast of M precipitation is obtained from either one of the two forecasting graphs, the forecast obtained from the other graph should be the final forecast.

The means given in Table 2 show that the ridge was typically a zone of confluence (parameter D. 1.) and convergence (C. 4.), whereas the trough was more frequently characterized by diffluence and divergence. This result, together with the fact that air reaching the trough is of more northerly origin and presumably drier than air reaching the ridge, helps explain the surprising equality of precipitation near both trough and ridge in the Tennessee Valley.

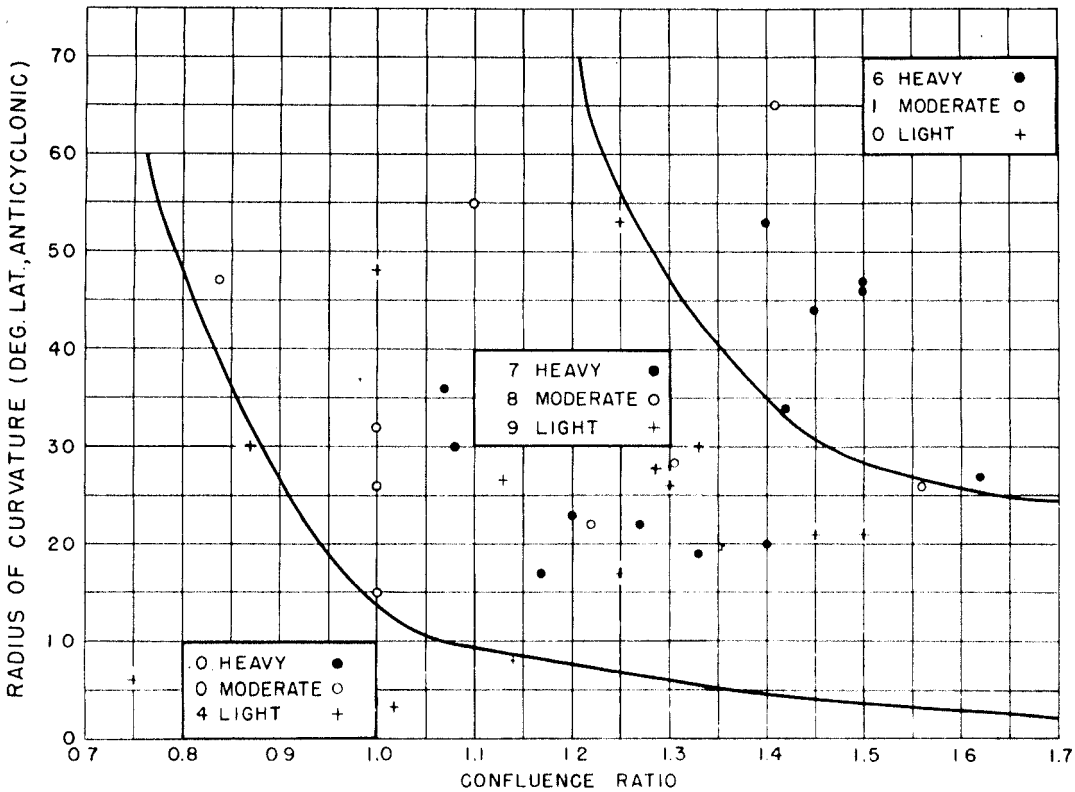

Figure 14.--Precipitation anomaly near the ridge for given confluence ratio and radius of curvature.

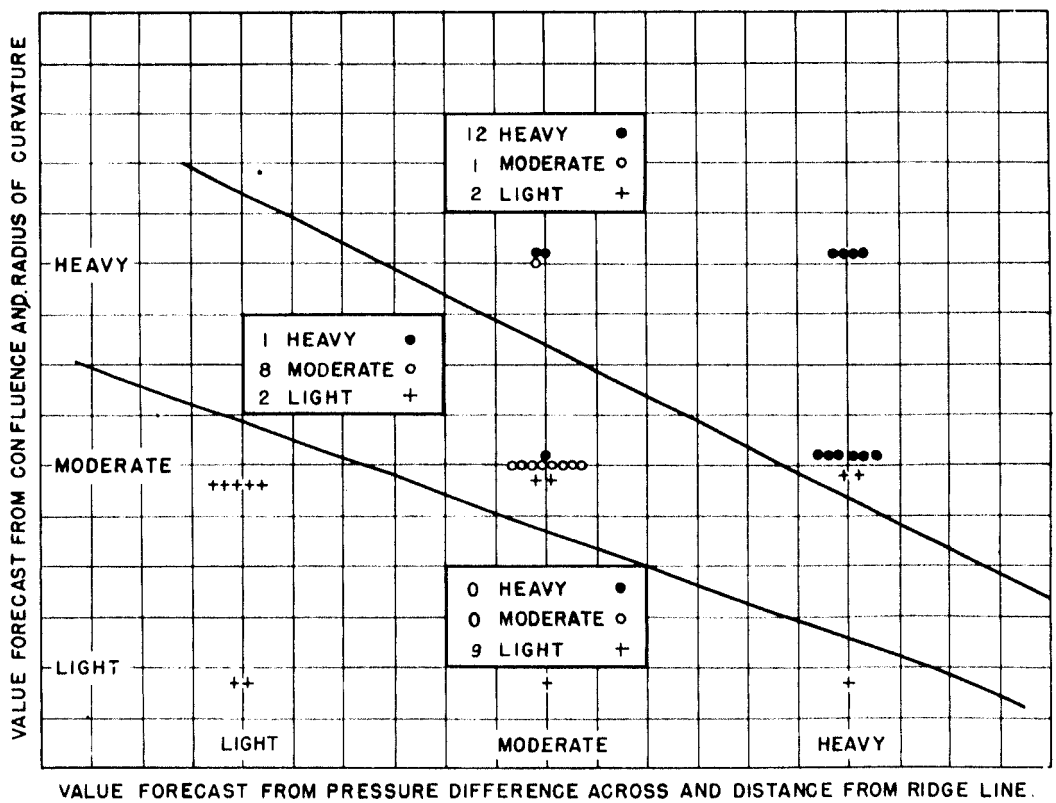

Figure 15.--Result of combining forecasts based on pressure difference and distance from ridge (Figure 13) with forecasts based on confluence ratio and radius of curvature (Figure 14).

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VI. TESTS OF THE FORECAST METHOD

The recommended procedure in preparing an objective precipitation forecast from the mean 700-mb. map is described in detail in Appendix II. The procedure there outlined was applied to both observed and prognostic mean maps to obtain a forecast of precipitation class L, M, or H. The resulting objective forecasts were then compared with a series of official and subjective forecasts and with results obtained from the original data.

To facilitate the comparison, contingency tables were prepared and skill scores computed for each set of test data. The skill score (S) is a forecast verification index, commonly used in the Weather Bureau, which gives a score of 100 for perfect forecasts and 0 for random forecasts. It is computed by the formula:

$$S = 100 \frac{(R - C)}{(N - C)},$$

where R is the number of correct forecasts (0 class error), C is the number which may be expected to be correct by chance, and N is the total number of forecasts[6].

Tests on Independent Data

The objective forecast method was first tested on three different sets of observed mean maps as follows.

1. Twenty-six 5-day mean maps for the period December 1946--February 1947, with verification by average 5-day precipitation anomaly observed in the section of the Tennessee Valley under consideration (Table 3).

2. Forty-three 5-day mean maps for 5 winter months for January 1938--February 1939, with verification by observed Knoxville 5-day precipitation, classified as L, M, or H, according to class limits recently revised by Brier [36] on the basis of 40 years of data (Table 4).

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[6] R is equal to the sum of the cases along the diagonal of the contingency table. C is computed from the margins of the contingency table by summing the product of the marginal totals of each of the three precipitation classes, L, M, and H, and then dividing by the grand total N. The percent forecast correct is defined as $100 \frac{R}{N}$; the percent expected correct by chance is defined as $100 \frac{C}{N}$. For a few cases in the rear of the trough the objective method forecasts either L or M. These were considered as forecasts of 1/2L and 1/2M in the statistical treatment of the data.

3. Twenty-two monthly mean maps for the winter months December 1932 - - December 1939, with verification by Knoxville monthly precipitation, classified as L, M, or H, according to class limits in current use in the Extended Forecast Section (Table 5).

Contingency tables for each of these sets of test data are presented in Tables 3, 4, and 5, respectively, and the results are summarized in Table 6, rows 1, 2, and 3. The objective method tested best (S = 49)in the Tennessee Valley, where forecasts were verified by precipitation at the same 30 stations using the same class limits as the original data. It tested poorest (S = 34) when the forecasts were verified by 5-day precipitation observed at the single city of Knoxville, in the center of the Tennessee Valley.

Table 5 shows that considerably more precipitation was forecast than was observed at Knoxville. It was suspected that this bias was due to the fact that the 6 years of data from which the original Tennessee Valley class limits had been derived constituted an unrepresentative sample of the 40 years of data upon which the Knoxville class limits were based. A comparison was therefore made between the observed Tennessee Valley and Knoxville precipitation anomalies for each 5-day period of the 18 winter months between December 1940 and February 1946. The results are summarized in Table 7. Comparison of the marginal totals and the number of cases above and below the diagonal demonstrates that the 6-year period from which the Tennessee Valley limits were derived, assuming equal probability of occurrence of L, M, and H, were characterized by less precipitation than normal at Knoxville. It is therefore probable that the Tennessee Valley class limits are too low and that the objective method accordingly tends to forecast more precipitation than observed. This bias appeared in all three test series, not only in the comparison of Tennessee and Knoxville precipitation, as is shown by the fact that there are more cases above than below the diagonal in each contingency table (Tables 3, 4, 5, and 7). Table 7 also shows that the Tennessee Valley and Knoxville had the same precipitation anomaly in only 74 percent of all cases compared, while they differed by two classes in 2 percent. About one-fourth of all objective forecasts verified by Knoxville precipitation could therefore be expected to be in error by one class, for this reason alone.

Table 3.---Verification of test forecasts for the Tennessee Valley prepared from observed 5-day mean 700-mb. maps for the winter of 1946-47.

		FORECAST				
		L	M	H	L-M	Total
OBSERVED	L....	6	1	0	1	8
	M...	1	2	4	0	7
	H...	0	1	9	1	11
	Total.....	7	4	13	2	26

Table 4.---Verification of test forecasts for Knoxville prepared from observed 5-day means for 5 winter months in 1938-39.

		FORECAST				
		L	M	H	L-M	Total
OBSERVED	L....	5	5	2	0	12
	M...	1	7	6	1	15
	H...	0	4	12	0	16
	Total...	6	16	20	1	43

Table 5.---Verification of test forecasts for Knoxville prepared from observed monthly means for 22 winter months, 1932-39.

		FORECAST					
		L	M	H	L-M	Indeterminate	Total
OBSERVED	L.....	1	3	0	1	1	6
	M.....	0	7	2	0	1	10
	H.....	0	1	5	0	0	6
	Total.....	1	11	7	1	2	22

Table 6.--Results of verification of all test forecasts

Maps tested	Percent forecast correct	Percent correct by chance	Skill score	Percent	
				1-class error	2-class error
A. Objective forecasts for Knoxville based upon observed mean maps:					
5-day means, 1938-39.....	57	35	34	38	5
Monthly means, 1932-39..	64	37	43	33	3
B. Forecasts for Tennessee Valley, based upon observed 5-day mean maps, winter 1946-47:					
Objective, 700-mb. only....	67	36	49	31	2
Subjective, 700-mb. only...	37	33	5	46	17
Subjective, 700-mb. plus sea level.....	48	32	23	29	23
C. Forecasts for Tennessee Valley, based upon prognostic 5-day mean maps, winter 1946-47:					
Objective, 700-mb. only....	23	33	-14	64	13
Subjective (official), all indications.....	31	32	-1	36	33

Table 7.-Comparison of Tennessee Valley and Knoxville observed 5-day precipitation anomalies, 18 winter months, 1940-46.

		Tennessee Valley			
		L	M	H	Total
Knoxville	L....	36	12	2	50
	M...	11	33	9	53
	H....	1	4	40	45
	Total.....	48	49	51	148

Although the forecast method here tested was derived from 5-day mean maps, it verified quite well (S = 43) when applied bodily to monthly mean maps, as is shown by Tables 5 and 6. In two cases, however, it was impossible to determine in which of the four basic zones (with reference to 10,000-foot isobaric pattern) Knoxville was located, so that no objective forecast could be made. These cases were classified as indeterminable and assumed to be forecast as 1/3 L, 1/3 M, and 1/3 H. Such a breakdown of the forecast method is more likely to occur on monthly than on 5-day mean maps because patterns are flatter and less distinct on the former. The similarity of the test results on monthly and 5-day mean maps lends further support to the conclusion that the relation of pressure patterns to weather is similar, whether taken on a daily, 5-day, monthly, or seasonal basis.

Application to Prognostic Maps

The objective method was next applied to official Extended Forecast Section prognostic 700-mb. 5-day mean maps. The period and area tested and the observed precipitation used in verification were identical with those used in the first test on observed maps, (Test A-1). The results, given in Table 8 and Table 6, row 6, show that all the skill attained by the objective method on observed maps (S = 49) was lost when prognostic maps were substituted (S =-14). This reduction in skill was larger than had been anticipated and may be due, in part, to the abnormality of the 1946-47 winter, described by Namias [37]. Nevertheless, it would appear from these results that objective forecasting of precipitation from 700-mb. prognostic maps alone cannot be of much practical value until the prognostic contour patterns themselves are forecast with much greater accuracy than at present.

Comparison with Subjective Forecasts

Three series of subjective forecasts were verified by average 5-day precipitation anomaly in the Tennessee Valley for December 1946--February 1947, the same data and period used in the first test on observed maps and in the test on prognostic maps. These forecasts were:

1. The official 5-day mean precipitation anomaly forecasts which had been issued twice-weekly by the Extended Forecast Section of the U. S. Weather Bureau.

2. Experimental forecasts made by inspection of the observed 700-mb. 5-day mean maps by one of the official forecasts of that Section.

3. Experimental forecasts by the same individual after inspection of the observed mean sea level map, in addition to the 700-mb. map.

Comparison of the two lines in Table 6, part C. shows that the forecasters of the Extended Forecast Section were more often correct and achieved a higher skill score using subjective methods than when they applied the objective method to the 700-mb. prognostic maps which they had drawn. On the other hand, there were more two-class errors and more bias in the subjective than in the objective forecasts. Analysis of Tables 8, 9, and 10 shows that the subjective forecasts indicated much less precipitation than was observed or was forecast by the objective method. The subjective and objective forecasts agreed completely in only 27 percent of the cases, probably because of the fact that the official forecasters rely heavily on indications, such as the mean sea level map, the last daily map, and persistence and trends in the anomalies themselves, other than the 700-mb. mean prognosis in forecasting the anomalies. It should also be noted that the official forecaster's skill score in this test (S = 1) is lower than might be expected on the basis of past performance (S = 12) for winter precipitation in the entire country [1], probably because of the abnormality of the 1946-47 winter.

Table 8.-Verification of test forecasts for the Tennessee Valley prepared from prognostic 5-day mean 700-mb. maps, winter 1946-47.

		FORECAST				
		L	M	H	L-M	Total
OBSERVED	L....	3	4	1	0	8
	M....	1	1	5	0	7
	H....	2	6	2	1	11
	Total.....	6	11	8	1	26

Table 9.– Verification of official forecasts for the Tennessee Valley, prepared from 5-day mean maps for the winter months 1946-47.

		FORECAST					
		L	M	H	L-M	M-H	Total
OBSERVED	L...	6	1	1	0	0	8
	M...	3	0	2	1	1	7
	H....	7	2	1	1	0	11
	Total....	16	3	4	2	1	26

Table 10.–Comparison of official and objective forecasts for the Tennessee Valley prepared from prognostic 5-day mean maps for the winter months, 1946-47.

		OBJECTIVE				
		L	M	H	L-M	Total
OFFICIAL	L....	4	9	2	1	16
	M...	2	0	1	0	3
	H....	0	1	3	0	4
	L-M..	0	1	1	0	2
	M-H..	0	0	1	0	1
	Total..	6	11	8	1	26

The subjective forecasts from observed mean maps are verified in Tables 11 and 12 and summarized in Table 6, rows 4 and 5. Results are generally similar to the earlier findings of Norton, Brier, and Allen [1]. In both investigations the initial precipitation forecasts (Test 1) were inferior to those made after the observed mean pressures were known (Tests 2 and 3). This again demonstrates the desirability of improving the quality of the prognostic mean maps, regardless of whether anomalies are forecast objectively or subjectively. In both experiments, also, the subjective forecasts were improved by addition of the mean sea level map to the mean 700-mb. map, which resulted in an increase in skill score from S = 5 to S = 23. It seems reasonable to assume, therefore, that the objective method could similarly benefit from addition of the mean sea level map. On the other hand, the addition of the mean sea level map to the subjective forecasting procedure increased the number of two-class errors (from 4 to 6) and introduced considerable bias into the forecasts (Table 12 shows less precipitation forecast than observed). Incorrect interpretation of the mean sea level map may therefore have been responsible for the bias in the official, or subjective, forecasts (Table 9). Table 6 shows that while the objective method was slightly inferior to the subjective method when prognostic maps were used (compare rows 6 and 7), it was definitely superior when observed maps were used (compare rows 3 and 4), even when the subjective method had the advantage of using the mean sea level map (compare rows 3 and 5).

This study had therefore succeeded in its goal of narrowing the gap between circulation patterns and concomitant weather, but it has failed to effect any immediate improvement in the official forecasts. It appears from these results that the objective method of anomaly forecasting from prognostic maps is potentially of great forecast value, but this value will not be realized until the quality of the prognostic maps is considerably improved.

Comparison with Original Data

In Table 13 the results of the three tests on independent data with observed maps (see numbered paragraphs 1, 2, and 3 on pages 35 and 36), comprising 91 cases in all, have been combined and compared with objective forecasts made from the original data from which the objective method was derived. Where 78 percent of the cases were forecast correctly (0 class error) on the original data, only 62 percent were correct on the test data. This reduction in accuracy is due in part to the poor quality of some of the test data (Knoxville, instead of Tennessee precipitation; monthly instead of 5-day mean maps), but is mainly due to the fact that the curves of separation on the forecasting graphs were drawn arbitrarily so as to produce the minimum number of errors on the original data. On the basis of the figures in Tables 6 and 13, objective forecasts from observed maps can be expected to be of the correct precipitation class about two-thirds of the time.

It is of interest to compare the accuracy of the forecast method in each of the four basic zones. Table 13 shows that the zones ahead of the trough and near the ridge tested best on the original data but poorest on the test data, taken collectively. The zone near the trough was best on the test data but third highest on the original data. The greatest reduction in skill from original to test data occurred in the zone near the ridge, where the proportion of correct test forecasts was about 20 percent lower than in any of the other zones.

Appropriate data from 91 test cases were plotted on each of the forecasting graphs. The only graph in which modification of the curves of separation was suggested by addition of this new data to the original data was suggested by addition of this new data to the original data was Figure 14. Figure 16 shows the revised as well as the original curves for this graph, and the new data upon which the revision was based. It will be noted that less precipitation will be forecast from the new curves than from the original ones, which had a definite bias towards forecasting too much precipitation. It is recommended that Figure 16 be substituted for Figure 14 in future application of the objective method.

Table 11.--Verification of subjective forecasts for the Tennessee Valley prepared from observed 5-day mean 700-mb. maps for the winter months, 1946-47.

		FORECAST				
		L	M	H	M-H	Total
OBSERVED	L...	4	2	1	1	8
	M...	1	2	4	0	7
	H...	3	4	3	1	11
	Total....	8	8	8	2	26

Table 12.--Verification of subjective forecasts for the Tennessee Valley prepared from observed 5-day mean 700-mb. and sea level maps for the winter months, 1946-47

		FORECAST				
		L	M	H	L-M	Total
OBSERVED	L...	7	1	0	0	8
	M...	2	2	2	1	7
	H...	6	2	3	0	11
	Total...	15	5	5	1	26

Table 13.--Comparison of objective forecasts, prepared from observed 700-mb. mean maps, on original and test data.

Zone	Percent forecast correct		Percent 1-class error		Percent 2-class error	
	Original	Test	Original	Test	Original	Test
Ahead of trough...	83	63	17	37	0	0
Rear of trough....	71	66	28	32	2	2
Near trough.....	75	68	22	32	3	0
Near ridge.....	83	46	12	39	6	15
All cases.....	78	62	19	35	2	3

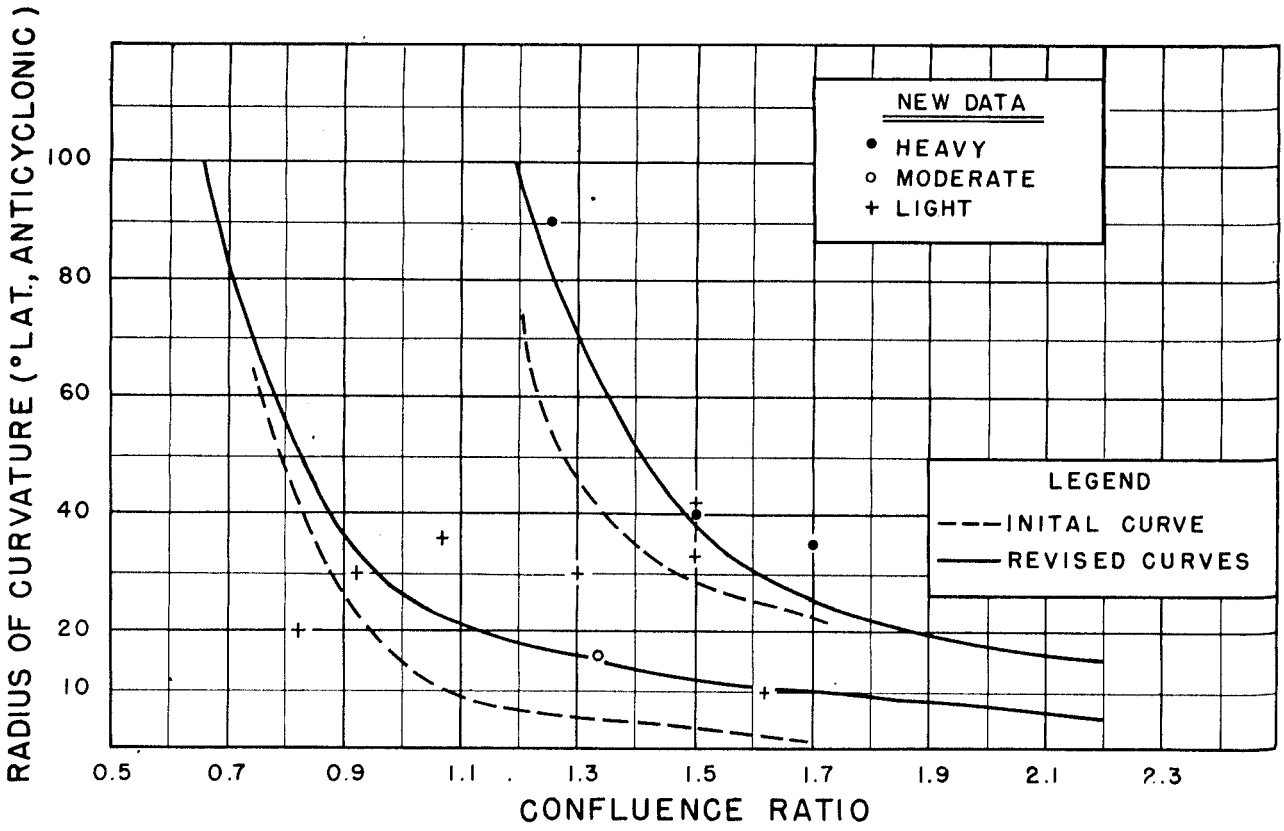

Figure 16.--Revised forecasting graph for precipitation cases near the ridge for given confluence ratio and radius of curvature (see Figure 14).

CONCLUSION

Summary of Results

This study has demonstrated that there are simple measurable parameters by means of which the 5-day winter precipitation anomaly in the Tennessee Valley can be successfully related to the contemporaneous 700-mb. mean map in an objective manner. That conclusion is the most important result of this investigation and constitutes further support for the assertion that the mean circulation pattern, regardless of how it is made up, has a definite physical meaning in terms of actual weather [5, 29].

Although the shape and position of the curves drawn on the various forecasting graphs, and the importance attached to the parameters tested, will probably undergo some modification when additional data become available, it is believed that the following conclusions are valid for forecasting 5-day winter precipitation in the Tennessee Valley. They are also believed to be generally applicable to most of the eastern United States, and to daily and monthly precipitation, though a separate study is undoubtedly required for the western half of the country because of its different climatology and topography.

1. Light (L) precipitation occurs most frequently in the zone to the rear of the 700-mb. trough; heavy (H) precipitation is typical of the zone ahead of the trough; and moderate (M) precipitation is the best forecast for cases near trough and ridge.

2. The most important general parameter determining precipitation is air trajectory; in all zones, except near the ridge, southerly flow is usually associated with H precipitation, westerly flow with M precipitation, and northerly flow with L precipitation.

3. The second most important general parameter is prevailing storm path. It is most effective when expressed as trough tilt for the zones near the trough and as the confluence ratio in all other zones, particularly near the ridge. H precipitation is intimately related to strong confluence and to troughs with northeast-southwest orientation; L precipitation is related to diffluence and to troughs with northwest-southeast orientation.

4. The next most important general parameter is local index. H-precipitation occurs with strong westerlies near the ridge, but with low zonal index (and presumably surface easterlies) in the other three zones.

5. Next in importance are the measures of convergence. Values of convergence computed from the Namias-Clapp divergence formula (equation 3) correlate positively with precipitation amount in all zones. Of the two factors within the formula, the meridional wind component is more closely related to precipitation than to the change of curvature term. The type of 700-mb. contour curvature has little significance for precipitation. The curvature measured quantitatively correlates positively with precipitation near trough and ridge but negatively with precipitation behind and ahead of the trough. Horizontal shear, local height change, and trough velocity appear to have little effect on precipitation.

6. Exact distance from trough or ridge line is of some importance in all zones except to the rear of the trough. Measures of intensity appear to be of little value, and it proved impossible to test measures of stability.

7. Calculation of trajectory origin by including a consideration of the geostrophic wind speed does not give better results than those obtained by neglecting this factor.

8. For any given distance ahead of the trough line, there is a certain critical amplitude which must be exceeded to give heavy precipitation. The optimum distance for H precipitation, regardless of amplitude, is about halfway from the 700-mb. trough to the first ridge downstream.

9. The surprising equality of precipitation near both trough and ridge can be explained in part by the prevalence of confluence and convergence near the ridge and of diffluence and divergence near the trough.

Schematic Precipitation Model

The conclusions listed above have been incorporated into a schematic precipitation model, Figure 17. This diagram can be considered to represent the central part of North America. The upper storm path would then illustrate the motion of "Pacific" and "Alberta" Lows along the northern boundary of the United States, while the lower storm path would be typical of storms originating in the southwestern United States and moving up the Mississippi and Ohio Valleys. The two storm paths converge in the New England area in a region of strong confluence and heavy precipitation.

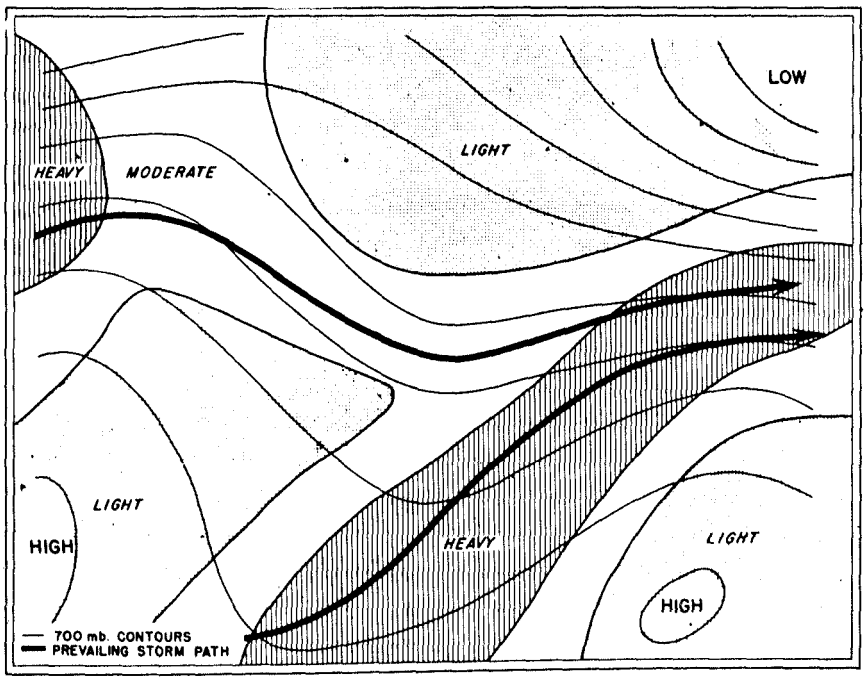

Figure 17.--Winter precipitation model.

An east-west section just below the center of Figure 17 would reveal the average precipitation model illustrated in Figure 2, with H precipitation in the southwesterly flow ahead of the trough, L precipitation in the northwesterly flow behind the trough, and M precipitation in the westerly flow near both trough and ridge. The center of the lower portion of Figure 17 indicates an extensive band of H precipitation near and ahead of a deep trough with northeast-southwest orientation. The left and right sides of the lower portion of the figure show L precipitation throughout an extended ridge and closed high, each characterized by lack of storminess, strong anticyclonic curvature, and weak westerlies.

The upper portion illustrates a large area of L precipitation in a region of strong northwesterly flow to the rear of the trough. Northwesterly flow in the center is characterized by M, rather than L precipitation because the upper storm path passes through the area. Precipitation L and M near the trough with northwest-southeast orientation in the center of the figure should be noted and contrasted with H precipitation in the lower portion of the same trough. There is less precipitation ahead of this trough in the north than in the south because the trough is flat in its northern portion but of large amplitude in the south.

Precipitation H is indicated near the flat ridges in the upper left and middle right sides of the figure, in contrast to precipitation L in the lower portion of the same ridges. The final feature to be noted is the strong confluence on the right-hand side, with resultant convergence of the storm paths and streaking of H precipitation in a narrow band far ahead of the trough and through the ridge.

Application and Improvement

The objective method developed in this study gave correct Tennessee Valley precipitation anomaly forecasts about three-fourths of the time when tested on the original data from which the method was derived; about two-thirds of the time when tested on 5-day and monthly mean observed 700-mb. maps, and about one-fourth of the time when tested on 5-day prognostic 700-mb. maps. Subjective forecasts were slightly superior to objective forecasts when prognostic maps were used but definitely inferior when observed maps were utilized. The practical value of the objective method of anomaly forecasting therefore depends upon the accuracy with which the mean circulation pattern can be prognosticated. At present the principal results of this study can best be applied in a qualitative fashion, but with increasing accuracy of prognostic maps; the objective method will be of great forecast value in a quantitative application.

It is unlikely that the results of this project could be appreciably improved by further study of the 700-mb. map, but some improvement would undoubtedly result from addition of the mean sea level map Most of the parameters used at the 700-mb. level could also be tested at sea level; and relevant information about vertical wind shear, lapse rate, and temperature distribution could be obtained. The improvement, however, would probably not be great because of the occasional occurrence of precipitation from factors not clearly reflected in the mean circulation pattern, and because of observational errors. It is therefore believed that further study along the lines of this project would not be as fruitful as studies designed to improve the accuracy of the mean circulation prognosis.

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APPENDIX I

Recommended Procedure in Preparing Objective Forecast

1. Locate the city of Knoxville (at 36° N. lat. and 84° W. long.) as the reference point from which all parameters are to be measured. The forecast is applicable to the entire area of the east-central section of the Tennessee Valley (Figure 1).

2. Draw the intermediate contour line passing through Knoxville.

3. Decide whether Knoxville is located within five degrees of longitude on either side of a trough or ridge line at 36° N. lat. If it is more than five degrees from the nearest trough or ridge, decide whether it is in the zone of southwesterly flow ahead (east) of the trough or in the zone of northwesterly flow behind (west) the trough. If it is ahead of the trough, go to step 4; if behind the trough, go to step 5; if near the trough, go to step 6; if near the ridge, go to step 7.

4. Ahead of the trough:

   a. Determine the distance from the trough upstream by subtracting 84° W. long. from the longitude of the trough line at 36° N. lat.

   b. Mark the point of intersection of the contour through Knoxville with the first trough line upstream. Subtract the latitude of this point from 36° N. lat. to obtain the amplitude.

   c. Enter Figure 5 with distance from trough as abscissa and amplitude as ordinate. If the point falls above the curve, forecast H; if the point falls below the curve, forecast M.

5. Rear of the trough:

   a. Draw a line tangent to the contour at Knoxville.

   b. Use a protractor to measure the direction of this line. Express the result as geostrophic wind direction from 0° to 360°, calling a west wind 270°.

   c. Measure the geostrophic wind speed at Knoxville in meters per second.

   d. Enter Figure 6 with wind speed as abscissa and direction as ordinate. Tentatively forecast L for a case above the upper curve,

M for a case below the lower curve, and L or M for a case between the two curves.

e. Mark off points on the contour 10 degrees of latitude upstream and downstream from Knoxville. Measure the perpendicular distance in degrees of latitude from each of these points to the tangent line constructed in step 5a. Call the difference between these two distances the change of curvature ($Y_a - Y_b$), positive for increasing cyclonic curvature, negative for increasing anticyclonic curvature. (In Figure 3, $\overline{AS} = Y_a$ and $\overline{BR} = Y_b$.)

f. Subtract the height in feet of the point 5 degrees of latitude to the left of Knoxville facing downstream and going out at right angles to the contour, from the height of the point 5 degrees to the right. Perform the same operation at a point 10 degrees of latitude upstream. Compute the dimension less the confluence ratio, defined as the height difference at Knoxville divided by height difference upstream.

(In Figure 3, confluence ratio = $\dfrac{P_E - P_F}{P_G - P_H}$)

g. Enter Figure 9 with confluence ratio as abscissa and change of curvature as ordinate. Tentatively forecast M for a point above the upper curve, L for a point below the lower curve, and L or M for a point between the two curves.

h. Enter Figure 10 with the forecast based on Figure 6 as ordinate and the forecast based on Figure 9 as abscissa. The final forecast should be M for a case above the upper line, L for a case below the lower line, and L or M for a case between the two lines.

6. Near the trough:

a. Count the number of degrees of longitude from Knoxville to the adjacent trough line at the same latitude. Call the distance from the trough positive when the trough is east of Knoxville, negative when west.

b. Obtain the trough tilt by subtracting the longitude of the trough line at 36° N. lat. from the longitude of the same trough line at 30° N. lat.

c. Enter Figure 11 with distance from trough as abscissa and trough tilt as ordinate. If the point falls above the upper curve, tentatively forecast H; below the lower curve L; between the two curves, M.

d. Mark the point of intersection of the contour through Knoxville with the first ridge line upstream. Subtract 36 degrees from the latitude of this point to obtain the amplitude.

e. Determine the distance in degrees of longitude between the trough line at 36° N. lat. and the ridge line upstream at the same latitude.

f. Compute the trajectory direction by taking the ratio of the amplitude (step 6. d.) to the half-wave length (step 6. e.).

g. Enter Figure 12 with this ratio as ordinate and the forecast based on Figure 11 as abscissa. The final forecast should be H for a case below the lower line, L for a case above the upper line, and M for a case between the lines.

7. Near the ridge:

a. Count the number of degrees of longitude from Knoxville to the adjacent ridge line at the same latitude. Call the distance from the ridge positive for a ridge to the east, negative for a ridge to the west.

b. Subtract the height (in feet) on the ridge line at 40° N. lat. from the height on the ridge line at 30° N. lat. If the ridge does not exist at both 30° N. lat. and 40° N. lat., substitute the 85° W. long. meridian for the ridge line at the parallel where the ridge is missing. Divide the 700-mb. height difference by 37.5 to express it as a 10,000-foot pressure difference.

c. Enter Figure 13 with distance from ridge as abscissa and pressure difference as ordinate. Tentatively forecast H for a point above the upper curve, L for a point below the lower curve, and M for a point between the two curves.

d. Measure the radius of curvature of the contour at Knoxville in degrees of latitude.

e. Compute the confluence ratio, exactly as in step 5. f.

f. Enter Figure 16 with confluence as abscissa and radius of curvature as ordinate. Tentatively forecast H for a point above the upper solid curve, L for a point below the lower solid curve, and M for a point between the solid curves.

g. Enter Figure 15 with the forecast from Figure 13 as abscissa and the forecast from Figure 16 as ordinate. The final forecast should be H for a case falling above the upper line, L for a case below the lower line, and M for a case between the lines.

APPENDIX II

Quantitative Precipitation

The body of this report dealt with forecasts of precipitation anomalies only; this appendix will present the results of an effort to forecast absolute precipitation amount on a quantitative basis.

The same maps, precipitation data, and measurements used in the main study were used in this supplementary investigation. Within each of the first five groups of parameters studied (see Section II), the two best individual parameters were selected on the basis of the results discussed in Section IV. Simple linear correlation coefficients were then obtained between each of these parameters, measured on the mean 10,000-foot map, and the contemporaneous 5-day precipitation amount, averaged over the east-central section of the Tennessee Valley during the winter months from 1940 to 1946. The results are given in Table 14.

Comparison of the magnitude of the different correlation coefficients substantiates the earlier evaluation of the parameters made on the basis of graphical and variance tests. For example, near the trough, trough tilt was again outstanding, while near the ridge the meridional pressure difference had the highest correlation coefficient. As before, trajectory was the best general parameter both behind and ahead of the trough. It is noteworthy that both convergence (measured by the divergence formula) and confluence (measured by the confluence ratio) correlated positively with precipitation amount in all zones. The correlation coefficients for all cases, regardless of zone, were 0.32 for convergence and 0.23 for confluence. As expected, isobaric curvature was positively correlated with precipitation near trough and ridge but negatively correlated in the zones behind and ahead of the trough. The correlations are also in agreement with earlier conclusions in showing more precipitation with more southerly trajectory (parameter B. 5.) and with lower zonal index (parameter E.3.) in all zones except near the ridge. Finally, it should be noted that the meridional wind component had the second highest correlation coefficient of any parameter ahead of the trough (0.50) and the third highest in the rear of the trough (0.29). These coefficients are in good agreement with a correlation coefficient of 0.48 obtained by Winston [14] between precipitation and meridional wind component, measured during each 5-day period of December 1945 at 25 points in the eastern half of the United States.

Table 14.--Linear correlation coefficients between 5-day precipitation amount in the Tennessee Valley and various parameters[1] measured on the contemporaneous 10,000-foot mean map.

Parameter	Ahead of trough	Rear of trough	Near trough	Near ridge
A. Measures of position:	.14	.05	-.14	.02
1. Distance from trough.....	.14	.05	-.14	.02
2. Distance from ridge.....		-.15	.06	.16
B. Measures of trajectory:				
2. Amplitude.....	.29	.32	.24	.03
5. Direction (t-r).....	.54	.38	.14	-.03
C. Measures of convergence:				
1. Isobar curvature.....	-.21	-.23	.07	.28
4. Divergence formula.....	.17	.23	.09	.43
D. Measures of storm path:				
1. Confluence ratio.....	.05	.16	.22	.27
2. Trough tilt.....	-.15		.44	
E. Measures of local index:				
3. Pressure difference (meridional).....	-.34	-.04	-.12	.44
4. Wind component (meridional).....	.50	.29		

[1] Parameters are named and numbered in accordance with classification in Section III of text.

An attempt was made to combine the different parameters by means of linear multiple regression equations. In each zone, however, after the best single parameter had been used, no additional parameter was able to account for any more of the precipitation variation than would have been expected on the basis of chance alone. The most useful equations for predictive purposes are therefore the simple linear regression equations given below:

Ahead of trough:	$A = 3.06D + 0.45$
Rear of trough:	$A = 0.71D + 0.58$
Near trough:	$A = 0.05T + 0.43$
Near ridge:	$A = 0.08P - 0.16$

A is the total 5-day precipitation amount in inches; D is the trajectory direction based on the trough or ridge upstream (parameter B.5.); T is the trough tilt (parameter D.2.); and P is the meridional pressure difference (parameter E.3.).

The simple linear correlation coefficients given in Table 14 show that none of the above equations accounts for more than about one-fourth of the variability of 5-day precipitation. Increased forecast accuracy can be achieved only through consideration of curvilinear relations among the independent variables, by either graphical or statistical methods. However, the present-day accuracy of prognostic maps does not justify the labor that would be required for derivations of such curvilinear relations for absolute precipitation amount.

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