QUANTITATIVE ANALYSIS AND FORECASTING OF WINTER RAINFALL PATTERNS

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[Manuscript received November 29, 1955; revised March 9, 1956]

ABSTRACT

A method is given for analysis of current rainfall intensity distribution and for preparation of short-period quantitative rainfall distribution forecasts using practical synoptic techniques. The analysis procedure is justified by a formulation which gives the condensation rate associated with the horizontal transport of saturated air through a stationary temperature field. The forecast procedure in addition utilizes (1) short-period extrapolations of the fields of moisture, motion, and temperature, (2) volumetric inflow of moisture in depth northward across a fixed boundary near the Gulf Coast as an approximation of the total rainfall during the forecast period, or when this is not applicable, the volume indicated by the moisture-depletion formulation, (3) envelopment of the initial and terminal period boundaries of moisture depletion to define the boundaries of the forecast pattern, (4) position of the maximum moisture advection to forecast the rainfall center, and (5) isohyetal analogues to fill in details of the pattern, particularly the orographic details which have not been treated otherwise in the present application. The results of a systematic test of forecasts using these ideas are also presented.

1. INTRODUCTION

One of the basic problems in hydrometeorology is the quantitative definition of rainfall distribution in terms of other meteorological parameters. Good correspondence between observed and computed rainfall patterns has been obtained by simultaneous treatment of the fields of motion, moisture, and temperature for each sub-layer of a multi-layered atmosphere. Thompson and Collins [1] used the vertical velocities obtained by divergence computations at 50-mb. intervals to compute the precipitation rate. Spar [2] also used 50-mb. intervals to obtain "integrated moisture transport vectors" for computing the rainfall rate. An approach suitable for high-speed numerical computations has been reported by Smagorinsky and Collins [3]; it was applied to a 3-level model of the atmosphere.

Another approach is to relate the rainfall rate directly to the transport of moisture through a single deep layer. This has been done analytically for the case of high orographic barriers in [4], [5] and other reports. Benton and Estoque [6] in a climatological-hydrologic study of water-vapor transport in the 1,000- to 400-mb. layer for the calendar year 1949 show a good relationship between monthly and seasonal transport patterns and precipitation.

The feasibility of simple dynamic treatment of moisture in depth for estimating the volume rate of rainfall for short-time periods was demonstrated by an experiment conducted in the Hydrometeorological Section in 1954 [7]. The instantaneous rate of northward mass transport of water vapor between the surface and 400 mb. across the Gulf Coast was computed once daily for two winter months. Assuming the instantaneous transport rate to persist for 24 hours, the 24-hour moisture transport for high inflow rates was found to be about equal to the observed 24-hour volume of rainfall measured over the area downwind from the inflow boundary the next day (fig. 1).

The present study was initiated in an effort to forecast the pattern and area of occurrence of the rainfall volume indicated by the Gulf inflow rate. The approach is to treat the precipitable water and thickness fields through a single deep layer in the lower troposphere with the motion indicated by the height contours at the middle of the layer. It has been used both for the determination of the current distribution of the rainfall rate, and for quantitative forecasts of rainfall patterns. Although the method is more restrictive than [3], for example, it seems especially useful for short-period forecasts of heavy, general, winter-type rainfall, and is simple enough for practical day-to-day use by conventional synoptic methods.

The point of departure in attacking this problem is given by the fact that warm air advection is very often observed upwind from and within the areas of general rainfall occurrence. (See, for example Appleby [8] and Means [9].) Temperature advection will concern us here, however, only as it is related to the horizontal advection of moisture. Our first purpose is to determine whether the condensation rate, which would seem to be necessarily associated with the apparent cooling of deep layers of saturated air in transport through a field of decreasing temperature, is reflected in the rainfall intensity distribution.

In section 2 of this paper a formulation relating hori-

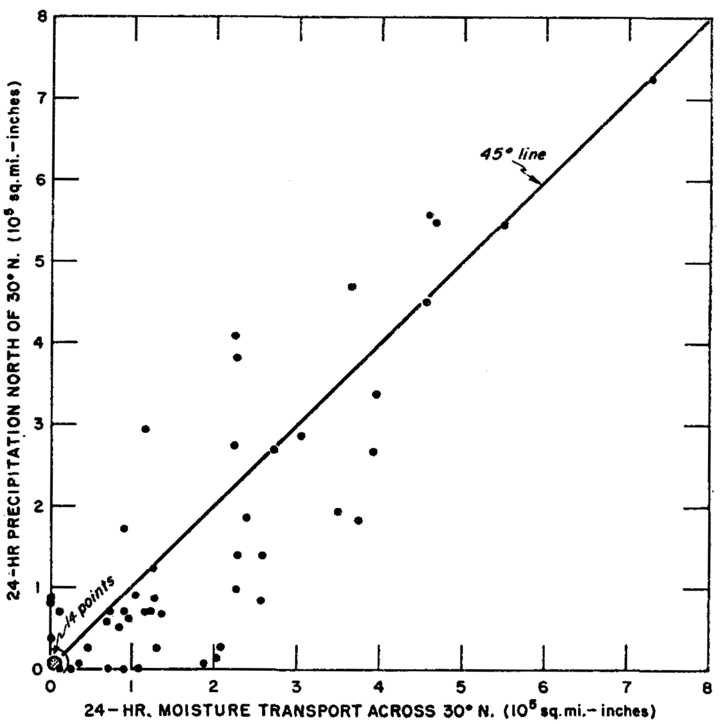

FIGURE 1.—Transport of moisture across 30° N. between longitudes of Tallahassee, Fla., and San Antonio, Tex., from surface to 400-mb. level (assuming 1500 GMT rate is maintained 24 hours) plotted against observed precipitation, during 24 hours beginning at 0630 CST of day moisture-transport measurement was made, measured downwind from the San Antonio-Tallahassee baseline.

zontal moisture transport to the rainfall rate is developed from simple physical and synoptic ideas. For practical synoptic application certain simplifying approximations and assumptions are required. These have not been tested intensively; instead, their validity as a set has been evaluated by the preparation of a series of rainfall rate analyses (section 3) and short-period forecasts (section 4).

2. MOISTURE TRANSPORT RELATED TO RAINFALL RATE

The distribution of rainfall is basically dependent on the transport and condensation of moisture. Thus, for a comprehensive treatment of rainfall it is necessary to relate moisture, temperature, pressure, and motion, at all levels in the atmosphere. A less comprehensive but still useful treatment is possible under certain simplifying assumptions.

ASSUMPTIONS

The rainfall rate can be related to moisture transport in a simple and convenient way with the following assumptions:

(1) To circumvent the difficulty of treating moisture layer by layer, precipitable water through a single deep layer in the lower troposphere is assumed to be an appropriate moisture variable. Moisture in depth (precipitable water) as related to rainfall intensity, is discussed extensively by Showalter [10], [11], [12], [13] and in reports of the Hydrometeorological Section [14], [15]. The selection of precipitable water as the moisture variable in this study has the further advantage that the horizontal distribution of precipitable water may be conveniently expressed in terms of thickness, the use of which is already well established in synoptic practice. The precipitable water is related to the thickness (mean virtual temperature of a layer between isobaric surfaces) by conversion to "saturation thickness". This is defined as the thickness between the specified constant pressure surfaces of a saturated pseudoadiabatic column having the same precipitable water value as the observed column. Tables 2 and 6 of "Tables of Precipitable Water" [16] provide the required values; table 2 gives the integrated values and increments of precipitable water for the various pressure intervals and height intervals, while table 6 gives the pressure-height values for a saturated atmosphere. Since the formulas on which the tables are based are simple and well-known [17, 18], we shall omit the thermodynamic theory and use the tabular values directly.

The relationship between saturation thickness and precipitable water for a saturated layer between 1,000 and 700 mb. is shown in table 1.

(2) An area of general, heavy, winter-type rainfall is assumed to occur within an area overlain by a deep saturated layer, that is, a layer whose observed thickness is approximately equal to the saturation thickness.

(3) Thickness lines in saturated areas are assumed to be fixed over the area for the duration of general rainfall. In a preliminary experiment, the 12-hour thickness change at all radiosonde stations where rainfall was continuous between soundings was tabulated for two winter months. In these cases it was found that despite strong warm advection, the average thickness change was about what would be expected from the standard observational error. Spar [2] and Locklear [19] also made this assumption for the computation of the rainfall rate.

(4) The transport of moisture through the deep layer is proportional to the geostrophic wind at the middle of the layer. In synoptic practice it is often assumed that the vector mean value of the horizontal motion at the base plus that at the top of an isobaric layer gives the mid-layer motion—the basis of differential analysis methods for interpolating a mid-layer surface contour field. Conversely,

TABLE 1.—*Thickness as a function of precipitable water in a saturated pseudoadiabatic column between 1,000 mb. and 700 mb. (Smoothed values). (Computed from tables 2 and 6 [16].)*

Precipitable water (inches)	Saturation-thickness (feet)	Precipitable water (inches)	Saturation-thickness (feet)
2.032	10,100	.499	9,300
1.734	10,000	.406	9,200
1.474	9,900	.328	9,100
1.248	9,800	.263	9,000
1.052	9,700	.211	8,900
.882	9,600	.171	8,800
.735	9,500	.142	8,700
.608	9,400		

it may be assumed that the mid-layer motion approximates the net motion of air through the layer. We are more concerned, however, with the approximation for moisture transport through a layer. A test was performed with data from the Gulf water vapor transport study. The following ratio was obtained for the northward component of moisture transport between two radiosonde stations: the sum of the moisture transport for the 1,000- to 700-mb. and the 700- to 400-mb. layers, divided by the product of the average precipitable water 1,000- to 400-mb. and the transport at 700 mb. The ratio was found to be close to unity for the higher transport values.

(5) Vertical moisture transport, other than that implied by the nonmovement of thickness lines in the rain areas (see assumption 3), is ignored in this formulation. Investigations of the local intensification of the vertical motion and associated rainfall by differential temperature advection, have been reported by Gilman [20], Appleby [8], and Miller [21].

(6) For convenience the variation of the Coriolis parameter and the effect of changes in spacing of contours of the mid-layer pressure surface will be neglected. These simplifications will not introduce appreciable error so long as actual computations are made for small increments of area.

Under the above assumptions a simple expression for the moisture transport can now be derived and related to the rainfall rate.

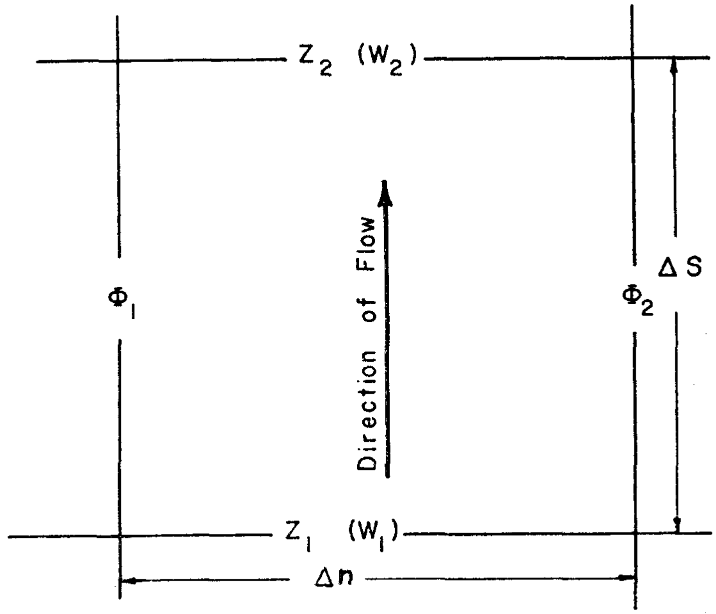

FIGURE 2.—Grid element of thickness and height contours in a saturated region. Z_1, W_1 and Z_2, W_2 are thickness and precipitable-water values at the inflow and outflow boundaries of the element, respectively. The geopotential heights, ϕ_1 and ϕ_2, are the geopotential height contours bounding the grid element. Since the region is saturated, Z defines the value of W. The symbols Δs and Δn are the distances between the thickness lines and the height contours, respectively. Also $\phi_2 > \phi_1$ and $Z_1 > Z_2$, conditions for condensation of moisture by horizontal advection (assuming no supersaturation).

MOISTURE TRANSPORT

Consider the case of a saturated layer, stationary temperature field, and horizontal geostrophic motion. Since, as table 1 shows, the thickness specifies the precipitable water value, the instantaneous moisture transport across a boundary in the saturated area is specified, under our assumptions, by superimposing the thickness field and the pressure contours at the middle of the layer. Thus, the moisture transport M across the segment of a thickness line Z that is intercepted by two adjacent contours of geopotential ϕ_1 and ϕ_2, with a spacing Δn, is given by

$$M = V_g W \Delta n \qquad (1)$$

where W is the precipitable water defined by the saturation thickness Z, and V_g is the geostrophic wind speed

$$V_g = \frac{1}{f} \frac{\phi_2 - \phi_1}{\Delta n} \qquad (2)$$

Equations (1) and (2) therefore give the following simple expression for the moisture transport:

$$M = \frac{1}{f} (\phi_2 - \phi_1) W \qquad (3)$$

The moisture transport as given by equation (3), though indicating the volume rate of rainfall (e. g., fig. 1), does not by itself specify the location or size of the area of rainfall occurrence. However, equation (3) can be used to obtain a convenient expression for moisture advection, which under the assumptions of this paper is proportional to rainfall rate.

RAINFALL RATE

Consider the condensation process for the limiting case of a saturated layer, stationary temperature field, and horizontal geostrophic motion. The difference between the moisture transport at suitably selected inflow and outflow boundaries, that is the moisture advection, is determined by the temperature advection. Where initially saturated air columns are moving into regions of lower temperature, water vapor must be condensed out (assuming no supersaturation); and where they are moving into warmer regions, the water-vapor capacity of the columns is increasing, thereby inhibiting the condensation process. This study is chiefly concerned with moisture depletion, that is, with moisture advection in saturated air associated with warm temperature advection.

In general, measurement of the moisture advection is not a simple computation. (See e. g., Spar. [2].) For the special case of saturated air with geostrophic motion, however, the indicated warm temperature advection pattern represented by the superposition of the thickness field and height contours at the middle of the layer gives a ready

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means of computing the moisture depletion (moisture advection) and the associated rainfall, as now will be shown.

Consider a small rectangular area bounded by a pair of thickness lines and a pair of contours for an isobaric surface at the middle of the deep saturated layer, with the flow directed in the sense of warm air advection (fig. 2). Since the region is saturated, Z_1 defines W_1 and Z_2 defines W_2. Thus, according to equation (3), the transport of moisture M_1 across the boundary Z_1 into this grid element is given by

$$M_1=\frac{1}{f}(\phi_2-\phi_1)W_1 \tag{4}$$

Similarly, the transport of moisture M_2 across the boundary Z_2 out of the grid element is given by

$$M_2=\frac{1}{f}(\phi_2-\phi_1)W_2 \tag{5}$$

Now the moisture depletion rate M_c due to condensation over the area of the grid element is M_1-M_2, which from (4) and (5) is given by

$$M_c=\frac{1}{f}(\phi_2-\phi_1)(W_1-W_2) \tag{6}$$

The author is indebted to a reviewer for pointing out that equation (6) follows immediately from Spar's [2] expression for precipitation intensity as a function of the "vapor transport vector" when one uses the mean geostrophic wind V_g for the layer and makes the assumptions that $\frac{\partial W}{\partial t}=0$ and $\frac{\partial V_g}{\partial s}=0$, as was done in the present paper.

The factor $W_c\equiv W_1-W_2$ represents the amount of water which would be condensed out by cooling a saturated column at the pseudoadiabatic lapse rate through the thickness interval Z_1-Z_2. Table 2 gives values of this factor for cooling through various thickness intervals. These values can be used to approximate the rate of condensation of water vapor within an isobaric layer, required by the apparent advection of saturated columns from higher to lower thickness values (neglecting vertical motion).

In equation (6), the factor $\frac{1}{f}(\phi_2-\phi_1)$ is the familiar geostrophic transport term, giving the area transported between height contours on a constant pressure surface at a given latitude per unit time. This factor has been calculated using the Smithsonian wind tables [18]. With use of this factor and values of W_c from table 2, values of M_c have been calculated from equation (6) for the 1,000–700-mb. layer. Values of M_c are given in table 3.

The average rainfall rate (R) over the area of the grid element, if all the condensed water falls out, is proportional to the moisture advection and is given by

$$R=\frac{M_c}{(\Delta s)(\Delta n)} \tag{7}$$

It can further be shown that

$$W=K\sum_{p(\text{base})}^{p(\text{top})}(\rho^*T^*)(\Delta p), \tag{8}$$

where $K=\frac{R_d}{g\rho_w\bar{p}}$, ρ^* is absolute humidity, T^* the virtual temperature, Δp the pressure interval between the top and bottom of an isobaric layer, ρ_w the density of liquid water, $\bar{p}$ the average pressure in the column, and R_d is the gas constant for dry air. Then the rate of condensation of moisture is given by

$$M_c=\left[\frac{1}{f}(\phi_2-\phi_1)\right]\left[K\sum_{p(\text{base})}^{p(\text{top})}(\rho_{w_1}T_1^*-\rho_{w_2}T_2^*)(\Delta p)\right]. \tag{9}$$

This is the relation between the transport, the absolute humidity, the virtual temperature, and the condensation rate.

More comprehensive treatment of the moisture continuity considerations will be found in two recent papers [2] and [3] in the *Monthly Weather Review* to which the reader is referred for discussion of assumptions. In their paper, Smagorinsky and Collins [3] proceed from the requirement for continuity of the mixing ratio r, given by

$$\frac{dr}{dt}=\frac{\partial r}{\partial t}+\mathbf{V}\cdot\nabla r+\omega\frac{\partial r}{\partial p}$$

TABLE 2.—*Amount of precipitable water condensed by cooling a saturated column through specified thickness intervals (prepared from data in table 1)*

Change in saturation thickness (feet)	Change in precipitable water (inches)	Change in saturation thickness (feet)	Change in precipitable water (inches)
10,100–10,000	0.298	9,400–9,300	0.109
10,000–9,900	.260	9,300–9,200	.093
9,900–9,800	.226	9,200–9,100	.078
9,800–9,700	.196	9,100–9,000	.065
9,700–9,600	.170	9,000–8,900	.052
9,600–9,500	.147	8,900–8,800	.040
9,500–9,400	.127	8,800–8,700	.029

TABLE 3.—*Hourly rate of condensation per thickness-contour grid element in the 1,000- to 700-mb. layer for various latitudes and thickness value intervals (in inch-square-miles per grid element, 100-ft. contour and thickness intervals)*

Thickness interval (feet)	Latitude ° N.						
	25	30	35	40	45	50	55
10,100–10,000	2,010	1,700	1,480	1,320	1,200	1,110	1,040
10,000–9,900	1,750	1,480	1,300	1,150	1,050	970	900
9,900–9,800	1,520	1,290	1,130	1,000	910	840	780
9,800–9,700	1,320	1,120	980	870	790	730	680
9,700–9,600	1,140	970	850	750	680	630	590
9,600–9,500	990	840	730	650	590	550	510
9,500–9,400	860	720	630	560	510	470	440
9,400–9,300	730	620	540	480	440	410	380
9,300–9,200	630	530	460	410	370	350	320
9,200–9,100	530	440	390	350	310	290	270
9,100–9,000	440	370	320	290	260	240	230
9,000–8,900	350	300	260	230	210	190	180
8,900–8,800	270	230	200	180	160	150	140
8,800–8,700	200	170	140	130	120	110	100

where $\mathbf{V}$ is the horizontal wind vector, $\omega=dp/dt$, and ∇ is the horizontal vector gradient operator. In a personal communication these investigators demonstrate that equation (9) in the text above can be obtained directly from their work [3] by essentially one approximation. They state:

. . . it is merely necessary to make the approximation that the non-conservation of the mixing ratio is given to a sufficiently good approximation by the horizontal advection of the mixing ratio $\left[\text{i. e., } \frac{dr}{dt} \approx \mathbf{V}\cdot\nabla r\right]$. This implies that the local change in the mixing ratio $[\partial r/\partial t]$ is for the most part balanced by the vertical advection $\left[\omega \frac{\partial r}{\partial p}\right]$. We know that especially in moist tongues there is at least a tendency for compensation in sign. However, from our own work we know that during the condensation process $\frac{\partial r}{\partial t}$, $\mathbf{V}\cdot\nabla r$, and $\omega\frac{\partial r}{\partial p}$ tend to be of the same magnitude, so one would expect situations where there is not adequate compensation between $\frac{\partial r}{\partial t}$ and $\omega\,\frac{\partial r}{\partial p}$.

3. ANALYSIS OF RAINFALL

ANALYSIS PROCEDURE

Details of the actual operations in analyzing the motion, thickness, and moisture fields for a specified isobaric layer will now be explained utilizing the observed 1,000- to 700-mb. thickness and precipitable-water fields and the 850-mb. contours. The 850-mb. contours give the geostrophic field of motion of the layer, the 1,000- to 700-mb. thickness pattern gives the temperature field, and the precipitable-water pattern gives the distribution of moisture in depth.

Thickness and contour lines were spaced at 100-ft. intervals. A finer grid would have been desirable, but the average error of observation [22, 23] would not seem to justify it. The scale is set by the grid interval. Even in the moisture-depletion areas associated with the heaviest winter rains, 100-ft. x 100-ft. grid elements are seldom smaller than perhaps 15,000 or 20,000 square miles. The aim is to define the average depth of rainfall by areas as large as or larger than this. It is not expected that the grid elements would represent intensity for time periods much shorter than 3 hours and it has been assumed that a 6-hour period is not too long.

The analysis steps are:

(1) The temperature advection pattern is obtained by superimposing the 850-mb. contours on the 1,000–700-mb. thickness pattern.

(2) A zero-advection line is then drawn on the superimposed field to separate the areas of warm- and cold-air advection.

(3) The isopleths of saturation thickness are drawn by converting the precipitable-water pattern to saturation thickness, using the conversion given in table 1.

(4) The 1,000- to 700-mb. observed thickness pattern is superimposed on the saturation thickness pattern. Those areas where the saturation thickness is within 100 feet of the observed thickness are outlined. This latitude is required because the humidity observations are known to be consistently low.

(5) The outline of the saturation area is placed over the advection pattern. In general, it is expected that the rainfall near observation time is occurring within the region enclosed upwind by the saturation line and downwind by the zero-advection line. This area is designated the moisture-depletion area, because the procedural hypothesis is that a necessary and sufficient condition for water-vapor condensation is the concurrent existence of saturation and warm air advection through a deep layer.

(6) The hypothetical lower limit to the hourly volume-rate of rainfall per grid element, as given by equation (6), is obtained from table 3 for the appropriate thickness interval and the latitude at the inflow boundary of each grid element. However, because 6 hours is considered to be a more representative time period for determining the rainfall intensity from the grid elements, each hourly value obtained from table 3 is multiplied by 6 and assigned to the appropriate grid element. The total 6-hour volume of rain for the moisture depletion area is obtained by adding the values for the grid elements.

In the application of the above procedure, it is of course well to keep in mind the limitations imposed by the underlying assumptions. The instantaneous rainfall pattern is visualized as a system of many moving cells, forming and dissolving in the general flow, the instantaneous intensities heavy over only a small part, and light over a much larger part, of the rain area.

The analysis, of course, neglects the contribution of ageostrophic motions and non-advective processes to the rainfall production. For example, the rainfall volume associated with gravitational displacement of warm by cold air at a steep, rapidly moving, cold front is not assessed. In general winter rains it is thought that this is small compared to the volume of the advective contribution. However, experience shows that the thickness-moisture analysis will generally differentiate the "wet" and "dry" sections of such a front.

The centers of heavy winter rainfall patterns are very often located in strongly orographic regions. In the present application the orographic contribution has not been treated; however warm moisture advection seems always to be present at the time of important rainfall occurrences over such regions.

One or both of two processes might end the rain at a given point during the 6-hour period. If the inflow moisture decreases, the upwind boundary of the rainfall area must move toward lower thickness values. (In such a case, the saturation line could conceivably move downwind out of the warm-advection area, and the rainfall area would vanish.) In the second process, layer motion may shift relative to the thickness lines in such a way that the net moisture advection vanishes or is directed toward greater thickness.

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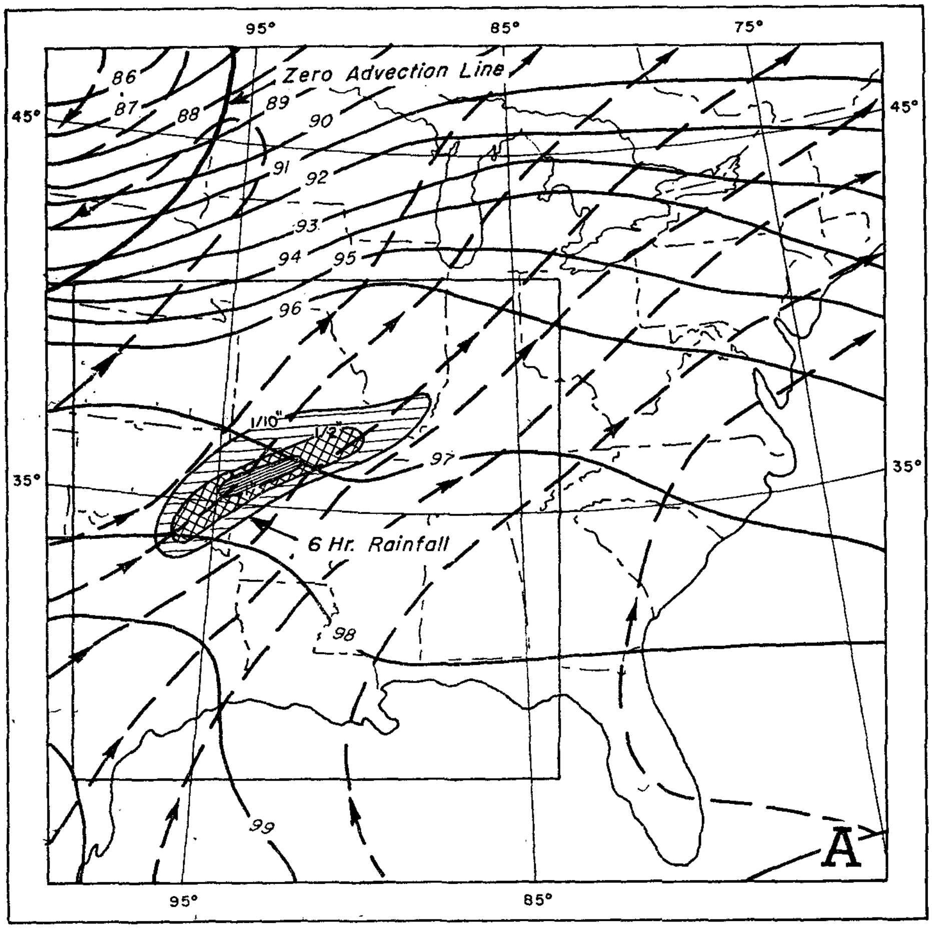
The procedure described above has been followed in analyzing the 6-hour rainfall rate centered at the 0300 GMT and 1500 GMT upper-air observations for January



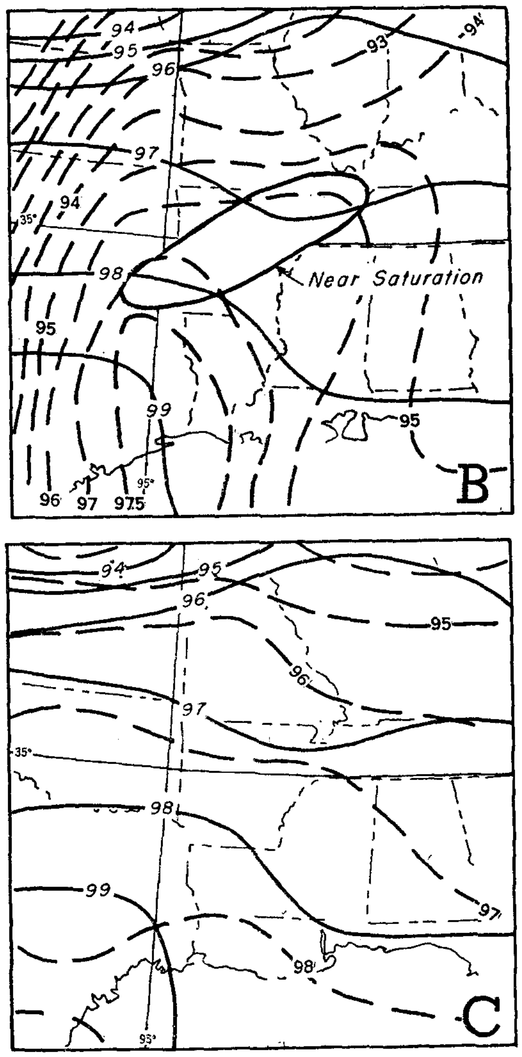


FIGURE 3.—(A) 1,000–700-mb. thickness (solid lines) superimposed on 850-mb. contours (dashed), 0300 GMT, January 20, 1954. The observed 6-hour rainfall pattern (3 hr. before to 3 hr. after map time) is shaded. (B) Thickness pattern (solid lines) and saturation-thickness (dashed lines), 0300 GMT, January 20, in the outlined area of (A). The near saturation area is that in which the saturation thickness lies within 100 ft. of the real thickness. (C) Thickness lines at 0300 GMT January 20 (solid) and 1500 GMT, January 19 (dashed) in the outlined area of (A).

1954. To make the analyzed series compatible with the forecast series (described in section 4), the analyses utilize the 850-mb. contours and the 1,000- to 700-mb. thickness. Some other constant level surface, and/or thickness interval might well have been used for indicating the moisture advection. However, daily forecasts (section 4) were an essential part of the procedure in this experiment; therefore, practical considerations determined the choice of thickness interval.*

Thermal winds were computed for every point where wind observations were available, using the approximation recently adopted by the National Weather Analysis Center that the thermal wind is the vector difference between the observed wind at the top of the layer and the sea level geostrophic wind. These were used as an aid in the analysis of the thickness pattern. Due weight was given to the observed winds in analyzing the 850-mb. contours.

* The National Weather Analysis Center prepares a mid-layer contour chart for the 1,000- to 700-mb. interval; time was not available for preparation of mid-layer contours for the 1,000- to 500-mb. interval in the daily forecast procedure.

No such guide as the geostrophic spacing is available in analyzing the moisture pattern; advecting it with the speed of the mid-layer wind from map to map appears to be the best way of keeping track of it in the sparse sounding network. This has been done with the analyzed examples.

The analysis procedure was that described previously, with the exception that the precipitable-water values between the surface and 700 mb. were used to construct the saturation thickness field.

Examples from an analyzed series are shown in figures 3 to 5. Three charts are shown for each date and time of observation. Chart A is the contour-thickness grid, with the zero-advection line indicated. The isohyetal pattern, based on a fairly dense network of recording gages, is also shown. Chart B shows the saturation-thickness field superimposed on the real thickness and an outline of the area over which the saturation thickness lies within 100 feet of the real thickness. That portion of the

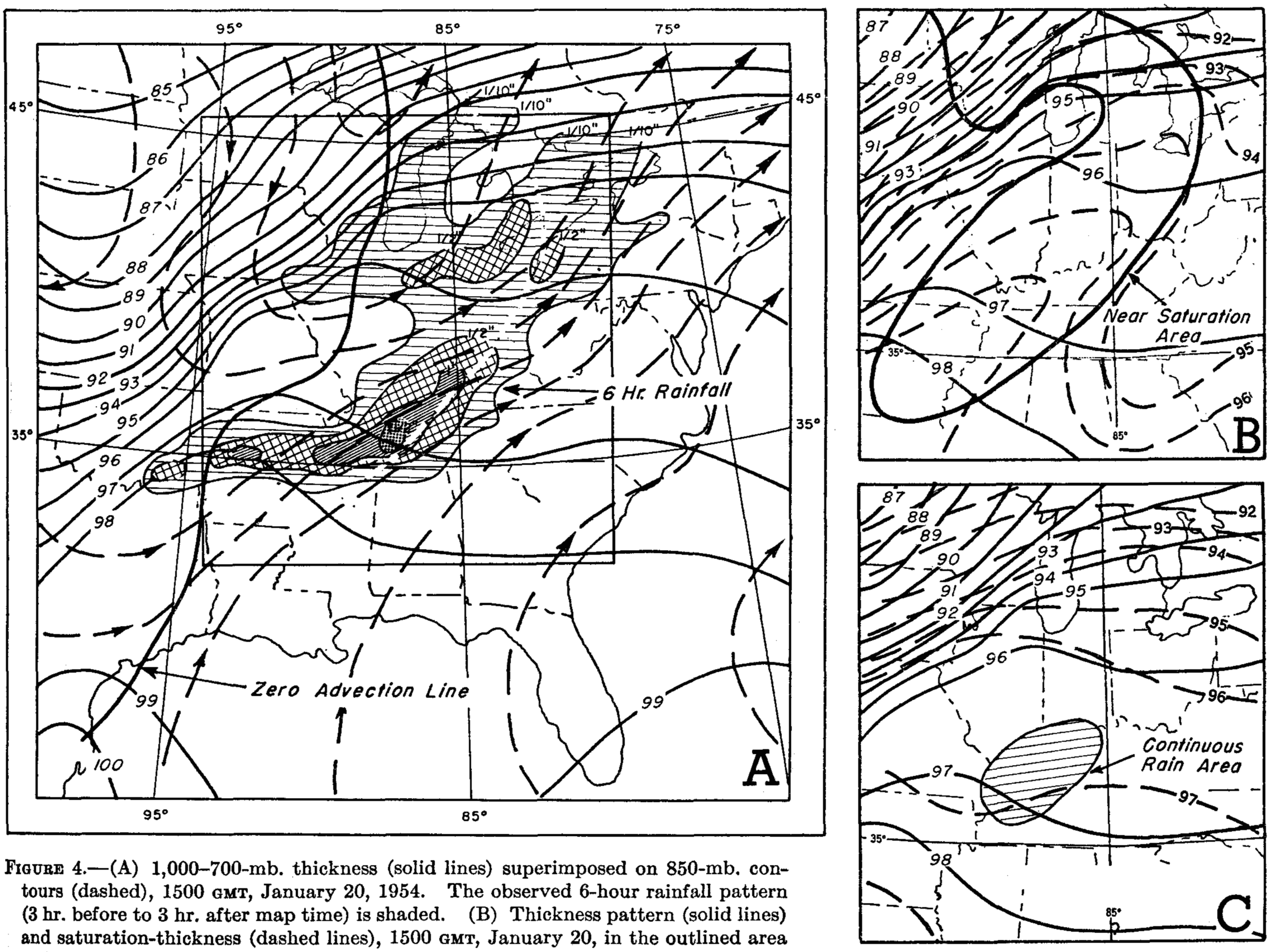


Figure 4.—(A) 1,000–700-mb. thickness (solid lines) superimposed on 850-mb. contours (dashed), 1500 GMT, January 20, 1954. The observed 6-hour rainfall pattern (3 hr. before to 3 hr. after map time) is shaded. (B) Thickness pattern (solid lines) and saturation-thickness (dashed lines), 1500 GMT, January 20, in the outlined area of (A). The near saturation area is that in which the saturation thickness lies within 100 ft. of the real thickness. (C) Thickness lines at 1500 GMT (solid) and 0300 GMT (dashed), January 20, 1954 in the outlined area of (A).

area of saturation that lies in a warm advection region is termed the moisture-depletion area. Chart C compares the position of the thickness lines at the time of observation with the position 12 hours earlier. From the figures it can be seen that the boundaries of the observed 6-hour rainfall patterns (3 hours preceding and 3 hours following the upper-air soundings) correspond well with the position of the moisture-depletion area. Furthermore, the higher rainfall values appear to be associated with the grids of smaller size. It will also be noted that in those areas continuously within the moisture-depletion area between observations the indicated thickness change is very small.

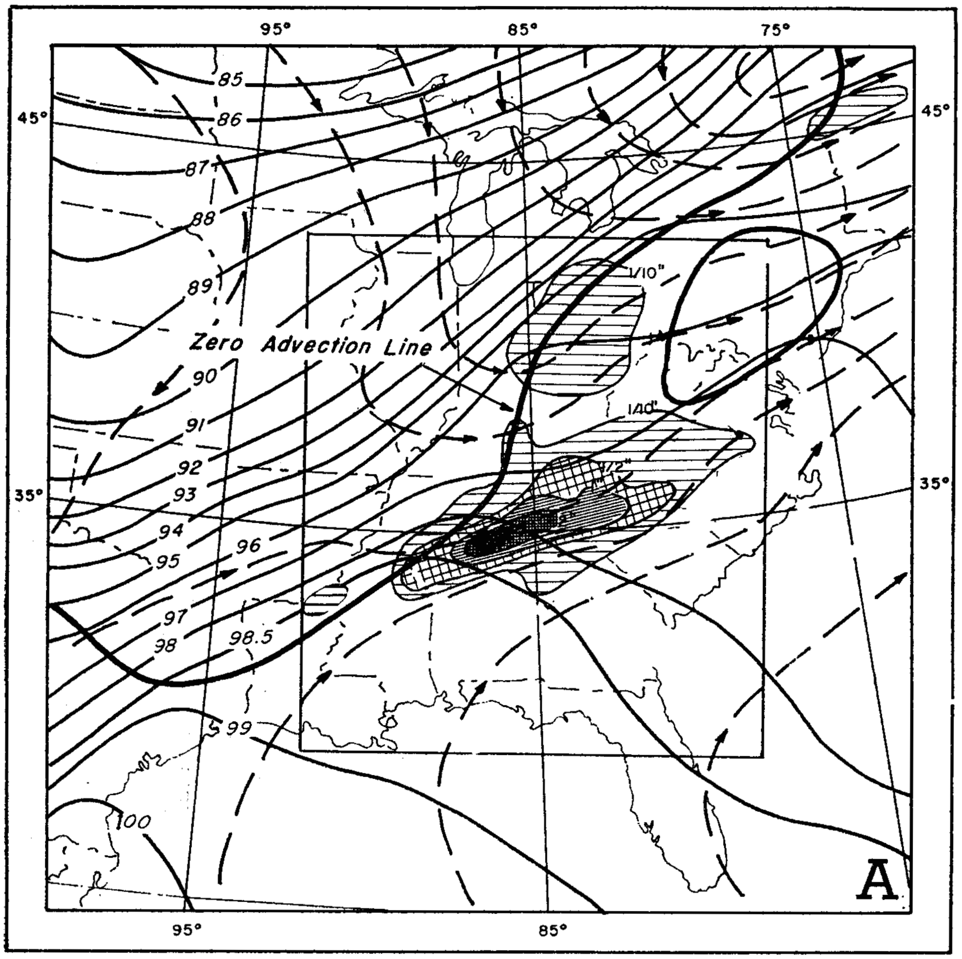
A day-to-day comparison of the current day moisture-depletion and rainfall patterns for more than a year substantiates the usefulness of these techniques; it appears that the heavier, general, winter-type precipitation patterns are especially well defined by the moisture-depletion pattern technique.

4. SHORT-PERIOD FORECASTS

An obvious but important inference from the results of the analysis of moisture depletion areas is this: A forecast of the moisture and thickness field, and of the contours of the middle pressure surface, defines a first approximation of the rainfall-intensity pattern at the time of forecast. A forecast experiment will be discussed later in this section, but first it is necessary to consider the transport and advection of moisture in unsaturated areas, attention thus far having been limited to saturated layers.

TRANSPORT OF MOISTURE IN UNSATURATED AREAS

It is clear that the horizontal moisture advection alone will not result in condensation until saturation is reached, whatever the rate of moisture transport. Therefore consideration of rate of change of moisture storage as related to the change in the water-vapor capacity of an un-



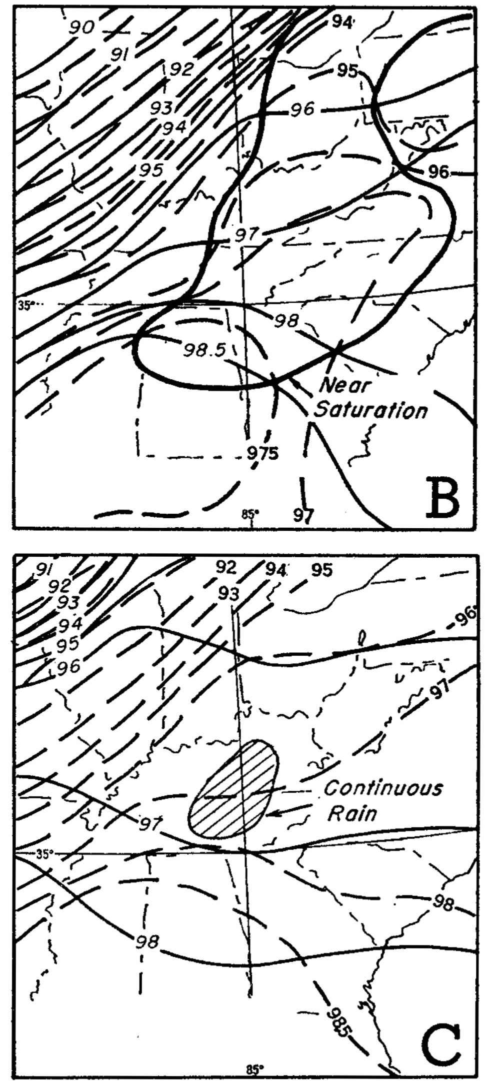


FIGURE 5.—(A) 1,000–700-mb. thickness (solid lines) superimposed on 850-mb. contours (dashed), 0300 GMT, January 21, 1954. The observed 6-hour rainfall pattern (3 hr. before to 3 hr. after map time) is shaded. (B) Thickness pattern (solid lines) and saturation-thickness (dashed lines), 0300 GMT, January 21, in the outlined area of (A). The near saturation area is that in which the saturation thickness lies within 100 ft. of the real thickness. (C) Thickness lines at 0300 GMT, January 21 (solid) and 1500 GMT, January 20 (dashed) in the outlined area of (A).

saturated layer is an important consideration in a rainfall forecast.

In general, the thickness lines move more slowly than the saturation thickness field, and this is especially true in warm-advection areas. Craddock [24] in a study of advective changes in the 1,000- to 700-mb., and 700- to 500-mb. thickness patterns, states that the effect of advection in modifying the thermal field appears to be offset by other processes, the resultant change being a residual with a correlation of about 0.6 with the advective component.

In a crude preliminary experiment, the precipitable-water field at 0300 GMT was moved with the streamline motion at mid-layer to the saturation position, assuming no later motion of the thickness lines. The placement of the saturation line found in this way often corresponded rather well with the position of the upwind boundary of the 24-hour rainfall pattern beginning 9 hours later. In any case, a forecast of the position of the upwind boundaries of general winter rains requires a quantitative appraisal of the rate at which the saturation thickness is overtaking the real thickness pattern; with a good forecast of the thickness pattern, the time of initiation and the placement of the upwind rainfall boundary should be usefully defined. (This paper is chiefly concerned with the treatment of moisture in depth, and discussion of techniques of forecasting development of thickness and contour patterns is outside its scope.)

With these considerations taken into account, a forecast procedure will now be developed for use in a short-period forecast experiment.

FORECAST PROCEDURE

The procedure for forecasting the rainfall pattern has two main steps: First, analysis of the current thickness-contour grid, and second, preparation and analysis of a forecast of the grid near the end of the rainfall forecast period. The analysis procedure has already been described (section 3). Upon completion of the analysis of the initial grid-element moisture pattern, the volume-rate of rainfall and the 6-hour average depth were estimated for each grid element. The total 0630–1230 GMT, 6-hour volume was then calculated.

For step two, a primitive method was used for developing the forecasted thickness-contour grids. The positions of the 1,000- to 700-mb. thickness lines were extrapolated 12 hours ahead of the 0300 GMT position at the rate of their previous 24-hour motion. Next, the 1500 GMT configuration of the 850-mb. contours was estimated by noting the changes during the 12 hours previous to 0300 GMT. The 0300 GMT saturation thickness pattern was then advected 12 hours ahead with the motion indicated by the initial geostrophic streamlines, and the analysis was carried through as in step one to obtain the 1230–1830 GMT rainfall pattern.

Finally a pattern was drawn whose volume was as near the sum of the initial and forecast computed volumes as a quick eye-estimation would permit, with the axis of heaviest rain drawn between the position of initial and forecast-period centers and the outside isohyets of appreciable rainfall (generally the ¼-inch isohyet) drawn within and of a shape similar to the swath of the successive positions of the moisture-depletion areas.

FORECAST EXPERIMENT

To test the forecast procedure and to assess its practical value, forecasts of rainfall distribution for the 12 hours beginning 0630 GMT were prepared on a daily basis for the period December 28, 1954, to March 1, 1955, using 0300 GMT data. Since the primary interest was in forecasting distribution of intense general rains, it was arbitrarily decided to prepare forecasts only for the days when the rate of water-vapor transport across the Gulf Coast exceeded 50,000 square-mile-inches per 12 hours. The implicit forecast for the other days is "less than 50,000 square-mile-inches, distribution not defined."

The basic working materials were the 0300 GMT charts of the National Weather Analysis Center for the 850-mb. level, and the 1,000- to 700-mb. thickness. (The 1,000- to 500-mb. thickness was used with the 850-mb. contours for the first two weeks.) The 0630 GMT Daily Weather Map and the 1500 GMT constant pressure charts of the previous day were also available, but little use was made of any but the 850-mb., 1500 GMT chart.

The strictures of a practical forecast situation were observed in every respect. The forecast preparation was begun as soon as the charts were available, and no later data were used. By the "rules of the game" no corrections were allowed after the forecast pattern was presented to a disinterested "referee" although a few obvious mistakes were discovered later. A rigidly standardized forecast scheme would have been desirable in many respects, but certain changes in emphasis and modifications in technique were strongly indicated as the experiment progressed. These are not fundamental and do not in our opinion invalidate the general inferences to be made from the set of forecasts as a whole.

The forecast patterns are compared with the observed patterns for each forecast day in figure 6.

CLIMATOLOGICAL AIDS

Although the larger features of the distribution are shown by the analysis, the detail is not clearly defined because the "model scale" defines average depth for sizes of area as large as or larger than the grid elements. In our experience nearly all heavy winter rains occur in rather simple and definite patterns. An "isohyetal analogue" is a convenient guide for drawing a forecast pattern. This is an observed pattern with the total volume equal to that forecast, in the general region of the moisture-depletion area, of its general outline, for the length of the forecast period. The analogue integrates two unassessed contributions—the orographic effect and convergence—in addition to that implied by our model.

A high water-vapor transport rate across the Gulf Coast is a good indicator of future rainfall volume if the moisture-depletion area lies over the Central States no more than a few hours downwind from the Coast. In such a case the forecast volume is better indicated by the inflow than by the depletion, since the inflow-rainfall relationship (see [7]) includes the unassessed contributions.

Having the volume-forecast, the initial and final positions of the grid elements of least size, and moisture-depletion boundaries, and an adequate file of isohyetal analogues, the experienced analyst should be able to develop a useful isohyetal pattern forecast.

In the first group of forecasts (fig. 6, page 62) the emphasis was on the "climatological aids," particularly the moisture inflow rate. Precipitable-water values were computed only for stations near the Gulf Coast. Later, the moisture-depletion computation was used in regions far downwind from the Gulf Coast where the inflow rate was not adequately defining the volume of rainfall. It was, of course, necessary to prepare the saturation thickness field for the entire area in using this method.

5. CONCLUDING REMARKS

The results of the forecast series indicate that the assumptions and approximations of the model are useful; and they may suggest that the most important of the processes contributing to general, heavy, winter-type rainfall is the ascending motion implied by the non-motion of the thickness contours. Methods for treating the orographic contribution are of course implicit in the model formulation, and work is underway on this aspect. Combined with adequate methods for treating the development, and perhaps other contributions to the vertical motion, the short period forecasts of rainfall would very likely be improved, and the period of the forecasts considerably extended. Whatever success was attained in

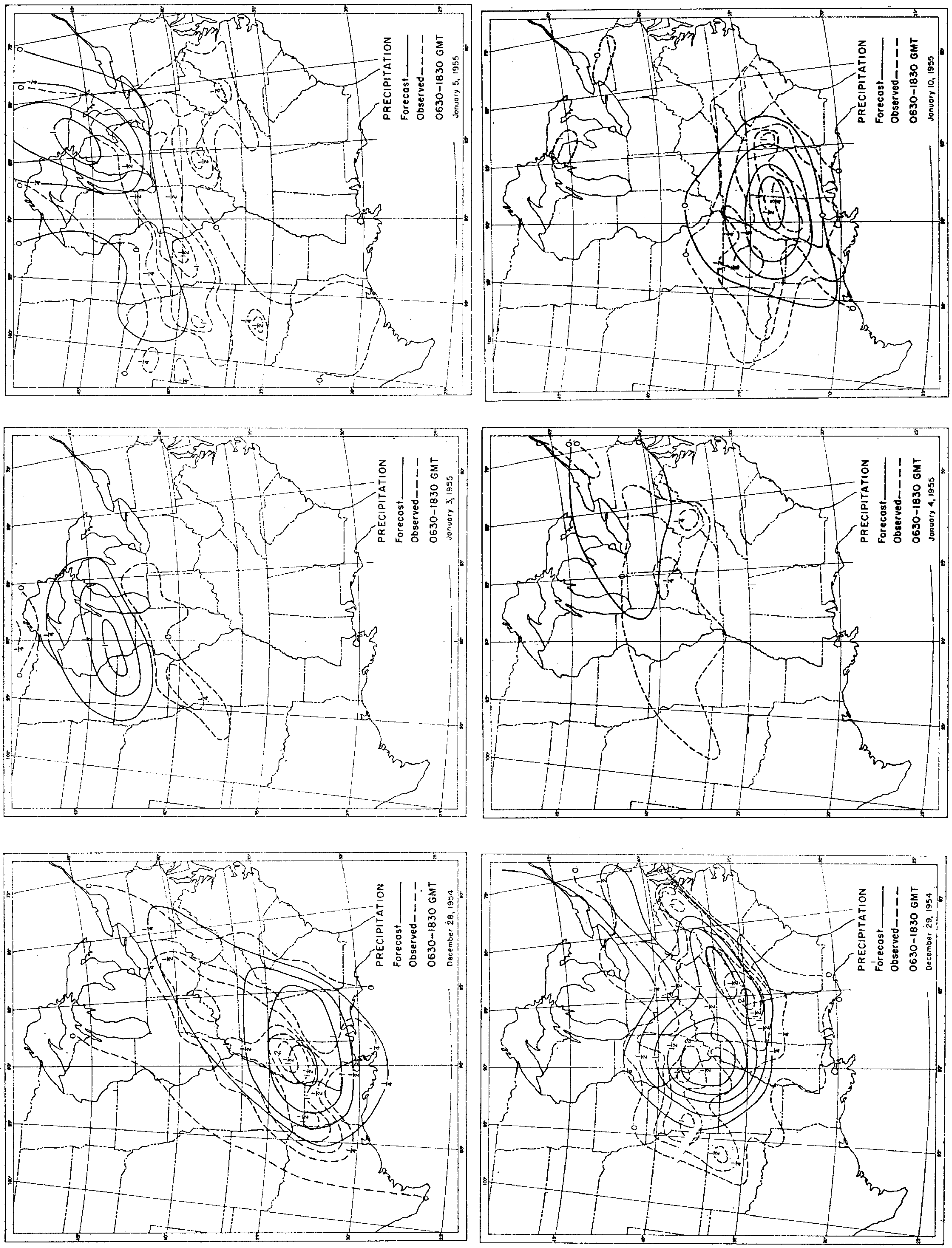


FIGURE 6.—Observed rainfall pattern superimposed on forecast pattern constructed by method described on pp. 60–61.

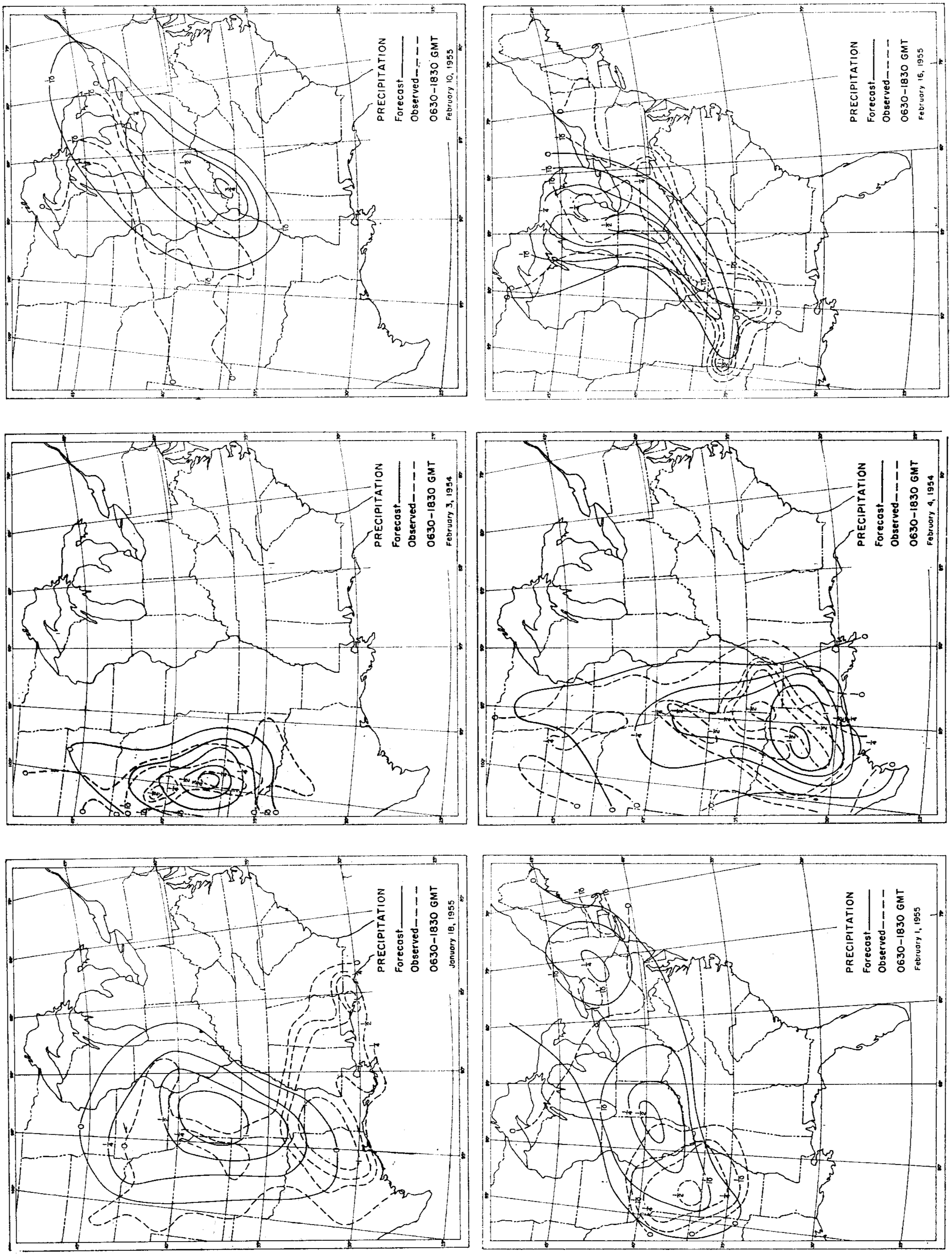
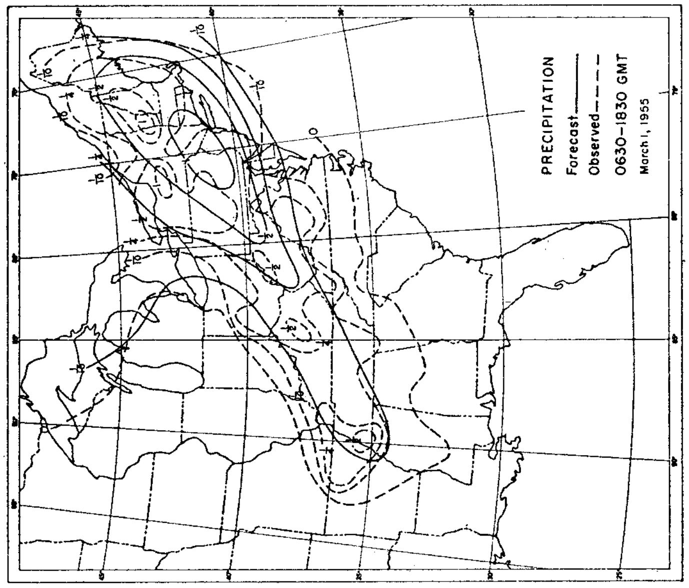
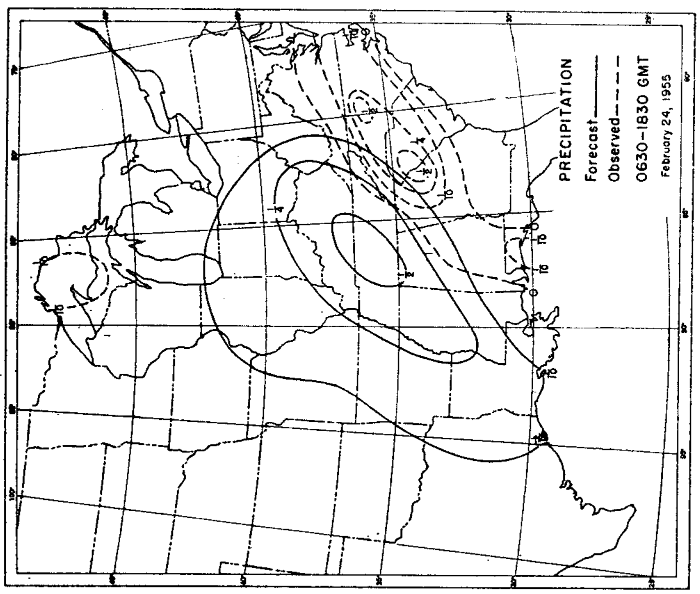
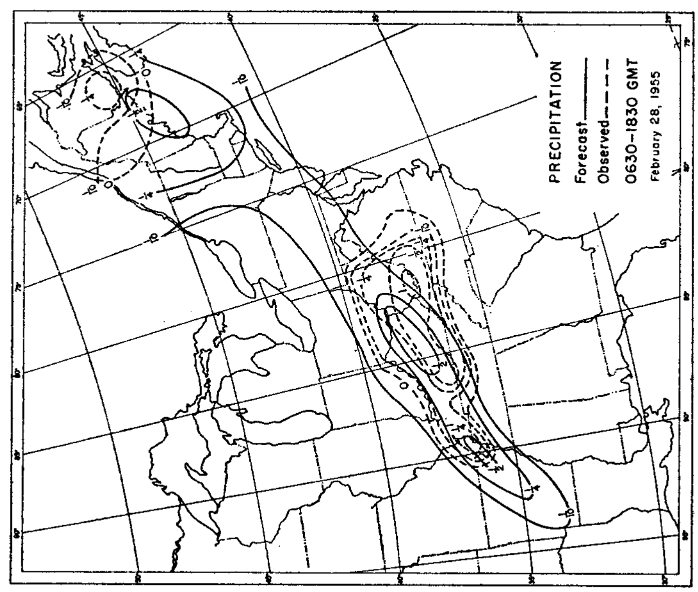
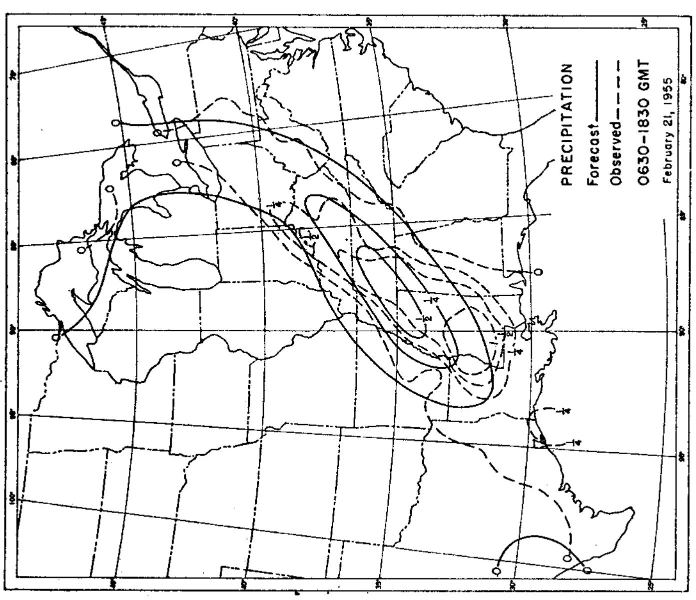


FIGURE 6—Continued.









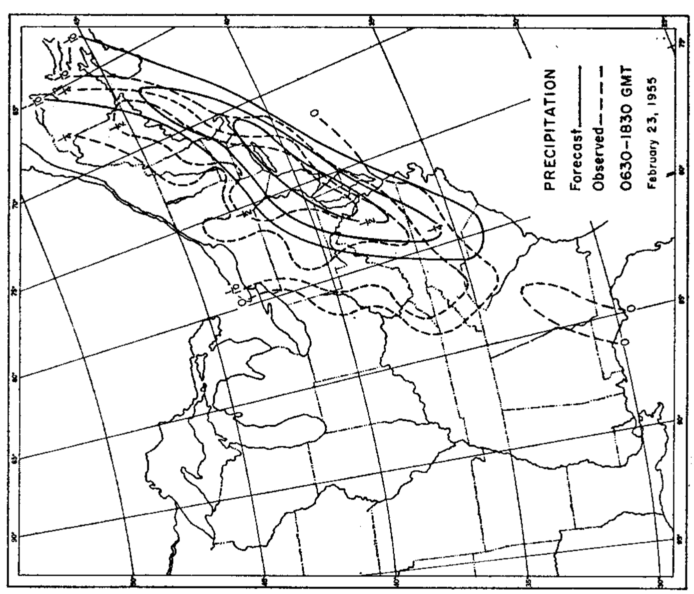


FIGURE 6—Continued.

the forecasts must be attributed to carrying out a systematic program of operations for treating the moisture in depth, and the use of such a program is commended to every meteorologist concerned with the forecasting of rainfall.

ACKNOWLEDGMENTS

The author is indebted to: Dr. Charles S. Gilman for fostering the interest in and environment for study of applications of dynamic concepts to the rainfall problem; Vance A. Myers for developing the geostrophic transport concept in application to synoptic climatology of rainfall, and for many suggestions which kept this work within manageable limits, and for monitoring the forecast experiment; Dr. Smagorinsky and Mr. Collins for their comments (see p. 57) elucidating the interpretation of the experimental results; A. E. Brown for his interest and facility in processing data for the daily forecasts; also Robert Frazier and James L. Keister for preparation of rainfall and moisture data.

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