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Hydrometeorological Report No. 23

GENERALIZED ESTIMATES OF MAXIMUM POSSIBLE PRECIPITATION OVER THE UNITED STATES EAST OF THE 105TH MERIDIAN

For Areas of 10, 200, and 500 Square Miles

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INTRODUCTION

Assignment

1. Preparation of generalized charts of maximum possible precipitation over the United States east of the 105th meridian was requested by the Corps of Engineers, War Department, in a memorandum to the Hydrometeorological Section dated October 2, 1946. Values were requested for the following areas and durations:

Area (square miles)	Duration (hours)
10	6, 12, 24
200	6, 12, 24, 36
500	6, 12, 24, 36, 48

2. Such a project requires both extension and adaptation of the procedures followed in the type of problem usually assigned the Section - the estimation of upper limits of precipitation over a specified drainage area. Approximately 20 major reports and 50 preliminary estimates (listed in the appendix) have presented these estimates as sets of depth-area or depth-duration curves or tables, applicable to specified basins. In the present study, the more recent methods used for such estimates, though still subject to revision resulting from further analysis of the fundamental rainfall process, have been applied in the development of a series of charts, not applicable to particular basins, but showing the regional variation over eastern United States of limiting rainfall rates for specific sizes of area. Each of the 12 charts is an "isohyetal map",

with isohyets connecting equal values of maximum possible precipitation for the specified duration and size of area.

Definition

3. The maximum possible precipitation for a given area and duration is defined as the depth of precipitation which can be reached but not exceeded under known meteorological circumstances. In this, as in all hydrometeorological reports, it is an estimate because the laws limiting precipitation rates are not completely known. Like any estimate, it implies a range of tolerance, the extent of which will depend upon deficiencies in data, limitations of technical knowledge, and degree of thoroughness of the analysis. The values derived are considered to be the maximum possible, since they have been derived, within the limitations of current theory and available data, from the most effective combination of the factors controlling rainfall intensity.

Background

4. Between the major reports on maximum possible precipitation (usually in published form) and the preliminary estimates of maximum possible precipitation (in letter form) there is a difference in detail and refinement rather than a difference in kind. At first, all reports were major, since lack of properly processed storm-rainfall data and the primitive state of the basic theory demanded time-consuming preparatory study. In more recent years, the major reports have been confined to basins presenting special difficulties and therefore requiring special approaches and special organization of data. The

foundations laid in these major reports have made possible the "preliminary estimate", an abbreviated but still dependable derivation of limiting storm rainfall designed to meet unexpected or urgent needs of the Corps of Engineers. For this type of report, methods and estimates already derived in a major report for the general region in which a newly assigned basin was located were applied to the new project basin. Because of the pressing need for these estimates, detailed analyses of the basins and the applicable storms were omitted.(For some areas, however, major reports, including such detailed analysis, were available.) Instead, a standardized production procedure was adopted. When necessary, the procedure included consideration of the shape, dimensions, orientation, and topography of the basin, but these were considered in a more general way than in the major report.

5. The generalized charts now presented thus constitute a natural evolution from the methods and results of all previous Section reports, both major and preliminary. The charts combine the hitherto more or less scattered results into one consistent pattern, but this unification is accomplished at the expense of details which are occasionally of great importance. The charts are based on the methods used in preliminary estimates, adapted to the panoramic nature of the assignment. There has been no generalized consideration of any basin-shape factor. Further, the generalized character minimizes detailed topographic refinements such as elevation, slope, orientation, and exposure. Therefore, regions like the more mountainous portions of the

Appalachians and the Rockies, where topographic modifications are particularly important, have been shaded on the isohyetal maps, to indicate the inadequacy of the generalized approach. Estimates of maximum possible precipitation which include evaluation of such detailed effects require special studies beyond the scope of this assignment.

Acknowledgments

6. R. A. McCormick and R. W. Schloemer were project leaders. A. L. Shands was supervising editor, assisted by H. C. Hamilton. Principal contributors were R. D. Fletcher, D. R. Harris, R. A. McCormick, W. E. Remmele, A. L. Shands, R. W. Schloemer, and W. W. Swayne, with technical assistance furnished by P. A. Carr, J. H. Cornish, J. V. McNairy, and M. M. Webster.

II

BASIC THEORY

Theoretical Computation

7. Except for modifications suggested by the peculiarities of the basin or the limitations of the available data, the fundamental assumption basic to the theoretical computation of the maximum possible rainfall remains essentially as stated in the Section's major reports, particularly nos. 2 and 3. Briefly summarized, the assumption is that the maximum possible precipitation can be computed from an optimum combination of moisture charge and convergence of the wind.

8. The moisture charge has been assumed equal to the moisture content of a saturated air mass with pseudo-adiabatic lapse rate. A steeper lapse rate, though unstable, would be accompanied by lower moisture content; a lesser lapse rate, indicating higher moisture content, would be stable. The further assumption that 1000 mb is a sufficiently close approximation to sea-level pressure makes the moisture content of such an air mass a unique function of the sea-level (1000-mb) dewpoint. Observations have indicated the validity of this assumption in storm situations. Statistical analysis and envelopment of the maximum dewpoints of record for a region then furnish the basis for the computation of the maximum possible moisture charge. In terms of precipitable water W_p between various levels, the moisture content corresponding to a wide range of 1000-mb dewpoints can be obtained from figure 1, reproduced from earlier reports.

9. To estimate the convergence of the wind, it is necessary to consider not only the speed and direction of the current flowing into the storm area but also the speed and direction of the current flowing out

of the storm area, and the horizontal and vertical distribution in each. Considered thus as a whole, the flow pattern constitutes also a precipitation mechanism or storm model through which the moisture is processed. Computation of the maximum possible precipitation requires selection of the most efficient model and the maximum inflow wind, or the most productive combination of the two.

10. Ideally, the model is a 3-dimensional flow pattern incorporating orographic or frontal barriers when necessary. In practice the model can often be reduced to two dimensions, on the assumption that a vertical cross-section adequately represents the pattern. Models of this type are illustrated and the corresponding moisture-storage equations formulated in the Los Angeles Report. In each equation, the moisture expression, of the form

$$W_{p_1} - \frac{\Delta p_1}{\Delta p_2} W_{p_2}$$

is a function of the storm model and the 1000-mb dewpoint. It equals the depth of rainfall deposited by each column of air of unit cross-section processed, and is called the <u>effective</u> precipitable water W_E. When the model is varied at a constant dewpoint, W_E becomes a measure of the comparative efficiency of the models. When the dewpoint is varied in a single model whose other properties are constant or are a function of the dewpoint, W_E becomes a measure of the effect of moisture charge.

11. The major obstacle to the determination of the actual flow pattern, or of the most efficient flow pattern possible in nature, is the absence of upper-air wind data in storm areas. Rawin* observations are

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* Winds-aloft observations made by radio methods without optical aid.

still too sparse and have too short a period of record. Models have been most successfully developed where orographic barriers play the primary role in producing precipitation, since the orographic part of the pattern is fixed and measurable. The test of a model has been the reproduction of observed rainfall by substituting observed values of wind and dewpoint in the particular storage equation developed from the model. However, regardless of the presence or absence of orographic features, the storm situation has been most successfully analyzed for reproduction when on a large scale rather than on the small scale specified by the sizes of area assigned in the present study.

Indirect Solution

12. In detailed studies for particular basins, it has sometimes been possible to use empirical-theoretical solutions for the maximum values or the maximum combination of values entering the storage equation. For the generalized study, as for the preliminary estimates, an indirect type of solution has been used. This approach depends on two assumptions: (1) that rainfall can be expressed as the product of unit inflow moisture charge and the combined effect of mechanism efficiency and inflow wind; and (2) that the most effective combination of storm mechanism and inflow wind has either occurred or has been closely approached in certain storms of record. It is the latter assumption which makes storm transposition necessary.

13. Because the location of a major storm involving no significant orographic control is fortuitous within certain geographic limits, it is possible to transpose storm events and thus to extrapolate the

number of storms that have actually occurred toward the number the region will ultimately experience. Determination of the limits of such areas of transposition is largely a problem of synoptic meteorology. The areas can be defined as areas of meteorological homogeneity, in which every point can experience a storm event with the same storm mechanism and total inflow-wind movement, but not necessarily with the same moisture charge or the same frequency. Thus, within the area of transposition of a major storm, the variation of a maximum storm of the same type will be proportional to the variation of the maximum available moisture charge. Furthermore, if one of the transposable storms has contained the most effective combination of storm mechanism and inflow wind, the result of adjustment to the maximum moisture content will be the maximum possible storm.

14. However, before the storm can be adjusted for changed moisture charge, a storm mechanism or model must be postulated, since the moisture-charge adjustment is a function of the model. Because thunderstorm-type rainfall is considered the most critical for the comparatively small areas and durations of this study, a thunderstorm-type rainfall mechanism has been postulated. Although some of the storms adjusted fall more naturally into a non-thunderstorm synoptic classification, confinement of the study to the peak isohyetal centers, encompassing areas no greater than 500 square miles, makes the thunderstorm mechanism the most appropriate.

Thunderstorm Model

15. The thunderstorm's characteristic cumulonimbus cloud suggests the type of flow essentially responsible for its formation - convergent

radial inflow at the bottom and divergent radial outflow at the top. Although peculiarities of topography and synoptic pattern often modify this basic pattern, the vertical velocities controlling the rainfall intensities may be reduced essentially to a function of the magnitude and depth of radial inflow.

16. In Hydrometeorological Reports Nos. 2 and 3 (for the Ohio River Basin above Pittsburgh and for the Sacramento River Basin, respectively) a radial-inflow model of the thunderstorm type was used for the computation of W_m as a function of the 1000-mb dew-point. Later investigations disclosed two major weaknesses in the model: (1) continuity of mass flow was violated, since equal heights rather than equal pressure intervals of inflow and outflow layers were balanced against each other in the storage equation; and (2) the cell heights did not agree with observations of extreme cumulonimbus heights. In the model currently used these weaknesses have been removed.

17. Continuity of mass flow has been maintained by stipulating equal mass (expressed as equal vertical pressure difference) in convergent and divergent layers of the same horizontal cross-section or, in the case of an inequality of mass in these two layers, by stipulating an outflow velocity equal to the inflow velocity multiplied by the ratio of inflow Δp to outflow Δp. This is an essential feature of all atmospheric storage equations consistent with a steady state.

18. Available data on observed cloud heights* show a variation of maximum heights of cumulonimbus tops from 28,000 feet in winter to 53,000 feet in summer, or from 300 mb to 100 mb in terms of pressure in a saturated pseudo-adiabatic atmosphere. These have been the basis of the new assumption on the variation of cloud or convection top. The upper limit is accepted as occurring at a 1000-mb dewpoint of 78 F because the Section's experience is that 78 F is the highest dewpoint in the United States representative of moisture to any great depth. The lower limit of 300 mb has been assumed to occur at a 1000-mb dewpoint of 50 F. The average cirrus-base level throughout the year is also 300 mb, which is therefore a good approximation of the top of cyclonic activity. Because, a priori, the most efficient thunderstorm cell should have a top no lower than the cyclone top and, furthermore, because thunderstorms are rare below the 50 F dewpoint, the 300-mb top was related to that dewpoint. Between the 100- and 300-mb limits, the total cell height was varied linearly with the vapor pressure corresponding to the 1000-mb dewpoint.

19. Within the limits thus determined, a series of models have been constructed and their W_E-dewpoint relations computed. The general shape of the cumulonimbus cloud suggests a vertical division of the cell or model into three layers having equal pressure differences, the lowest third representing depth of inflow and the uppermost third depth of outflow. However, since there is no known fact which restricts the hypothetical cell to three equal divisions (by pressure or height), the

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* F. H. Bigelow, Report on International Cloud Observations, May 1, 1896, to July 1, 1897, Report of the Chief of the Weather Bureau, 1898-9, v. 2.

E. Kidson, Cloud-heights from Melbourne Observatory photographs, Report of the Australasian Association for the Advancement of Science, v. 16, 1923, p. 153-92.

cells tested by the Section were varied in two ways. In one series the three divisions were retained but the inflow and outflow layers were gradually increased by equal pressure differences until the middle layer was eliminated. In the second series, the outflow layer was kept at one-third the total pressure height of the cell, while the inflow layer was gradually increased from one-third to two-thirds the total pressure height of the cell, thus eliminating the middle layer again.

20. The various cells tested are described in the first column of table 1, where pressure differences Δp_1, Δp_2, and Δp_3 refer to inflow, middle, and outflow layers, respectively. Corresponding W_E values for a range of dewpoints were computed from the expression

$$W_{p_1} - \frac{\Delta p_1}{\Delta p_2} W_{p_2}$$

These W_E values, expressed both in inches and in percent of the W_E at the highest dewpoint, 78 F, are also presented in the table.

Table 1

COMPARATIVE W_E

Δp_1	Δp_2	Δp_3	W_E @ 50	% W_E @ 78	W_E @ 60	% W_E @ 78	W_E @ 70	% W_E @ 78	W_E @ 78
(in 18ths		$\Sigma \Delta p$)							
6	6	6	0.51	26.7	0.81	42.5	1.29	67.7	1.90
7	4	7	0.55	26.7	0.87	42.6	1.39	67.7	2.05
8	2	8	0.57	26.7	0.91	42.6	1.45	67.8	2.14
9	0	9	0.58	26.7	0.92	42.4	1.47	67.7	2.17
8	4	6	0.61	26.2	0.98	42.4	1.57	67.6	2.33
10	2	6	0.67	25.3	1.09	41.2	1.77	67.1	2.64
12	0	6	0.71	24.7	1.16	40.8	1.89	66.9	2.83

21. A salient fact in this array of data is that, although W_E for a specific dewpoint varies with the cell model, the ratio of the W_E values for two specific dewpoints is about the same no matter what the cell model. Each ratio is approximately equal to the ratio of the W_p values for the two dewpoints involved, W_p being accumulated from 1000 mb to the cell-top pressure for the particular dewpoint. Tabulated, the W_p values and the corresponding percentages of the W_p for the maximum dewpoint of 78 F, are:

Table 2

COMPARATIVE W_p

(thunderstorm model)

W_p @ 50	% W_p @ 78	W_p @ 60	% W_p @ 78	W_p @ 70	% W_p @ 78	W_p @ 78
0.84	24.9	1.38	41.2	2.27	67.7	3.35

Moisture Adjustment

22. W_E values have two principal uses. One is the reproduction of a storm, by computation of the observed rainfall, in order to check the validity of the model before using it for extrapolation to upper limits of rainfall. However, as previously indicated, such a reconstruction cannot very well be made, particularly for small-area rainfall, because the inflow velocities are unknown. They are not directly measurable because they occur over too small an area to be observed by the usual network of meteorological stations. The Joint Thunderstorm Project of the Army, Navy, NACA*, and Weather Bureau may provide such data. Furthermore, as is pointed out in the Section's report, "Thunderstorm

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* U.S. National Advisory Committee for Aeronautics

rainfall", concentrations of rainfall resulting from temporary suspension of raindrops make the rate of fall differ from the rate of formation. The usual working assumption is that the rate of precipitation is proportional to the rate of condensation or formation. Until detailed further information on the structure of thunderstorms becomes available from such investigations as the Thunderstorm Project, the validity of the specific model to be used cannot be checked against observations.

23. The facts cited above limit but do not cancel the usefulness of the W_E concept in hydrometeorological computations, for its second principal use is in the adjustment of observed rainfall toward the maximum possible solely on the basis of possible change in moisture charge. The comparative W_E values tabulated above (table 1) show that this type of adjustment may be made without stipulating the exact model by which the rainfall is produced, since, throughout the series of models tested, the moisture adjustment remained about the same for the same difference between observed and maximum possible dewpoint.

24. Since the W_E ratios are more closely related to the ratios of W_p than to any other constant parameter of the cell models, the W_p ratio has been employed as the moisture-adjustment factor. With the W_p at 78 F as the base, these ratios are given in figure 2. The validity of the use of this moisture adjustment for extrapolation to upper limits of rainfall depends upon the validity of the assumption that a sufficiently large sampling of major storms is available to provide an optimum or near-optimum combination of inflow-wind movement and storm mechanism. Actually this sampling must be increased by storm transposition, as previously explained.

Elevation Adjustment

25. Thunderstorm models of the type thus far considered have had a common base at 1000 mb, which has been interpreted as sea level. For occurrence at higher elevations - therefore at lower pressures - models based at pressures lower than 1000 mb must be considered. The assumption basic to this further computation is that occurrence at a higher level has a depleting effect. The higher the level at which the storm occurs, it is reasoned, the less the total W_p that can be processed and therefore the less the rainfall. While this is fundamentally true as stated, there are other significant factors involved. In regions of upslope topography there are orographic intensifying effects which may overbalance the W_p-depletion effect. Moreover, in regions of very abrupt slope, the precipitation produced in a cell based at a low elevation may be transported so as to fall at a higher adjoining elevation. In the development of the generalized charts, these modifying effects have usually been treated in one of two ways. In some transpositions the intensifying effect has been assumed to cancel the depleting effect. In others, the transposition has been restricted to regions of similar topographic characteristics.

26. In computing the orographic depletion effect the assumption was made that occurrence at a higher elevation than sea level would not change the pressure at the cell top. At each elevation the total cell depth was decreased by the elevation above sea level of the base, in terms of pressure in a saturated, pseudo-adiabatic atmosphere, and the two or three layers constituting the cell decreased in depth by the same ratio. For example: since a 950-mb pressure at the base calls

for a 50-mb (1000-950) decrease of the 900-mb (1000-100) height of the thunderstorm cell at 78 F, all the layers are reduced by 1/18 (50/900) before the storage equation is applied. The result of the computation is the residual effective precipitable water (W_E'), or the W_E characteristic of the cell at its new and higher base. Three of the cells previously described were tested and the results, in terms of W_E' and in terms of the percentage ratio of the residual to the original, or total, W_E of the cell based at 1000 mb, are given in the following tabulation:

Table 3

COMPARATIVE RESIDUAL W_E

Δp_1 (in	Δp_2 18ths of	Δp_3 $\Sigma\Delta p$)	Base Mb	W_E' @ 50	% W_E @ 50	W_E' @ 60	% W_E @ 60	W_E' @ 70	% W_E @ 70	W_E' @ 78	% W_E @ 78
6	6	6	975	0.46	91.5	0.75	93.1	1.21	93.2	1.80	94.7
8	4	6	975	0.55	91.4	0.90	92.6	1.48	93.8	2.20	94.6
10	2	6	975	0.61	91.3	1.01	92.4	1.66	93.5	2.49	94.4
6	6	6	950	0.42	83.0	0.69	85.6	1.13	88.1	1.70	89.5
8	4	6	950	0.50	82.7	0.83	85.1	1.38	87.6	2.08	89.4
10	2	6	950	0.55	82.5	0.93	85.0	1.55	87.4	2.36	89.1
6	6	6	900	0.34	67.7	0.58	72.3	0.99	76.6	1.51	79.5
8	4	6	900	0.41	67.4	0.70	71.5	1.19	75.8	1.84	79.1
10	2	6	900	0.45	67.1	0.78	71.1	1.34	75.5	2.07	78.5
6	6	6	800	0.21	41.7	0.39	48.2	0.71	55.2	1.14	60.3
8	4	6	800	0.25	41.1	0.46	47.6	0.86	54.4	1.39	59.7
10	2	6	800	0.27	40.9	0.52	47.2	0.96	53.9	1.56	59.0
6	6	6	700	0.11	22.4	0.23	29.0	0.47	36.5	0.82	43.1
8	4	6	700	0.13	22.0	0.28	28.5	0.56	35.7	0.98	42.2
10	2	6	700	0.15	21.9	0.31	28.1	0.62	35.3	1.10	41.4

27. As in the previous array of comparative W_E values, the foregoing array of residual W_E values also shows a practically constant ratio of adjustment, since the residual percentage constitutes the ratio to be used for the adjustment for orographic depletion. The W_E

ratios, however, are not as close to the corresponding W_p ratios as in the previous comparison. Using similar symbolism, the corresponding W_p ratios are given below:

Table 4

COMPARATIVE RESIDUAL W_p

	Base Pressure (mb)										
1000-mb	1000	975		950		900		800		700	
Dewpoint	W_p	W_p'	$\%W_p$	W_p'	$\%W_p$	W_p'	$\%W_p$	W_p'	$\%W_p$	W_p'	$\%W_p$
50	0.84	0.76	91.1	0.69	82.5	0.56	66.9	0.34	41.0	0.19	22.3
60	1.38	1.27	92.2	1.17	84.7	0.98	70.6	0.64	46.3	0.38	27.4
70	2.27	2.11	93.2	2.96	86.6	1.68	74.1	1.17	51.8	0.76	33.3
78	3.35	3.15	93.9	2.95	88.0	2.57	76.8	1.87	55.9	1.28	38.2

28. Because of the somewhat greater discrepancy between the residual W_E and residual W_p ratios, the decision was made to use the mean of the computed residual W_E ratios. A chart giving these residual percentages, as a function of elevation and 1000-mb dewpoint, is given in figure 3.

III

BASIC DATA

29. For application of the moisture adjustments theoretically derived in the previous chapter, four types of basic data are required. They are observed storm-rainfall data, observed representative dewpoints in these storms, maximum possible dewpoints throughout the United States east of the 105th meridian, and a contour map for the same region. The nature and sources of these data are discussed in this chapter.

Storm Rainfall

30. Because high-intensity, short-duration rainfalls over small areas are practically confined to the warmer months, the storms studied were limited, with three exceptions, to the months May through November. The three exceptions, chosen because of the exceptional magnitude of their small areal values, occurred in March and April. Although only a comparatively small number of the selected storms finally furnished the controlling values, all the available storm studies were processed to preclude oversight of any significant value. Depth-duration-area values, location of storm center, and isohyetal pattern were taken directly from the approved Part II of the storm study if available. In the absence of approved Part II data, preliminary or incomplete data were used when considered fairly reliable. All storms processed in the development of the generalized charts are listed in appendix B.

Representative Storm Dewpoints

31. For moisture adjustment, the observed storm-rainfall depths are multiplied by the ratio of maximum possible to observed moisture charge. On the basis of the theoretical and empirical considerations presented in the previous chapter, the observed moisture charge is determined from the 1000-mb dewpoint representative of the moisture flowing into the rain area of the storm. The chronological sequence of these dewpoints and the corresponding dewpoint-duration relations were determined for each of the storms processed. Ideally, each dewpoint sequence within the storm should be related to a corresponding rainfall period, appropriately lagged, but in practice this is rarely found to be feasible, especially in a project of the scope of the generalized charts. It was sufficiently accurate to use the 12-hour adjustment for all durations. The 12-hour period of maximum rainfall is closely associated with the 12-hour period of maximum dewpoints. The adjustment for other durations differs only slightly from the 12 hour adjustment. Furthermore, the major portion of the total-storm rainfall falls within a 12-hour period.

32. In each storm the rain area was defined as being bounded by the 1- or 2-inch isohyet of the total storm, and the area was then outlined on successive 12-hour synoptic maps for the storm period. With the aid of these maps, the air in the rain process was identified and its trajectory retraced to a region with available observed dewpoints. When no front separated the rain area from the surface observations representative of the air mass involved in the rain process, the representative dewpoints were selected at stations along this trajectory

as close as possible to the edge of the rain area. In the presence of a separating front, dewpoints were selected from the warm sector, as near as possible to the front. Rapid movement of the front, in some of the storms, made selection of long-duration dewpoints difficult, but the decision to use 12-hour dewpoints in storm adjustment eliminated most of such difficulties.

33. It was uncommon to find a station so located that its dewpoint was uniquely representative of the storm moisture charge. Furthermore, because of occasional lack of representativeness of surface data, it was generally found preferable to make use of a group of stations. An effort was made to select the group so that its geographical center fell on the inflow trajectory. This was also the point for which the maximum possible dewpoint was later determined in order to adjust the rainfall for occurrence at its original location.

34. The dewpoints used in the study were obtained from the original station records for all observation times within the storm period. The minimum temperatures occurring during the period were also obtained, since the dewpoint persisting for any period cannot exceed the minimum temperature observed during the same period. The dewpoints and minimum temperatures for the group of selected stations were pseudo-adiabatically reduced to 1000 mb (station elevation assumed to be in a pseudo-adiabatic, saturated atmosphere with sea level at 1000 mb) and reduced values of each were then averaged for each observation time. The lower mean thus obtained was considered to be the representative dewpoint at observation time for the geographical center of the station group. Both in the chronological sequence of these means, and in the derived dewpoint-

duration array, the representative dewpoint for each duration was the lowest observed, i.e., the dewpoint equaled or exceeded throughout the indicated period.

Maximum U.S Dewpoints

35. In order to have available a consistent basis for the estimate of the maximum possible moisture charge, maps showing the distribution of maximum possible 12-hour dewpoints, reduced to 1000 mb, were constructed for every month. Since the emphasis was on representativeness in depth as well as in area, some outstanding values of observed dewpoint were discarded in the chart construction. The Section's experience with storm analysis, for instance, disqualified all values exceeding 78 F from use in storm adjustment While some of the outstanding reported values apparently resulted from errors of observation, others were considered representative of only a shallow surface layer of air. The values charted can be defined as values of wet-bulb potential temperature which cannot be exceeded aloft. They are also the highest dewpoint values which can be equaled or exceeded (at 1000 mb) for the number of consecutive hours comprising the indicated duration, while the representative dewpoints previously discussed are the highest actually equaled or exceeded for the duration in a particular storm. As constructed, the charts give the maximum values for the indicated month. They may reasonably be assumed, therefore, to apply to the end of the month in the spring and to the beginning of the month in the fall.

36. Analyses of two types of dewpoint data contributed to the construction of the charts. The data considered most reliable, because of the length of available record, were the 30 to 50 years of observations made two to four times a day by the long-established first-order

Weather Bureau stations. Records from about fifty of these stations were analyzed, the calendar month being used as a unit in tabulation and analysis. Unless otherwise indicated by an intervening minimum temperature, as in the representative-storm-dewpoint analysis, it was assumed that between observation times the dewpoint had not fallen below the values recorded.

37. To the data from the first-order stations was added a 5-year record of hourly observations from 115 airway stations. From this record the total number of occurrences of each dewpoint for each calendar month had already been tabulated for another project For the purpose of the maximum dewpoint charts, the frequencies indicated in these tabulations were divided by five (the number of years of record) to obtain the average monthly frequencies, in hours, of occurrence of the higher dewpoint values. The assumption was made that in the maximum case the average monthly number of hours of occurrence could be consecutive. From a graphical accumulation of these average monthly frequencies, the values equaled or exceeded for any duration were obtained directly or by interpolation.

38. After reduction to 1000 mb, the maximum values from both sets of data were plotted on suitable maps. As in the case of the representative storm dewpoints, station elevation was assumed to be in a saturated, pseudo-adiabatic atmosphere with sea level at 1000 mb. Since values from both sets of data were available at some stations, the relationships indicated were used in drawing the final isolines, with greater weight given the longer record. Moisture-flow patterns of frequent occurrence were also considered, but special efforts were made to be guided by extreme rather than mean flow patterns.

Generalized Contours

39. The assumption of complete saturation and pseudo-adiabatic lapse rate in the air flowing into the maximum possible storm entails the corollary assumption of a shorter saturated column, and therefore less available moisture, above elevations higher than sea level or 1000 mb. For evaluation of the depleting effect a map of comparative elevations was necessary. A generalized contour map was therefore developed for the generalized-chart project.

40. Over large areas of gradual slope the generalized contours were almost identical with the actual contours, except that small, isolated areas of abrupt change of elevation were disregarded. Where considerable small-scale ruggedness existed, the actual contours were smoothed to obtain the generalized contours. Greater smoothing was imposed on the actual contours in the more mountainous regions where actual contours are extremely irregular and valleys of considerable width cross the main ridges. Since the effect of the transverse valleys is to allow inflow of a greater depth of air than indicated by the smoothed contours, the contours on the generalized chart were placed up slope from their smoothed position. Particularly in these regions, consideration also had to be given to a generalized storm-wind direction. As finally drawn, the generalized contours were thus truly effective barriers only when associated with up-slope winds directed normal to the contours. Along river valleys elsewhere the practice was to follow the actual contours paralleling the river upstream to a point where the valley became so constricted that the volume of air allowed passage could be considered negligible.

Limitations of Data

41. The storm-rainfall depths obtained from the Part II of each storm study, or from a preliminary evaluation of the available rainfall values, are approximations. Study of the reliability of areal rainfall determinations* indicates that the percent standard error of average depths obtained from an average gage density increases with decreasing area, the error being positive or negative. On its negative side it may be partly neutralized by the Part II procedure of finally drawing an enveloping rather than a mean curve through the computed depth-area values. However, no rainfall reliability factors are incorporated in the generalized charts.

42. Since only a moisture adjustment is imposed on the rainfall values used, the rainfall values should be the greatest that can occur at the representative dewpoints. The method assumes that the storms of record, together with additional values made possible through transposition, provide rainfall values indicative of maximum rainfall-producing efficiency. No completely analytical demonstration can be made to prove that this is so. However, there is support for the assumption in the following facts. When only the greater depths are considered, without regard to location, the range of the highest values at each dewpoint is of the order of magnitude of the corresponding range in extrapolated moisture content. Such a relation indicates that the highest rainfall values are representative of near-maximum storm efficiency, unless the assumption can be accepted that a

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* Hydrometeorological Section, Office of Hyd. Dir., U.S. Weather Bureau, Thunderstorm rainfall, Hydrometeorological Report No. 5, in coop. with Eng. Dept., Corps of Eng., War Dept., 1947.

mechanism approaching the most efficient has never occurred. Most of the greatest depths for the areas and durations assigned, for instance, occurred in the Thrall, Tex., storm (Sept. 8-10, 1921), which is characterized by the highest representative dewpoint, and a liberal storm-transposition procedure takes advantage of such a fact. However, it is also rare for one storm to control for all sizes of area and all durations. Comparison of two storms may show that, with increasing area and duration, difference in depth is often decreased and the relative depths even reversed. The procedure of envelopment of values from several storms all occurring in or transposable to the same region takes advantage of all the highest values for the durations considered.

43. The representative dewpoint fixes the denominator of the moisture adjustment ratio. If, on the basis of pseudo-adiabatic extrapolation aloft, it yields an overestimate of the actual moisture charge in the inflowing air, the result is a moisture adjustment that is too low. In the range of dewpoints of most interest to this study, there are indications that it does at times yield such an overestimate. However, if the maximum possible moisture charge should also be overestimated for the same reasons, the effect on moisture adjustment would be neutralized. Further analysis of aerological soundings is required for any quantitative statement of the proper moisture relationships in depth. It is apparent, for instance, that these relationships would vary with region and season.

44. The absence of observations at the point ideally situated for location of the representative dewpoint usually acts to increase the moisture adjustment used. The ideal location would probably be the

region of the highest dewpoints for the latitude, along the axis of the moist tongue involved in the storm. Averaging the observations from a group of stations surrounding the ideal point would thus yield a lower value. An opposite effect arises from the occasional need to go far to the south of the rain area in order to find the representative dewpoint. At lower latitudes, in general, the range of dewpoint is less, the dewpoints in the warm sector or the moist tongue being closer to the maximum possible. There is an increasing range northward. Thus, if it were possible to find the dewpoint in the rain area, the spread between representative and maximum possible dewpoint would usually be greater and the moisture adjustment would be greater. This effect is counteracted slightly by the fact that, for the same spread of dewpoint, the adjustment is greater in the higher range of dewpoints.

45. The maximum-possible-dewpoint patterns are not final. Many more stations remain to be analyzed, and at the stations already analyzed there are longer records to consider. Dependence, in the main, on records of not more than two-to-four, rather than 24, observations a day is a deficiency that only further accumulation of airport data can lessen. Use of additional data at a station can serve only to increase the station values, but these increases may already have been added by the envelopment involved in smoothing. However, the revision of interpolations and extrapolations after acquisition of data from additional stations may be either toward higher or toward lower values. Solution of the problem of the surface dewpoint's possible representativeness in depth, if it shows lower dewpoints to be more representative than higher dewpoints, would reduce the magnitude of the possible moisture adjustment.

IV

PROCEDURE AND DEVELOPMENT

46. From the basic data available three sets of charts were developed as aids to the analysis of the final generalized charts. One set was based on the moisture adjustment and unlimited transposition of all the known maximum observed rainfall values in the United States for the areas and durations assigned. For the second set of charts, all the storms listed in appendix B were adjusted for moisture content but without transposition of any kind. These two sets of charts were intended to serve as guides to the approximate upper and lower limits of the generalized values and also to the patterns and gradients which the generalized isohyets with modifications, should exhibit. The third set was a necessary tool in determining the distribution of the basic values on the generalized charts even before patterns or gradients could be considered. This set consisted of maps delineating the limits of transposition of the comparatively small number of storms whose adjusted values proved to be controlling. The controlling storms were selected by inspection of the charts of storms adjusted in place.

Adjustment of Maximum Observed Rainfall

47. The maximum observed rainfall data were obtained from the storms listed in appendix B. All the values, for the particular areas and durations assigned, came from three storms; all but three came from one storm. The values are tabulated below:

Table 5

MAXIMUM OBSERVED U.S. RAINFALL (INCHES)

Area	Duration (hours)						
(sq. mi.)	6	12	18	24	30	36	48
10	24.7a	29.8b	35.0b	36.5b	37.2b	37.6b	37.6b
200	17.9b	24.3b	28.7b	29.7b	30.4b	30.7b	31.9c
500	15.4b	21.4b	25.6b	26.6b	27.3b	27.6b	30.3c

The letters a, b, and c refer to the Smethport, Pa., storm (OR 9-23, July 17-18, 1942), the Thrall, Tex., storm (GM 4-12, Sept. 8-10, 1921), and the Miller Island, La., storm (LMV 4-24, Aug. 6-9, 1940), respectively.

48. Before adjustment and transposition to specific regions, the maximum observed values were adjusted for occurrence at sea level at a 1000-mb dewpoint of 78 F (for storm evaluation, considered the maximum possible for any region in the United States). These computed values were then adjusted for occurrence at each intersection of a 2-degree grid covering the United States east of the 105th meridian. The elevations at these intersections were obtained from the generalized contour chart. The maximum possible dewpoints used were not those at the point of intersection but, rather, the maximum possible dewpoints within a radius of 200 miles from the intersection. In the three storms adjusted and transposed, the average distance between location of storm center and location of the representative dewpoint observation was also 200 miles. In order to assume an extreme possibility, the actual direction from storm center to dewpoint location was ignored.

49. The unlimited transposition given these storm values implies neglect of all the synoptic and orographic limits on transposability, later to be discussed. In regions beyond the meteorologically determined limits of transposability of these storms, this procedure will generally produce the highest values. Neglect of the true moisture-inflow direction also tends to increase the values. For storms of short duration over small areas, however, both procedures can be defended. Over small areas for short durations, the efficiency of the storm mechanism may be independent of the visible large-scale synoptic situation. In effect the transposition is of rainfall values rather than of synoptic causes or conditions. Flow patterns, for instance, which may or may not be related to frontal structure, can effectively replace the orographic barriers which have apparently intensified the precipitation. Also, over a small area and for a short period, the inflow may conceivably be from any direction. Since, in addition, the major portion of the rainfall is invariably confined to a comparatively short period, the values obtained from the unlimited transposition of the maximum observed values must be given serious consideration in the final analysis of the generalized charts. They constitute a first approximation of the maximum possible precipitation values and appear to be usually, but not always, on the high side.

Adjustment Without Transposition

50. The second set of charts, of storms adjusted in place, produces some values that exceed those of the first set. This arises from the fact that the highest observed rainfall values are not necessarily also the highest after adjustment, even without transposition. A greater

spread between representative and maximum possible dewpoint means a greater moisture adjustment, sufficiently greater, occasionally, to change a lesser observed value to a higher adjusted value. In transposition to different elevations, similar effects may be observed. It thus becomes apparent that consideration should be given to "adjustment potentials" as well as observed rainfall depth. It was in the selection of storms with high adjustment potentials, though sometimes moderate rainfall values, that the charts of storms adjusted in place were the most useful.

51. All available storm data were used in developing these charts. On them each storm was located by a point plotted at the isohyetal center, the station with the peak rainfall. The storm value for each of the assigned areas and durations was adjusted for moisture content after comparison of the representative and maximum possible reduced dewpoints, at the location of the former. A leeway of 15 days from storm date was allowed in the choice of the maximum possible dewpoint. As in all other moisture adjustments, 12-hour dewpoints were used throughout.

52. On this set of charts the observed rainfall values have thus been given a minimum increase and therefore can be considered as lower limits of the estimate of maximum possible precipitation. However, on account of the effect of adjustment potential, some values are actually higher than corresponding values on the first set of charts. The portion of the adjustment potential revealed in these charts - that due entirely to dewpoint difference - could be found by inspection, for use

in the selection of the controlling storms whose transposition would determine the values finally plotted on the generalized charts. The elevation portion of the adjustment potential became a minor effect, since elevation adjustments were later limited or eliminated. In any case, it averages only about 10% per thousand feet and, if necessary, its contribution to the adjustment potential could be estimated during inspection of the charts. A common value of the dewpoint adjustment potential was about 30%, however, and in the maximum case it was 113%.

Transposition of Controlling Storms

53. Isohyets of the rainfall values resulting from adjustment in place make a chaotic pattern bearing, at best, a rough relation to major-storm frequency. Even liberal envelopment of the values would reveal no pattern climatologically justifiable unless a basis for a wide transposition of the values were also developed. The demarcation of the limits of such transposition, for each storm selected as probably controlling, was therefore the next step necessary to the development of the generalized charts.

54. The transposition limits of each storm are the geographical limits within which another storm of essentially the same synoptic characteristics can occur. Because the synoptic storm can be transposed it is further assumed that its rainfall characteristics, shown by its depth-duration-area curves, can also be transposed. This is also true of the accompanying isohyetal pattern, from whose transposition specific basin-configuration factors may be derived. However, no such basin factors have been used in this study.

55. On a large scale, the main features dividing the United States into separate regions of storm transposition are the Appalachian and the Continental Divides. Few storms cross these barriers without modifications drastic enough to change the synoptic type. Furthermore, transposition from the windward to the leeward slopes of these barriers will generally result in rainfall values much lower than those resulting from transposition confined to the windward slopes. Except for a short distance beyond the crest of the divide, where spillover (carryover) of rain may take place, the leeward transposition requires the complete orographic depletion adjustment without consideration of any counteracting adjustment for orographic intensification. For these reasons, transpositions have been confined to the windward slopes of the main barriers, the wind direction being that of moisture inflow in the storm transposed. On these slopes the orographic depletion and intensification effects act in opposite directions. Since a quantitative expression of only the first effect was available, there was a tendency to confine the transposition to an area of similar topography defined by narrow limits of both elevation and slope (on the basis of the generalized contour map). This resulted in a distribution of adjusted values climatologically so untenable that finally only the most important features such as the main divides or portions of the windward slopes of these divides were used as limits. Within these expanded areas of transposition, the mechanical adjustment for elevation, based solely on its depleting effect, had to be modified by a study of the individual storm. In general it was found necessary to make the assumption that slope was a function of elevation, i.e., the higher the elevation

the steeper the slope and the greater the intensification effect on rainfall. Further, the intensification effect was assumed to be equal but opposite to the depletion effect. For the controlling storms considered, the result was almost complete elimination of the elevation adjustment.

56. If the effect of topographic slope had apparently contributed to the rainfall intensity in a particular storm, no adjustments for transposition to either higher or lower elevations were made. Just as the decreased W_p above higher elevations would be compensated by the effect of steeper slope, so the increased W_p above lower elevations would be compensated by the effect of lesser slope. When there had been no slope effect contributing to the rainfall intensity, transposition to higher elevations was made without elevation adjustment because increased elevation would be compensated by increased slope. Transposition to lower elevations included adjustment for increased W_p since the slope could not further decrease; even at elevations above sea level - plateaus or gradually sloping plains - the effective slope might be zero, and transposition to lower elevations would therefore require adjustment for increased W_p.

57. No definite over-all latitudinal limitations on transposition were adopted, but possible latitudinal effects were considered separately for each storm or class of storms. Apart from moisture availability, these effects become evident principally in the change in character of tropical storms as they move northward and the decrease of temperature contrast across fronts as they move southward. Synoptic experience, rather than theory, furnished the primary grounds for each decision,

with available files of Northern Hemisphere maps and charts of hurricane tracks providing much of the comparative data.

58. In the preliminary work, transposition limits were determined for about 40 of the most important storms. When the resulting adjusted precipitation values for the various areas and durations were plotted in the transposed positions it became evident that 18 of these storms would yield the controlling values. The transposition limits for these 18 were then reviewed very carefully, since they would directly determine the final values plotted on the generalized charts. After the limits were fixed, the adjusted precipitation values were plotted in enough transposed positions to delineate as completely as possible the form of the final charts.

59. Although the transposition of each storm was considered individually, the storms naturally fell into types. This tendency was more noticeable when all the storms used in the preliminary work were being considered than in the final, shorter list. The storms in the final, controlling list will be discussed in some detail.

60. The Trenton, Fla., storm of Oct. 17-22, 1941 (SA 5-6) was associated with a mild tropical disturbance first noticed in the Caribbean on the 17th, subsequently moving into the eastern Gulf and then recurving into the Florida Peninsula near Cedar Keys on the 19th. After moving very slowly northeastward, it became practically stationary near the east coast of Florida during the 20th and 21st. By the 22d it had practically lost its identity as a tropical disturbance.

61. There is abundant observational evidence demonstrating that tropical storms can move inland anywhere along the Gulf Coast and along

the Atlantic Coast northward to Cape Cod. Sluggish movement, though more characteristic of low than of middle latitudes, is not unknown farther north. For example, a tropical storm, not of hurricane force, remained in the vicinity of Cape Hatteras for several days in July 1901. No such case has been observed farther north. As in most other tropical storms considered, it was apparent that convergence or lift at the coastline had an important effect on the location and magnitude of the heavy rain in the Trenton storm. Thus, transposition was limited to the coastal area from Brownsville to Cape Hatteras, no farther inland than the actual occurrence of the observed storm. No elevation adjustments were necessary.

62. The Altapass, N.C., storm of July 13-17, 1916 (SA 2-9) resulted from a hurricane moving inland on the South Carolina coast on the 13th and 14th. There was heavy rain along the coast but the center of heaviest rainfall was in North Carolina at an elevation between 2000 and 3000 feet, near the crest of the Appalachians. Since hurricanes can move inland anywhere along the Atlantic Coast and since the heaviest rain was so intimately associated with slope and altitude, the storm was transposed along the eastern slopes of the Appalachians between latitudes 34 and 40, without change of elevation. These narrow limits defined a region of not only the same elevation but of approximately the same slope, and thus held approximately constant the orographic intensification of rainfall in the original storm.

63. The Thrall, Tex., storm of Sept. 8-10, 1921 (GM 4-12) is one of the greatest storms of record. All but three of the maximum observed U.S. values for the areas and durations assigned occurred in this storm.

The mechanism producing the exceptionally heavy rain appeared to be convergence caused by a change from anticyclonic (with higher than geostrophic velocities) to straight flow. A tropical storm moving inland over Tampico, Mexico, provided moisture supply in great depth, while another tropical storm moving west-northwestward from the vicinity of Barbados served to warp the isobars of the wedge between the Lows into the shape of extreme effectiveness for the convergence process. Because such a pattern, particularly since it includes a warm anticyclonic wedge, belongs to Gulf State latitudes, all the Gulf States were included in the area of transposition. The western limit was the 3000-ft contour and the eastern limit the Atlantic Coast, including the Florida Peninsula.

64. There was no elevation adjustment, for reasons which have been given previously. Particularly in Texas, the omission of the mechanical adjustment seems especially justified. In this region many rainfall values similar in magnitude to the Thrall values have occurred at much higher elevations, as in the Kerrville and Snyder storms, to be discussed later.

65. The Ewan, N.J., storm of Aug. 31-Sept. 1, 1940 (NA 2-4), although considerably removed geographically from the Thrall storm, has many similar characteristics. Both storms were associated with tropical disturbances, but the heavy rain was not caused directly by the passage of a tropical Low. The tropical storm supplying the moisture for the Ewan storm was located off the Virginia coast. There was also present, though to a less marked degree than in the Thrall storm, a change in isobaric curvature indicating convergence.

However, in this case the change in curvature occurred in a portion of the pressure field between the tropical storm and a High to the north-northeastward; no second tropical storm was involved.

66. The storm was transposed northward along the coast to Cape Cod and southward to central South Carolina. The modifying effect of the relatively cold waters north of Cape Cod fixed the northern limit. The southern limit was in part due to the observed change in character of tropical storms moving from low to middle latitudes, in part due to the fact that the Ewan storm was no longer controlling south of that limit. Because of the storm's actual location and the fact that the pressure pattern, particularly the small anticyclonic wedge through which there was a flow of tropical air, is characteristically coastal, the east-west transposition limits were the coast and the 500-ft contour. No elevation adjustments were used.

67. The early rain in the Hearne, Tex., storm of June 27-July 1, 1899 (GM 3-44) was associated with a decadent tropical storm which moved inland between Corpus Christi and Galveston. The remains of the Low later became part of a quasi-stationary frontal trough extending west-southwestward from a Low which had moved across the Great Lakes to the Atlantic. As in many major Texas storms, an ill-defined Low persisted in northern Mexico.

68. Two factors, not altogether independent, served to restrict the transposition of this storm. The Mexican Low appears to be an essential part of the storm. Also, there is a tendency, apparently associated with this Mexican Low, for trailing cold fronts to develop heavy-rain-producing waves or cyclonic systems in the region. Transposition was therefore confined approximately within the boundaries of

Texas, excluding the Panhandle. The western limit was placed at the 3000-ft contour. No elevation adjustments were made.

69. The Manahawken, N.J., storm of Aug. 19, 1939 (NA 2-3) was also a decadent tropical storm. The Low passed inland over extreme northwestern Florida on August 12-13. After remaining practically stationary over Alabama until the 17th, it began to move slowly northeastward, attended by heavy rains. By the time of the heavy rain in New Jersey on the 19th, the cyclonic circulation was quite weak. Two days later, when practically no indication of the Low remained, a severe local storm occurred at Baldwin, Maine, apparently as a result of the moisture brought in by the same tropical storm.

70. Since the storm was accompanied by heavy rain along most of its path and since heavy rains caused by tropical storms have been observed as much as several hundred miles inland, the area of transposition was from Cape Cod to the Florida Keys and westward to the Alabama-Georgia border or the 1000-ft contour. Despite the occurrence of the Baldwin storm, Maine was excluded from the area of transposability of the Manahawken center because more than a moisture change was evidently involved. No elevation adjustments were used.

71. No tropical storms were associated with either the Kerrville, Tex., storm of June 30-July 2, 1932 (GM 5-1) or the Snyder, Tex., storm of July 19-20, 1939. In both storms the moisture was supplied by sustained flow around the westward extension of the Bermuda High. The movement, into the area of interest, of a cold front trailing southwestward from a Low in the Great Lakes region brought about a change in isobaric curvature from anticyclonic to cyclonic, with the resulting

marked convergence responsible for the heavy rain. The Snyder storm occurred the farthest northwest of all the known Texas "cloudburst" storms. In both storms the orographic influence was so marked that transposition was confined to the area between the 1000-ft and 3000-ft contours running the length of Texas from the Mexican border to the Panhandle border. There were no elevation adjustments.

72. The storm of May 30-31, 1935, in eastern Colorado (MR 3-28A) occurred in wave action along a quasi-stationary front. In this case, also, a Low had moved eastward north of the Great Lakes to the Atlantic, with a cold front trailing west-southwestward, but by the time of the heavy rain the northern Low had become an indistinct portion of the Icelandic Low. Both frontal and orographic effects were important in the production of the heavy rain. The region extending approximately 300 miles north and south of the storm location was accepted as the region in which a front of similar contrast could be expected in a similar synoptic situation. The transposition area extended westward to the Continental Divide and eastward to the 2000-ft contour, with no elevation adjustments.

73. The discussion of this storm would not be complete without mention of the D'Hanis, Tex., storm (GM 5-20) which occurred in the early morning of May 31. Occurring within the same stream of tropical air supplying moisture to the eastern Colorado storm, the D'Hanis storm was one of the most intense small-area, short-duration storms of record in the United States. Had the present project included a 3-hour duration, the D'Hanis storm would have controlled the values over its area of transposition, but its short duration allows it to

be overshadowed when durations of six hours or longer are considered. It is of particular interest that, despite the much higher elevation of the eastern Colorado storm, its 6-hour values sometimes exceed and are never significantly less than the corresponding values of the D'Hanis storm.

74. The storms centered at Stanton, Nebr., June 10-13, 1944 (MR 6-15), at Hayward, Wis., August 28-31, 1941 (UMV 1-22), at Cooper, Mich., Aug. 31-Sept. 1, 1914 (GL 2-16), and at Beaulieu, Minn., and Ironwood, Mich., July 18-23, 1909 (UMV 1-11A and B), can be considered as a group. They all belong to the class of wave-type cyclones occurring in the northern portion of the country between the Rockies and the Lower Lakes region, a class of frequent and widespread occurrence. Some southern limit of transposition was necessary because of the appreciable southward decrease of air-mass contrast in the season of occurrence of these storms. This limit was set roughly at the southern borders of Kansas and Missouri. Eastward and westward, the transposition extended to the foothills of the Appalachians and the Rockies, respectively, with no elevation adjustments. In practice the extreme eastern limits were not used because other storms controlled the values immediately west of the Appalachians.

75. The Springbrook, Mont., storm of June 17-21, 1921 (MR 4-21) is representative of many eastern Montana storms in which tropical air undergoes cyclonic turning around a Low. Since topography also played an important role in this storm, transposition was confined to the east slopes of the Rockies, between the Continental Divide and the 2000-ft contour, and from the Colorado-Wyoming border northward. No elevation adjustments were used.

76. The Cheyenne, Okla., storm of April 2-4, 1934 (SW 2-11) accompanied wave action along a quasi-stationary front. The storm type has widespread occurrence but the orographic effects involved in this storm confined transposition to elevations between 1000 and 3000 feet, without elevation adjustment. Northward it was transposed to the southern limits of the Springbrook storm transposition and southward to about latitude 30.

77. An especially important storm because of its adjustment potential, occurred at Hallett, Okla., on Sept. 2-6, 1940 (SW 2-18). Because the dominant feature of this storm was a northeastward-flowing current of moist air aloft, it was considered transposable over a large area. Longitudinally its limits were about the same as for the group of northern wave cyclones like the Stanton, Nebr., storm. The Gulf Coast was made the southern limit while the northern limit curved from the Texas Panhandle to central Indiana, overlapping part of the Stanton area of transposability. The storm occurred at an elevation of 1000 feet, on a gradually sloping plain. No significant slope effect was involved. For these reasons elevation adjustments were used in transposition to lower but not to higher elevations.

78. The Smethport, Pa., storm of July 17-18, 1942 (OR 9-23) is a storm of a different type although also characterized by a moist northeastward-flowing current aloft. In storms of this type, one immediate cause of the heavy precipitation is cyclonic turning into a trough aloft in the vicinity of the Appalachians. Another is the western slope of the Appalachians. For these reasons transposition was limited to the west slopes, northward to the Canadian border and

southward to southern Tennessee. Eastern limit was the Appalachian Divide and western limit the location of the Newcomerstown, Ohio, storm of Aug. 6-7, 1935 (OR 9-11), which is of the same type. No elevation adjustments were used. The rather liberal southern transposition is supported by the occurrence of two other intense storms of the same type, at Rodburn, Ky., on July 4-5, 1939, and on the Little Kanawha in West Virginia on Aug. 4-5, 1943 (OR 3-30). All these storms belong to the class designated Type V in the Pittsburgh Report.

79. The storms thus far considered have been predominantly warm-season storms. Only the Cheyenne, Okla., storm occurred earlier than May 30. The last storm to be discussed is definitely a spring storm. Centered at Elba, Ala., on March 11-16, 1929 (LMV 2-20), it was characterized by exceptionally strong inflow from the south between a warm High off the Atlantic Coast and a slowly moving frontal trough in the Mississippi Valley. Because of the season of occurrence, transposition was confined to the portions of the Gulf States with unobstructed flow from the Gulf. No elevation adjustments were used.

80. In all transpositions, distance and direction of maximum possible dewpoint from adjusted storm center was kept the same as the distance and direction of the representative storm dewpoint from the unadjusted center. Also, as before, a leeway of 15 days from storm date was allowed in the selection of the maximum possible dewpoint and only 12-hour dewpoints were used in the adjustment. A few additional storms, with heavy rainfall but no controlling values, were plotted on the charts in their actual and transposed positions as an aid in drawing the final lines. This procedure was especially necessary along

the east slope of the Rockies where the gradient of values is exceptionally steep.

Limitations of Procedure

81. The first two sets of preliminary charts, of maximum observed rainfall adjusted and transposed without limit and of all available rainfall values adjusted without transposition, were meant to serve as guides to the upper and lower limits of the generalized values. For some areas and durations, nevertheless, the values of the first chart would be exceeded if storms of sufficiently high adjustment potential, though with lower observed rainfall values, were used in the limited transposition for the final charts. However, such high values, in the location of actual storm occurrence, also became visible on the charts of storms adjusted in place. The combination of charts thus provided a good estimate of the upper values to be considered, within the limitations of basic theory and data. Likewise, the charts of storms adjusted in place provide the lower values to be considered at the location of each storm occurrence. At some of these locations, the upper and lower values are identical, but at many they are so wide apart that the results of limited transposition must serve as an additional guide.

82. The transposition procedure thus involved the most important margin of error. Determinations of areas of transposability, based largely on synoptic experience, are necessarily qualitative. When not influenced by barriers or coastlines, the limits have usually been generous. Nevertheless, new storm occurrences may indicate the necessity

for an expansion of transposition areas. On the other hand, there has been some transposition into doubtful regions because of the need for some guide to upper limits of rainfall in a region of infrequent major-storm experience.

83. Other problems, to which no ready solutions were available, presented themselves during the consideration of transpositions. Within the same storm, for instance, are the limits of transposition the same no matter what the size of area or duration considered? With respect to area the question is probably academic in the present study, because of the small range of area assigned. However, there is no such assurance with respect to the larger range of durations assigned. It seems probable that the area of transposition should decrease as duration increases but there is no acceptable method for expressing such a trend. In the procedure adopted, the trend has been disregarded, except as indicated by the differences between adjusted values in adjoining areas of transposition. The effect was to enlarge the transposition areas of long-duration rainfall.

84. The all but complete elimination of the elevation adjustment in the final transposition procedure acted in the same direction. It served to increase the area of transposition, when necessary, without introducing a one-sided adjustment. In specific basin studies and preliminary estimates further refinements, depending on the availability of storm data and detailed consideration of the topography, must be considered. The result would usually be a decrease in the values obtained from the present transposition, but occasionally there might be an increase.

V

THE GENERALIZED CHARTS

Analysis

85. In the development of the preliminary charts and in the plotting of the transposed values on the generalized charts, the paramount aim was to provide for an objective analysis of the final data. However, complete objectivity in the analysis was impossible. The final pattern, for example, had to be climatologically and meteorologically tenable. It did not necessarily have to reproduce some preconceived pattern, but it had to be justifiable on the basis of climatological and meteorological theory and experience. At the very least, it had to be consistent with such theory and experience. A pattern or portion of a pattern which was difficult or impossible to justify meteorologically or climatologically was usually found to be the result of some aspect of procedure followed with rigid objectivity - for instance, drastic reduction in areas of transposability by specification of narrow restrictions of slope and elevation, or mechanical application of the elevation adjustment. In the light of the results produced, these features of the procedure had to be modified. The critical examination of the results had to be largely qualitative on the basis of experience and accepted theoretical concepts.

86. Even after modification of certain features of the procedures, the plotted data could not be interpreted literally or mechanically. Along the lines limiting the transposition of the six or seven potentially greatest storms, for instance, there were sharp discontinuities

in the plotted data. Improbable in nature, these had to be modified by introduction of an isohyetal gradient based on no definite objective data, avoiding any oversimplification of patterns and preserving significant variations between regions and within regions.

87. The limit of an area of transposition often had to be considered as a zone instead of a line. Where it limited a very narrow area, as along a coastline and not much farther inland than the actual storm occurrence, it had to be considered, strictly, as the limit to the area where only a moisture adjustment was necessary. The storm - it was often a hurricane - might actually move farther inland but with its dynamics so changed that moisture adjustment would be insufficient. At the present stage of hydrometeorology, modification for changed dynamics can be made only by interpolation between the transposition limits of the storms not so modified. Other regions, outside the proper transposition limits of the controlling storms, lie between the Atlantic tidewater area and the eastern slopes of the Appalachians, and between the Great Plains and the eastern slopes of the Rockies. In such regions an accurate delineation of the maximum possible precipitation values would probably produce a much more irregular pattern than the smooth interpolation of the generalized charts.

88. The mechanical phase of the analysis was aimed at establishing continuity and consistency of pattern between charts adjacent in area or duration. The first chart to be analyzed was the 500-square-mile, 6-hour chart - the one which would have the lowest values of maximum possible precipitation because it was for the largest area and the shortest duration. The isohyets were drawn for a minimum, yet smooth,

envelopment of the plotted data. Then the other 500-square-mile charts were analyzed for each succeeding duration. There were two main steps, not necessarily in the order mentioned, in the analysis of these succeeding charts. The first was a smooth envelopment of the plotted values where they exceeded the enveloping values at the corresponding points on the preceding chart. The second was a further smoothing of the isohyets to preserve consistency of pattern, or of variation of pattern, between each chart and its predecessor - by following the pattern of the preceding chart and by avoiding irregular displacements of isohyets of equal value from chart to chart. In effect, there was a smoothing of the rainfall increments between charts. At times there had to be retroactive correction of the preceding charts.

89. After all the 500-square-mile charts were analyzed, the analysis of the 200-square-mile charts was begun, first for the 6-hour duration and then for the succeeding durations. Similar analytical procedures were followed except that, now, smoothing had to be applied for areal as well as for duration increments. The 200-square-mile, 12-hour chart, for example, had to be consistent not only with the preceding 200-square-mile, 6-hour chart but also with the preceding 500-square-mile, 12-hour chart. The 10-square mile charts were processed in the same way.

90. Two checks were made on the results of these analytical procedures. In one the progression of the analysis was reversed, that is, instead of starting with the lowest values of maximum possible precipitation, the chart which would produce the highest values was first analyzed. This was the chart for 10-square-mile, 48-hour rainfall.

(This chart and several others, although not included among the generalized charts presented with the report, were used in the analytical development.) The reversed procedure proved to be more difficult, but did not indicate any need for revision of the results of the original procedure.

91. Some revisions were found necessary as the result of the second check. To make this check, depth-area and depth-duration curves were constructed for representative locations throughout the portion of the United States covered by the charts, using values read or interpolated from the charts. The curves were then carefully examined for smoothness and consistency at each location, and for consistency, including trend of variation, between locations.

Limitations in Use of Generalized Charts

92. The final charts, developed in the procedures outlined above, are reproduced in figures 4 to 15, inclusive. From them can be taken estimates of maximum possible precipitation for the areas and durations designated and, by interpolation, for all intermediate areas and durations. No special advice on the manner of interpolation is required. Possible variations due to type of plotting paper used and type of curve used to fit the plotted data are generally well within the margins of uncertainty of the charted values.

93. An array of values, taken from the chart to represent the maximum possible precipitation for various sizes of area and various durations, may or may not be identical with a corresponding array of values in a maximum possible storm. The values have been derived from all types of storms and no one type may produce the maximum depths

for all durations over an area of specific size nor the maximum depths over all sizes of area for a specific duration. In this particular study, because of the small range of area, an array of the latter type is the more likely to characterize a single storm.

94. Except as limited by the values read or interpolated from the charts, there is no implied chronological sequence of the rainfall increments. In the chapter on the hydrologic aspects of thunderstorm rainfall in Hydrometeorological Report No. 5, an average relation between the mass curve of point rainfall and the mass curve of areal rainfall is indicated, but for hydrologic trial any critical sequence may be used. Also, there is no implied isohyetal pattern. Except for basins of extreme shape, any isohyetal pattern which will produce the maximum values should be assumed. The charts do not specify any season for the occurrence of the maximum values. Most of the values are for the warm season, but there is some variation in the month of occurrence which has not been investigated. There is also no implication of a specific frequency or probability corresponding to any of the maximum values.

95. All of the isohyets shown are not of equal reliability. Areas where they are least reliable have been shaded on the charts. Mostly these are mountainous areas to which any type of transposition, no matter how modified, is hazardous. Particularly for small basins in such rugged regions, an accurate estimate of maximum possible rainfall would require calculation of the spillover effect, whose importance varies inversely with the size of the basin. Upwind rainfall and the funneling of air by gorges or steep valleys would have to be evaluated. Another

problem is the representativeness of any "mean" barrier for air currents of small width or the effectiveness as a barrier of such local topographic features as the Ozarks, which can be surrounded by the inflow current.

96. In certain regions, such as upper New England and upper New York State, southern Indiana, and the vicinity of Memphis, there is the added difficulty of absence of major-storm data. For the purpose of the generalized charts, these regions have been covered by transposition, but the sometimes great difference between the values transposed to the region and the values adjusted in place within the region makes the finally charted values at least more questionable than if the difference were small. However, such regions have not been shaded on the charts unless orographic complications also contributed to the unreliability of the isohyets.

97. Other regions, though unshaded on the charts, presented special problems to the analyst. The area influenced by the Great Lakes, particularly the State of Michigan, is such a region. The relatively cool waters of the Lakes undoubtedly exert a stabilizing effect upon convective activity in the region during the warm season, an effect which varies within the warm season and with the trajectory of the inflowing air. Since no quantitative evaluation of this effect was available, the isohyetal gradient in this region was drawn to be consistent with adjacent areas.

98. The generalized charts are thus preliminary versions, subject to revision as changes in theory, data, or procedure warrant. Estimates based on the charts should be considered first approximations, to be

replaced, when greater reliability is required, by preliminary estimates and, finally, by major basin studies.

APPENDIX A

Preliminary Estimates (PE) and Major Basin Reports (MR) prepared by the Hydrometeorological Section

River	Location	Area (sq.mi.)	Type of Report	Completion Date
Alabama	Ala., Ga., Tenn.	100-22,400	PE	9/46
Altamaha	Ga.	100-20,000	PE	9/46
Anacostia	Md., D.C.	10-170	PE	4/46
Apalachicola	Fla., Ala , Ga.	100-17,150	PE	2/46
Arkansas 1/	Colo., N.Mex.	500-20,000	MR	4/39
Bill Williams	Ariz.	4770	PE	10/45
Black*	N.Y.	199	PE	8/45
Black	Wis.	10-2120	PE	9/46
Cedar	Iowa, Minn.	10-7500	PE	8/46
Cherry Creek	Colo.	416	MR	1/40
Chippewa	Wis.	10-9010	PE	9/46
Clinton	Mich.	750	PE	7/40
Coeur d'Alene	Idaho	1470	PE	6/45
Colorado	Tex.	1000-32,000	PE	10/46
Columbia	Wash., Oreg., Idaho, Mont.	2000-50,000	MR	1/45
Connecticut	Conn., Mass., Vt., N.H.	10-10,000	PE	6/46
Contocook*	Vt., N.H.	10-200	PE	12/44
Delaware	N.J., Pa., N.Y.	10-4600	PE	10/46
Eel	Ind.	200-400	PE	5/46
Elk	W.Va.	537	PE	4/46

Appendix A (cont.)

River	Location	Area (sq.mi.)	Type of Report	Completion Date
Farm Creek*	Ill.	5-40	PE	11/45
Florida Barge Canal	Fla.	10-10,000	PE	10/43
Fourche la Fave*	Ark.	680	PE	8/39
Gauley	W.Va.	791	PE	4/46
Genegantslet Creek	N.Y.	93	PE	8/46
Genesee*	N.Y.	1040	PE	8/45
Guadalupe	Tex.	1490	PE	3/46
Illinois*	Ill.	200-20,000	PE	12/43
James*	Va.	322-6745	PE	2/44
Lackawaxen*	Pa.	10-1000	PE	8/44
Lehigh	Pa.	288	PE	4/47
Los Angeles area	Calif.	1-10,000	MR	12/45
Mamaroneck*	N.Y.	23.4	PE	5/45
Menominee*	Wis., Mich.	100-5000	PE	10/44
Meramec	Mo.	754-1505	PE	3/45
Merrimack	Mass., N.H.	10-10,000	PE	6/46
Mill Creek	Ohio	154	MR	5/38
Missouri 2/	N.Dak., Mont., Wyo.	2000-50,000	MR	11/45
Missouri 3/	Nebr., N.Dak., S.Dak., Mont., Wyo.	2000-50,000	MR	6/46
Muskingum	Ohio	10-8000	PE	10/46
Natchaug	Conn.	159	PE	11/44

Appendix A (cont.)

River	Location	Area (sq.mi.)	Type of Report	Completion Date
Neches	Tex.	3453-7585	PE	9/45
North Concho	Tex.	10-1511	PE	1/46
Ohio[4]	Pa., W.Va., Md., N.Y.	500-19,117	MR	6/41
Ompompanoosuc[5]	Vt.	100-1000	MR	3/40
Ouachita and Red	Ark., Tex.	10-3400	PE	10/46
Panama Canal[6]	C.Z.	37-1322	MR	11/42
Passaic	N J.	30-1000	PE	6/46
Patuxent	Md.	136	PE	1/44
Pecan Bayou	Tex.	10-1544	PE	1/46
Pecos[7]	N.Mex., Tex	10-18,097	MR	6/44
Pemigewasset, Soucook, and Suncook	N.H.	15-1021	PE	1/46
Popolopen Brook*	N.Y.	12.6	PE	3/45
Potomac and Rappahannock	Md., Va., W.Va., Pa.	215-11,580	MR	7/43
Raritan	N.J.	468	PE	1/45
Red[8]	Tex., Okla., N.Mex.	38,400	MR	10/39
Republican*	Nebr.	15,000	PE	4/43
Roanoke	Va.	7,800	PE	8/45
Russian	Calif.	88-105	PE	1/47
Sacramento[9]	Calif.	772-25,200	MR	5/42
Saginaw	Mich.	6,000	PE	7/40
St. Croix	Wis , Minn.	10-4180	PE	9/46

Appendix A (cont.)

River	Location	Area (sq.mi.)	Type of Report	Completion Date
St. Francis	Mo.	1310	MR	7/38
Salt and Cuivre	Mo., Iowa	10-3000	PE	12/46
Savannah	Ga., S.Car.	6144	PE	7/45
Skagit and Nooksack	Wash.	100-5000	PE	7/46
Smith*	Va.	212	PE	4/46
South Platte	Colo.	10-1000	PE	5/44
Susquehanna[10]	Pa.	963	PE	4/47
Thames	Conn.	10-200	PE	12/44
Tombigbee	Ala., Miss.	15,300	PE	10/45
Upper Susquehanna[11]	N.Y.	108-164	PE	11/45
Upper Susquehanna[12]	N.Y	57	PE	8/46
Upper Trinity	Tex.	10-2000	PE	1/46
Verdigris	Kans.	500-1160	PE	5/46
West	Vt.	100	PE	1/44
White[13]	Wash.	400	MR	7/39
White	Mo.	4000	PE	11/44
Willamette[14]	Oreg.	104-265	MR	7/39
Winooski*	Vt.	39-109	PE	9/45
Wisconsin	Wis , Mich.	10-11,700	PE	9/46
Wolf Creek[15]	Okla.	1650	MR	3/38
---	North-Central Ohio	50-500	PE	1/45

Appendix A (cont.)

Notes:

*	Prepared by Corps of Engineers, War Department; reviewed by Hydrometeorological Section.
1	"Caddoa Report"; Supplement, 5/39
2	"Garrison Report"
3	"Oahe-Ft. Randall Report"
4	Hydrometeorological Report No. 2
5	Hydrometeorological Report No. 1
6	Hydrometeorological Report No. 4
7	Unpublished
8	"Denison Report"
9	Hydrometeorological Report No. 3
10	Raystown Branch
11	Above West Oneonta and Davenport Center Dams
12	Above South Plymouth Reservoir
13	"Mud Mountain Report"
14	Above Cottage Grove, Dorena and Fern Ridge Dam sites
15	"Fort Supply Report"

APPENDIX B

Storms Processed

Year	Date	Assignment No.* (or center)	# Type of Data
1875	July 25-Aug. 3	OR 4-1	a
1878	Sept. 10-13	OR 9-19	a
1886	June 13-18	LMV 4-27	a
1887	July 27-31	SA 3-1	a
1889	May 30-June 1	SA 1-1	a
1892	July 24-28	UMV 1-1	a
1894	May 17-22	NA 1-4	a
1894	May 29-June 1	MR 6-14	p
1894	Sept. 18-20	SA 1-13	a
1896	Sept. 27-30	SA 1-19	a
1897	July 18-22	UMV 1-2	a
1897	July 25-27	GL 4-5	a
1897	July 26-29	NA 1-7	a
1898	May 2-6	SW 1-2	a
1898	June 2-6	UMV 1-3	a
1898	Aug. 3-5	SA 1-4	a
1898	Sept. 21-23	SA 2-3	a
1898	Sept. 28-Oct. 1	LMV 1-3	a
1898	Sept. 28-Oct. 1	LMV 1-3A	a
1898	Sept. 28-Oct. 1	LMV 1-3B	a
1899	June 27-July 1	GM 3-4	p
1900	Apr. 15-18	LMV 2-5	a
1900	Oct. 27-30	UMV 1-7A	a
1900	Oct 30-Nov. 1	UMV 1-7B	a
1901	July 1-6	UMV 1-8	a
1901	Sept. 16-19	SA 2-5	a

* Location of center given for storms lacking assignment number.

\# "a" = approved Part II data; "p" = preliminary data.

Appendix B (cont.)

Year	Date	Assignment No. (or center)	Type of Data
1902	July 3-10	GL 1-7	a
1902	Sept. 24-27	SA 1-5	a
1903	June 7-15	GL 4-8	p
1903	July 12	SA 1-6	a
1903	Aug. 24-28	MR 1-10	a
1903	Aug. 25-30	GL 1-9	a
1903	Sept 28-Oct. 1	SW 1-4	a
1903	Oct 7-11	GL 4-9	a
1904	Sept. 12-15	NA 1-9	a
1904	Sept. 26-30	SW 1-6	a
1904	Oct. 24-26	GM 3-11	a
1905	June 3-8	GL 2-12	a
1905	June 9-10	UMV 2-5	a
1905	July 18-21	SW 1-7	a
1905	July 18-21	SW 1-7A	a
1905	July 18-21	SW 1-7B	a
1905	July 21-25	GM 3-13	a
1905	Sept. 12-19	UMV 2-18	a
1905	Oct. 16-19	UMV 2-6	a
1906	May 21-26	SA 4-9	a
1906	June 6-8	MR 5-13	a
1906	Aug. 24	SA 1-20	p
1906	Nov. 17-21	LMV 1-4	a
1907	May 28-31	LMV 3-13	p
1907	July 13-16	MR 1-23	a
1908	May 22-25	SW 1-10	p
1908	June 4-10	MR 1-24 (Zone A)	a
1908	June 4-10	MR 1-24 (Zones C, D, E)	a
1908	July 26-Aug. 2	LMV 3-14	a
1908	Aug. 23-28	SA 2-6	a
1908	Oct. 19-24	SW 1-11 (Zones A, B, C, D, E, F, L)	a
1908	Oct. 19-24	SW 1-11 (Zones G, H, I, J, K)	a
1909	May 30-June 4	LMV 2-10	a
1909	June 2-5	GL 1-11A	a
1909	June 2-5	GL 1-11B	a

Appendix B (cont.)

Year	Date	Assignment No. (or center)	Type of Data
1909	July 4-7	UMV 2-8	a
1909	July 18-23	UMV 1-11A	a
1909	July 18 23	UMV 1-11B	a
1909	Sept. 19-22	LMV 3-16	a
1909	Nov. 10-16	MR 1-29	a
1910	Oct. 3-6	OR 4-8	a
1912	May 19-22	GL 3-1	a
1912	July 19-24	GL 2-29	a
1913	June 6-12	SW 1-14	a
1913	July 12-15	OR 3-7	a
1913	Aug 8-10	GL 3-2	a
1914	May 10-12	GL 2-15	a
1914	Aug. 31-Sept. 1	GL 2-16	a
1914	Oct. 13-16	SA 2-8	a
1915	May 25-29	MR 2-7	a
1915	Aug. 1-3	SA 4-15	a
1915	Aug 16-21	LMV 1-10	a
1915	Aug. 21-22	SA 1-7	a
1915	Sept. 6-9	MR 2-11	a
1915	Sept. 11-16	UMV 1-15	a
1916	June 2-5	GL 1-16	a
1916	July 5-10	GM 1-19	a
1916	July 13-17	SA 2-9	a
1916	July 13-19	SA 2-9A	a
1916	July 13-17	UMV 1-16	a
1917	July 21-23	GL 2-30	a
1918	May 22-23	UMV 3-5	a
1918	Oct. 24-27	SA 2-10	a
1918	Nov. 6-8	MR 2-18	a
1919	July 18-23	NA 1-11	a
1919	Aug. 13-14	NA 1-12	a
1919	Sept. 14-15	GM 5-15A	a
1919	Sept. 15-17	GM 5-15B	a
1919	Sept. 16-19	MR 2-23	a
1919	Oct. 25-28	LMV 1-13A	a
1919	Oct. 30-Nov. 1	LMV 1-13B	a

Appendix B (cont.)

Year	Date	Assignment No. (or center)	Type of Data
1920	June 15-18	GL 1-18	a
1920	July 16-17	MR 4-18	a
1920	Aug. 18	SA 1-8	a
1921	June 2-6	SW 1-23	p
1921	June 17-21	MR 4-21	a
1921	Sept. 8-10	GM 4-12	a
1921	Oct. 29-Nov. 2	OR 3-12	a
1921	Nov. 16-19	SW 1-24	a
1922	June 8-11	GL 2-21	a
1922	July 9-12	MR 2-29 (Zones A, B)	a
1922	July 9-12	MR 2-29 (Zones C, D)	a
1922	Sept. 1	UMV 3-9B	a
1922	Sept. 2-3	UMV 3-9A	a
1922	Oct. 9-10	SA 1-9	a
1923	June 6-11	SW 1-25	a
1923	July 27-Aug. 1	SA 1-15	a
1923	Sept. 13-19	SW 1-26	a
1923	Sept. 27-Oct. 1	MR 4-23	a
1923	Oct. 11-16	SW 1-27A	a
1923	Oct. 11-16	SW 1-27B	a
1924	May 7-12	SA 1-24	a
1924	June 24-29	GL 1-20	a
1924	Aug. 3-6	GL 2-22	a
1924	Aug. 18-20	UMV 4-11	a
1924	Sept. 13-17	SA 3-16 (Zones B, C, D, F, G)	a
1924	Sept. 12-18	SA 3-16 (Zones A, E, H, I)	a
1924	Oct. 4-11	SA 4-20	a
1925	May 27-29	GM 4-21	a
1925	Aug. 8	SA 1-10	a
1925	Sept. 23-26	SW 1-29	a
1926	Aug. 23-26	LMV 4-5	a
1926	Aug. 31-Sept. 5	MR 3-8	a
1926	Sept. 2-5	SW 1-30	a
1926	Sept. 8-9	OR 4-22	a
1926	Sept. 15-19	MR 4-24	p
1926	Sept. 11-16	SW 2-1	a

Appendix B (cont.)

Year	Date	Assignment No. (or center)	Type of Data
1927	May 17-19	UMV 4-12	a
1927	July 12-15	SW 2-5	a
1927	Sept. 28-Oct. 2	MR 3-14	a
1927	Nov. 2-7	NA 1-17	p
1928	June 1-5	LMV 2-18	a
1928	June 12-17	LMV 2-19	a
1928	June 16-20	MR 3-15	p
1928	June 28-30	OR 7-10	a
1928	July 5-8	UMV 1-18	a
1928	July 27-29	GL 4-21	a
1928	Aug. 9-13	SA 1-25	p
1928	Aug. 13-17	SA 2-13	a
1928	Sept. 4-7	SA 2-14	a
1928	Sept 16-19	SA 2-15	a
1928	Nov. 15-17	MR 3-20	a
1929	Mar. 11-16	LMV 2-20	a
1929	May 29-June 3	MR 3-25	a
1929	Aug. 1-2	UMV 2-17	a
1929	Sept. 23-28	SA 3-20	a
1929	Sept. 29-Oct. 3	SA 3-23	a
1930	May 15-19	LMV 2-24	a
1930	June 12-15	UMV 2-14	a
1930	Oct. 9-12	SW 2-6	a
1930	Oct. 18-20	GL 1-26	a
1931	July 20-25	GL 1-27	a
1932	June 2-6	SW 2-7	a
1932	June 2-6	SW 2-7A	a
1932	June 30-July 2	GM 5-1	a
1932	Aug. 1-3	OR 2-8	p
1932	Aug. 15-17	SW 2-8	a
1932	Sept. 16-17	NA 1-20	p
1932	Oct. 4-6	NA 1-21	a
1932	Oct. 14-18	SA 5-11B	a
1932	Oct. 15-18	SA 5-11A	a
1932	Nov. 4-9	SA 4-28	p
1933	June 28-29	UMV 2-15	a
1933	July 22-27	LMV 2-26	a
1933	July 24	SA 1-11	a
1933	Aug. 19-24	NA 1-24	p

Appendix B (cont.)

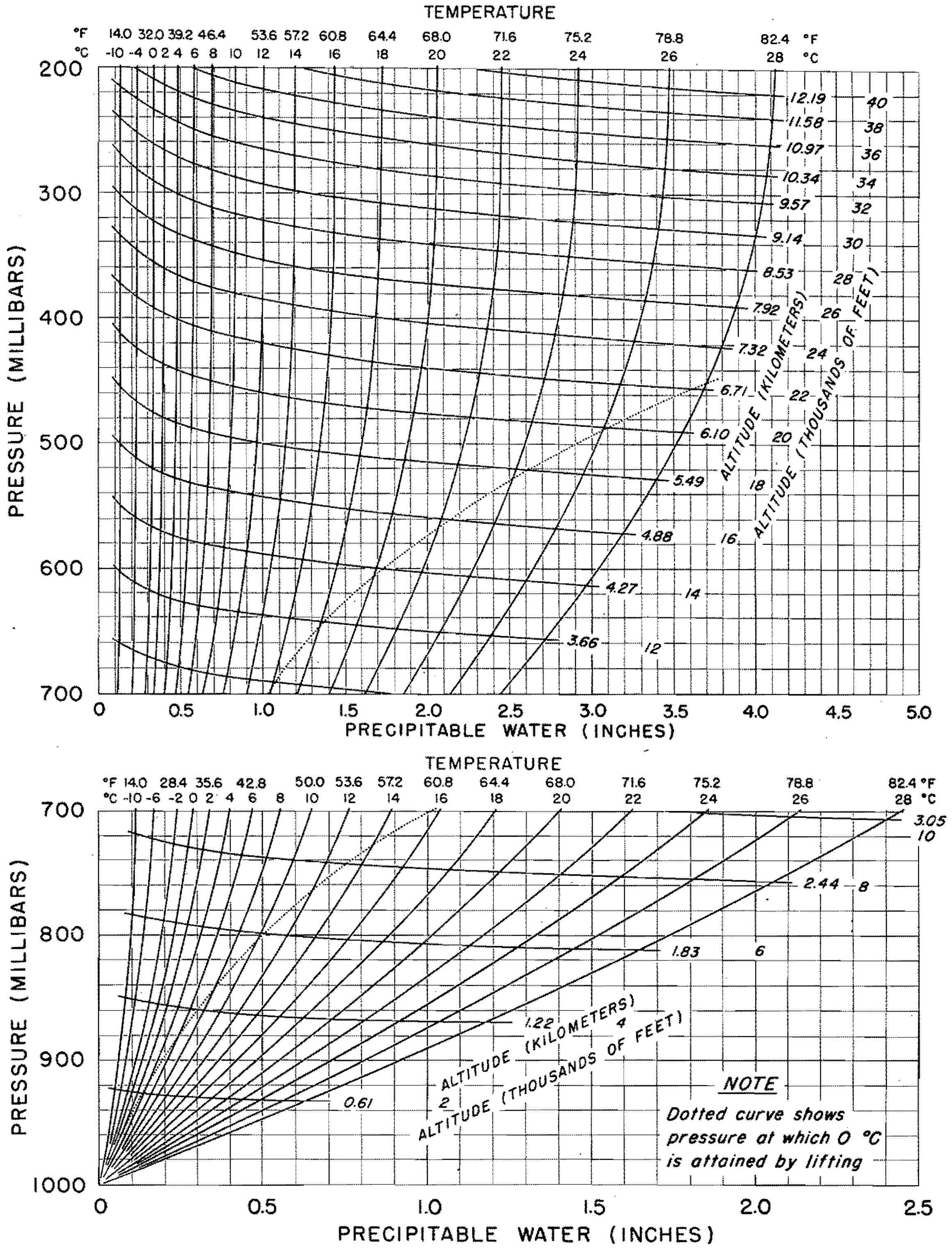
Year	Date	Assignment No. (or center)	Type of Data
1934	Apr. 2-4	SW 2-11	p
1934	June 12-16	SA 5-1	a
1934	Sept. 5-9	SA 5-12	a
1934	Nov. 19-21	LMV 1-18	a
1935	May 27-June 2	MR 3-28B	a
1935	May 30-31	MR 3-28A	a
1935	May 31	GM 5-20	p
1935	June 10-15	GM 5-2	a
1935	June 12-18	SW 2-13	a
1935	June 25-26	UMV 3-14	a
1935	July 6-10	NA 1-27	a
1935	Aug. 6-7	OR 9-11	a
1935	Sept. 2-6	SA 1-26	a
1936	Sept 14-18	GM 5-7	a
1937	May 26-30	GM 5-17	a
1937	July 11-16	UMV 1-20	a
1937	Aug. 31-Sept. 3	GL 3-5	a
1937	Sept. 6-10	SW 2-15A	a
1937	Sept. 6-10	SW 2-15B	a
1937	Oct. 16-21	SA 5-14	a
1938	May 17-20	MR 5-6	a
1938	May 30-31	MR 3-29	a
1938	June 10-11	UMV 3-17	a
1938	June 29-July 1	GL 3-11	a
1938	July 19-25	GM 5-10	a
1938	Aug. 30-Sept. 4	MR 5-8	a
1938	Sept. 16-21	SA 5-16	a
1938	Sept. 17-23	NA 2-2	p
1939	June 19-20	(Snyder, Tex.)	p
1939	July 4-5	(Rodburn, Ky.)	p
1939	Aug. 19	NA 2-3	a
1939	Aug. 21	(Baldwin, Maine)	p
1939	Aug. 25	UMV 3-19	a
1940	Aug. 6-9	LMV 4-24	a
1940	Aug. 10-17	SA 5-19	a
1940	Aug. 31-Sept. 1	NA 2-4	p
1940	Sept. 2-6	SW 2-18	a

Appendix B (cont.)

Year	Date	Assignment No. (or center)	Type of Data
1941	May 20-25	GM 5-18	a
1941	May 22	UMV 2-19	p
1941	Aug. 28-31	UMV 1-22	a
1941	Sept. 20-23	GM 5-19	a
1941	Oct. 2-7	UMV 3-20	p
1941	Oct. 17-22	SA 5-6	a
1941	Oct. 18-22	MR 6-2	a
1942	May 19-23	NA 2-5	a
1942	June 23-26	MR 6-1	a
1942	July 2-6	GM 5-12	a
1942	July 7-9	UMV 3-21	a
1942	July 17-18	OR 9-23	p
1942	Aug. 7-10	NA 2-3	a
1942	Sept. 15-19	UMV 1-25	a
1942	Oct. 11-18	SA 1-28	p
1943	May 6-11	SW 2-20	p
1943	Aug. 4-5	OR 3-30	p
1944	June 10-13	MR 6-15	p
1946	Aug. 12-16	MR 7-2B	p

DEPTHS OF PRECIPITABLE WATER IN A COLUMN OF AIR OF GIVEN HEIGHT ABOVE 1000 MILLIBARS

Assuming Saturation with a Pseudo-Adiabatic Lapse Rate for the Indicated Surface Temperatures

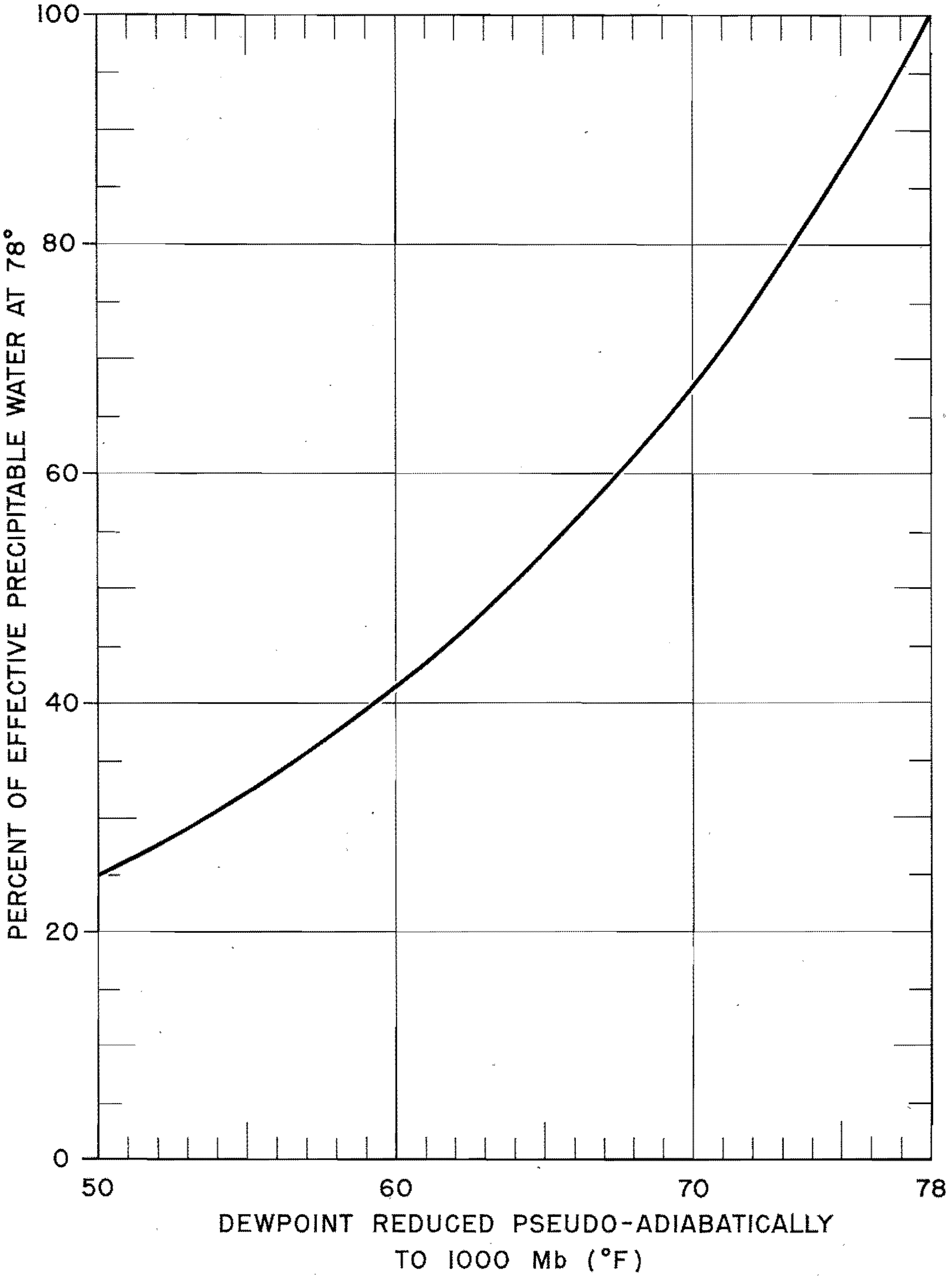


NOTE

Dotted curve shows pressure at which 0 °C is attained by lifting

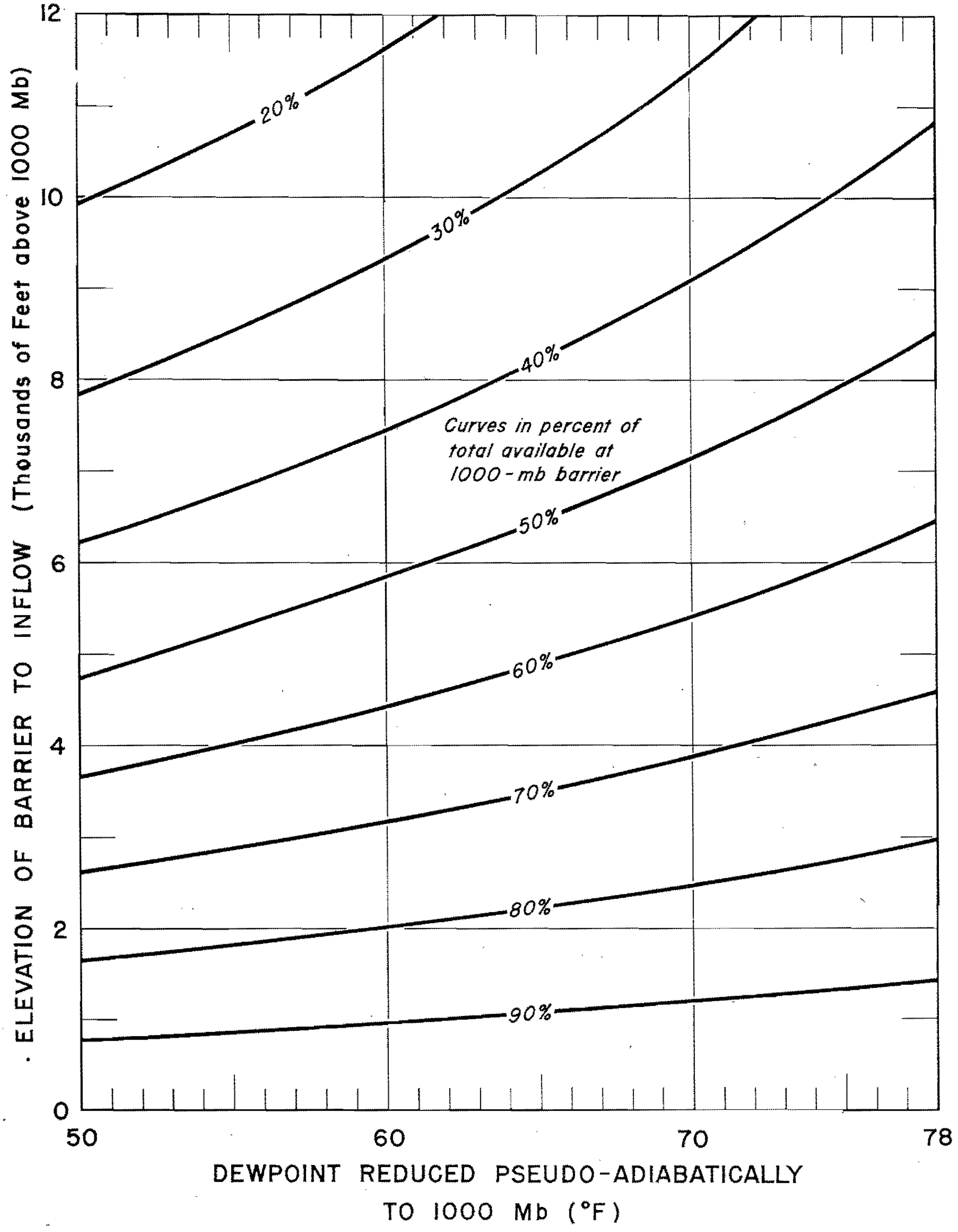
EFFECTIVE PRECIPITABLE WATER AS A FUNCTION OF DEWPOINT

(Thunderstorm Model)

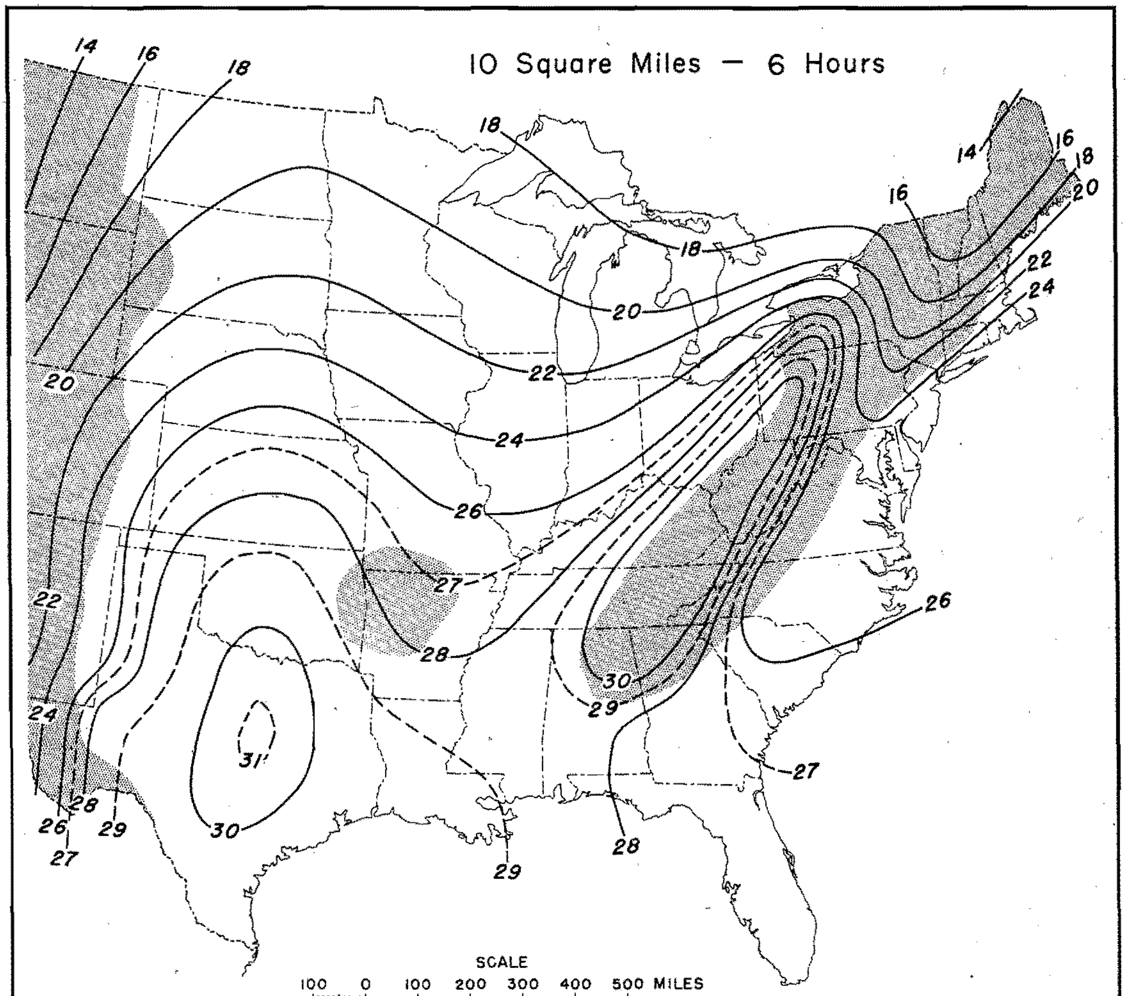


RESIDUAL EFFECTIVE PRECIPITABLE WATER AS A FUNCTION OF ELEVATION AND DEWPOINT

(Thunderstorm Model)

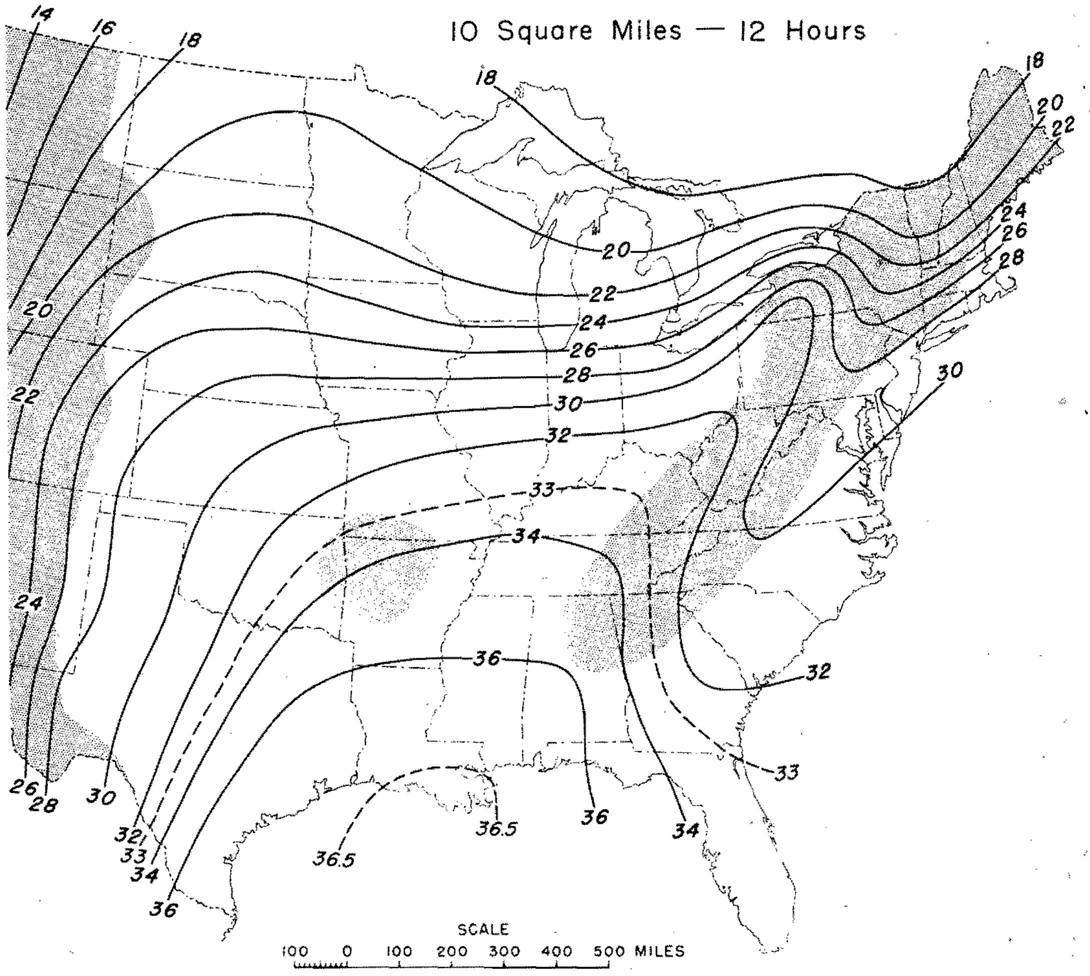


GENERALIZED ESTIMATES
MAXIMUM POSSIBLE PRECIPITATION



THIS CHART is based on data hydrometeorologically analyzed as of April 1947. Limitations of both data and assumptions are discussed in detail in the text, which should be consulted before application of the values. Areas of least reliability are shaded.

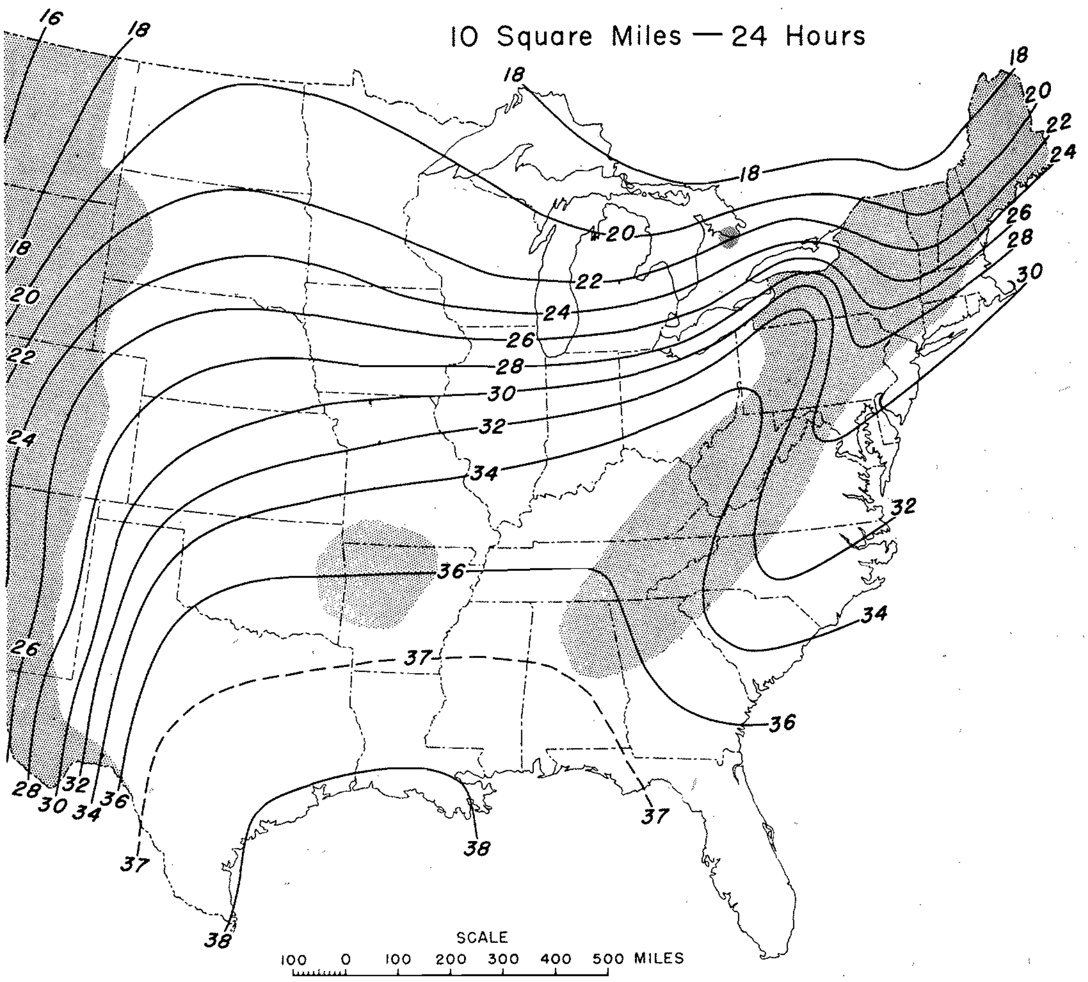
GENERALIZED ESTIMATES
MAXIMUM POSSIBLE PRECIPITATION



THIS CHART is based on data hydrometeorologically analyzed as of April 1947. Limitations of both data and assumptions are discussed in detail in the text, which should be consulted before application of the values. Areas of least reliability are shaded.

Figure 5

GENERALIZED ESTIMATES
MAXIMUM POSSIBLE PRECIPITATION



10 Square Miles — 24 Hours

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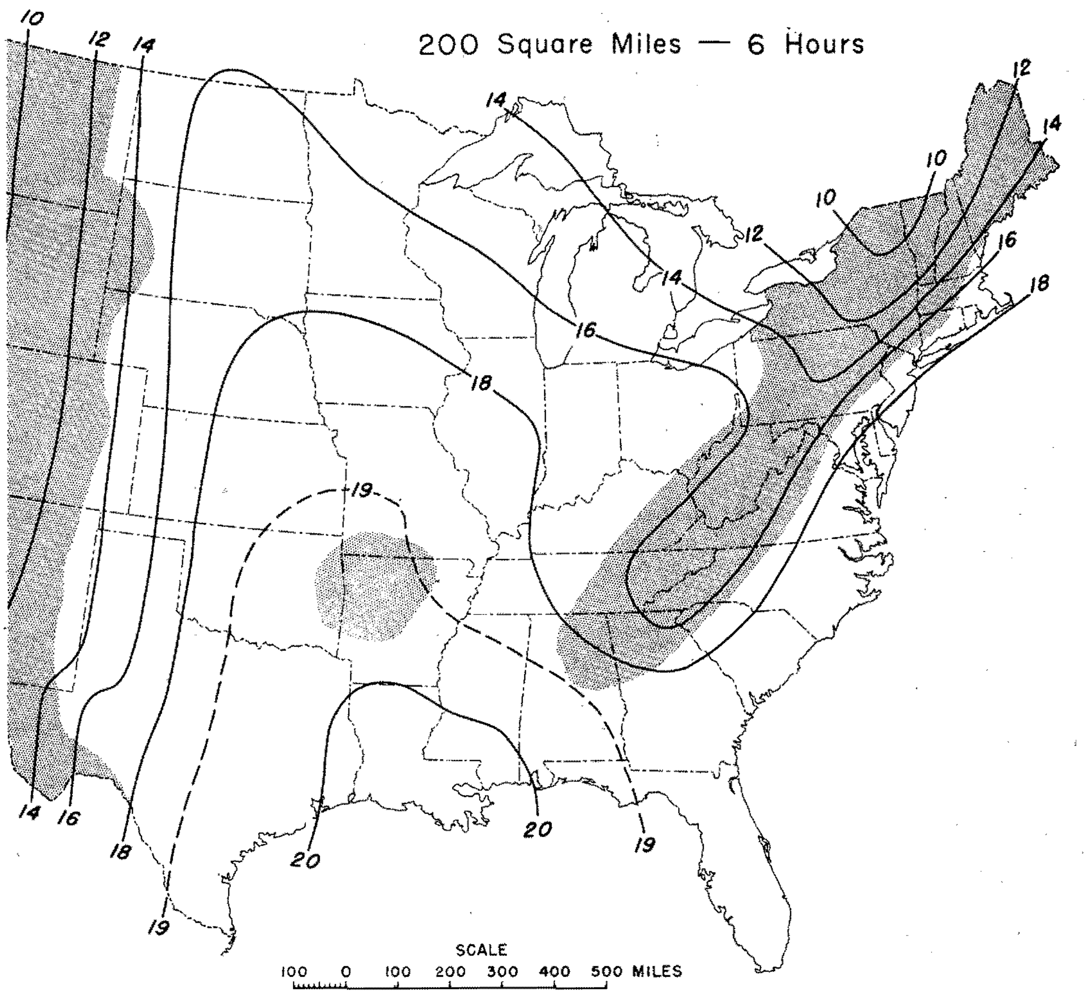
Figure 6

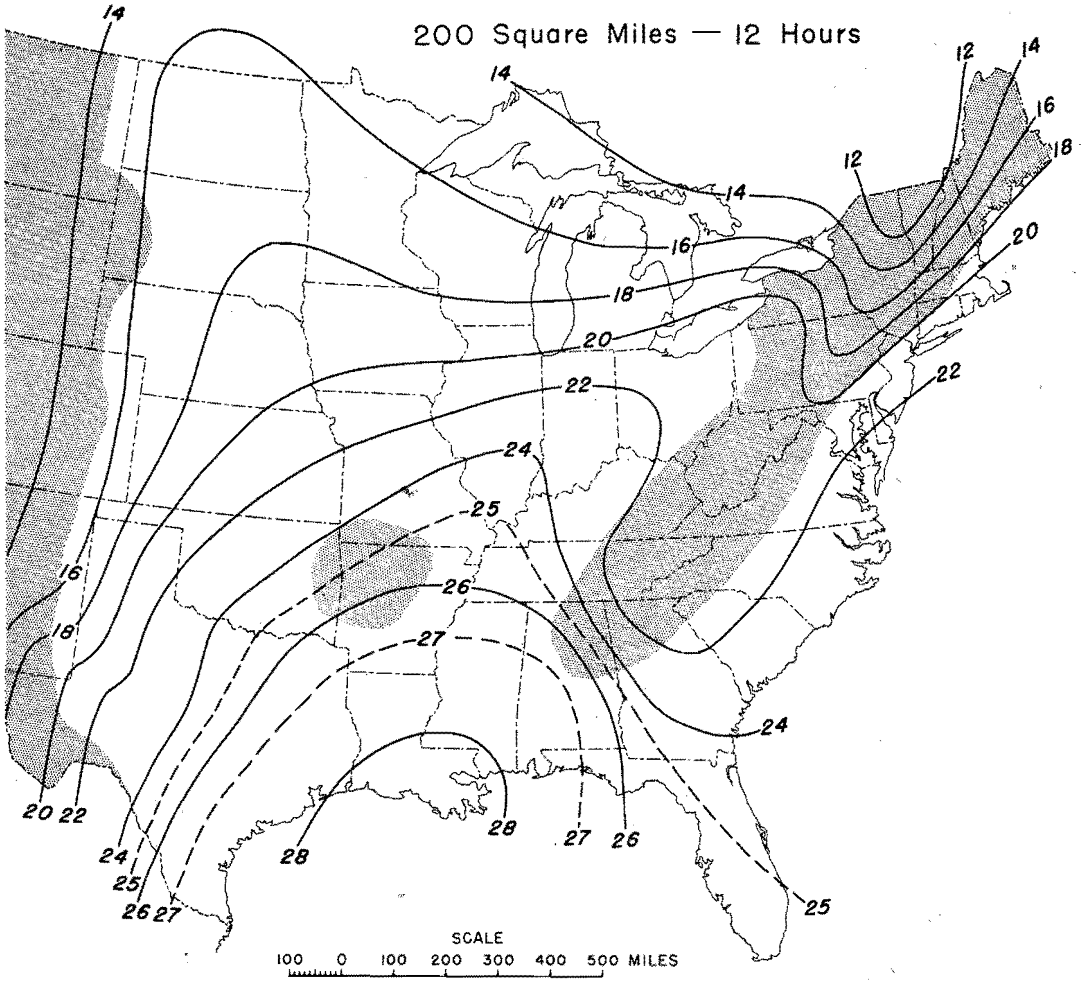
GENERALIZED ESTIMATES
MAXIMUM POSSIBLE PRECIPITATION



THIS CHART is based on data hydrometeorologically analyzed as of April 1947. Limitations of both data and assumptions are discussed in detail in the text, which should be consulted before application of the values. Areas of least reliability are shaded.

Figure 7

GENERALIZED ESTIMATES MAXIMUM POSSIBLE PRECIPITATION



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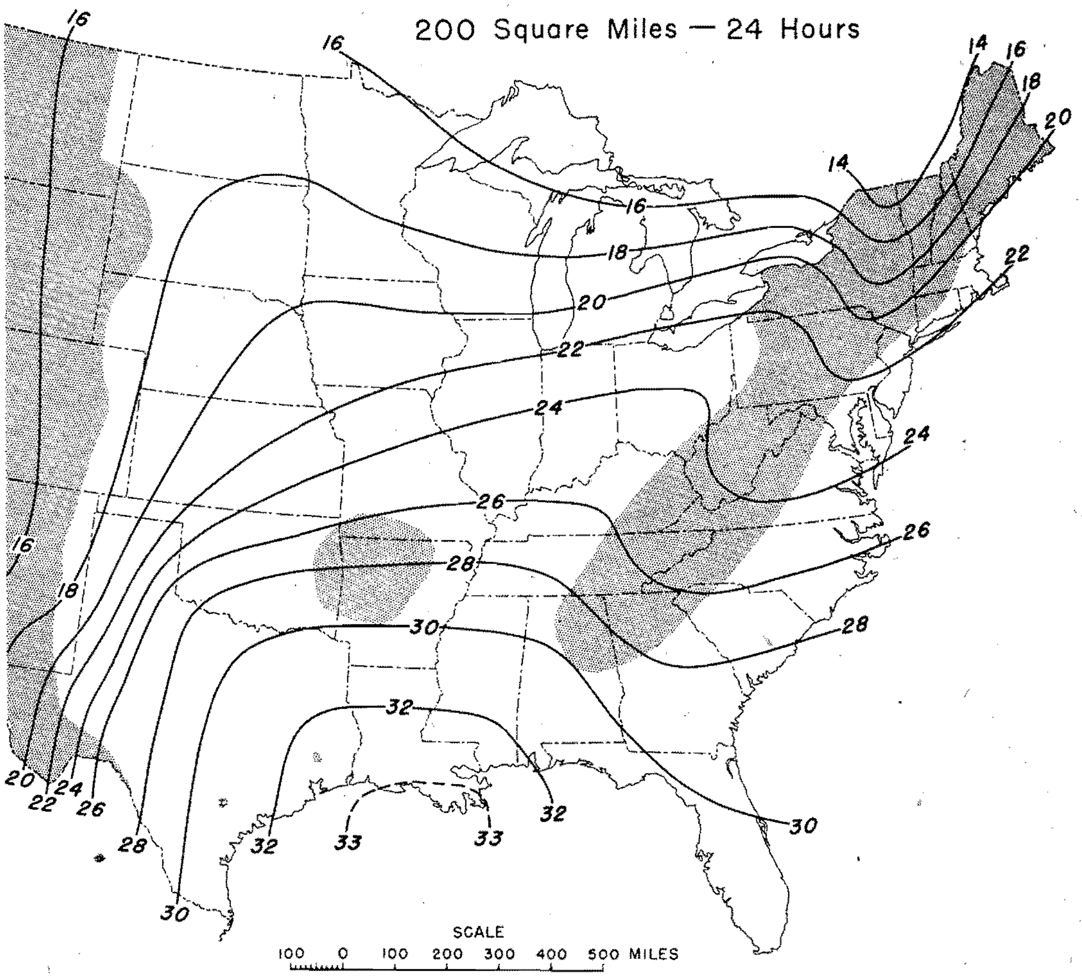
GENERALIZED ESTIMATES
MAXIMUM POSSIBLE PRECIPITATION

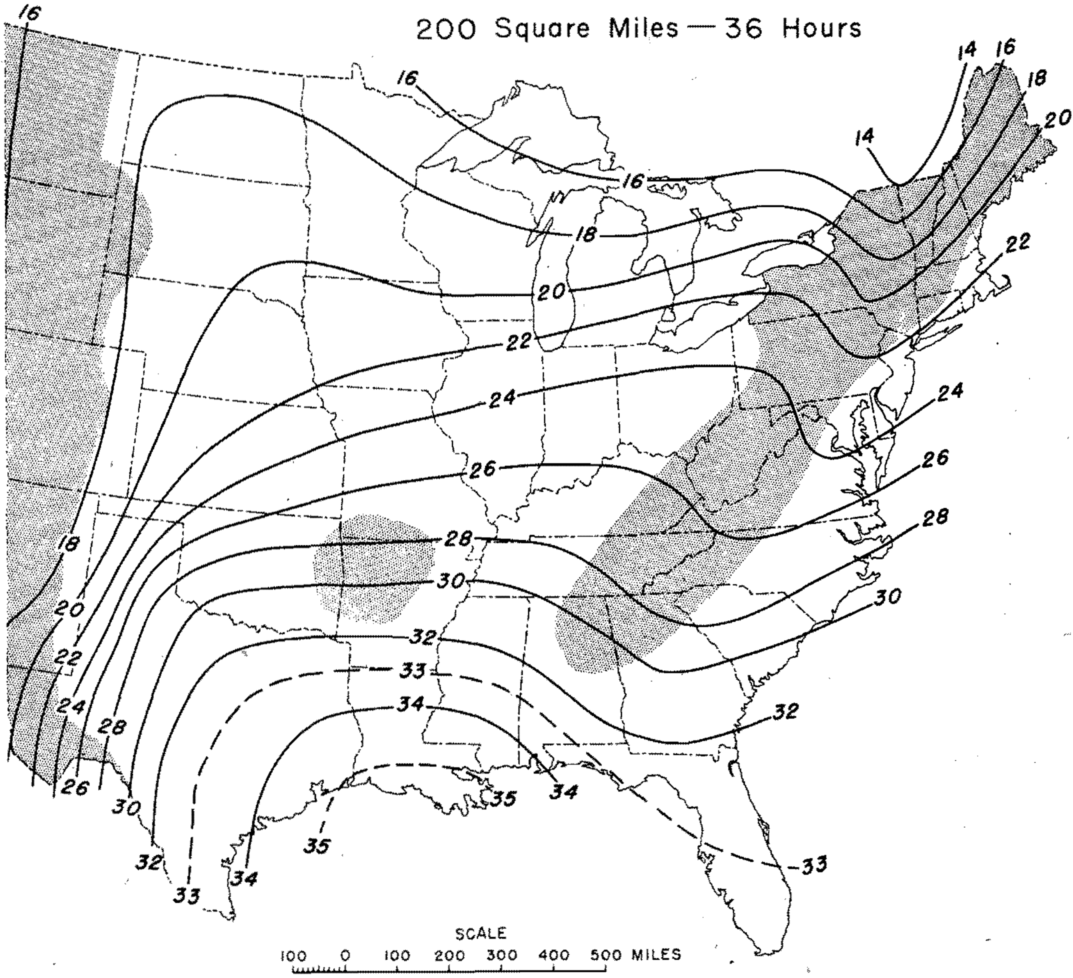


THIS CHART is based on data hydrometeorologically analyzed as of April 1947. Limitations of both data and assumptions are discussed in detail in the text, which should be consulted before application of the values. Areas of least reliability are shaded.

File 47003 Hydrometeorological Report 23 **Figure 9**

GENERALIZED ESTIMATES
MAXIMUM POSSIBLE PRECIPITATION

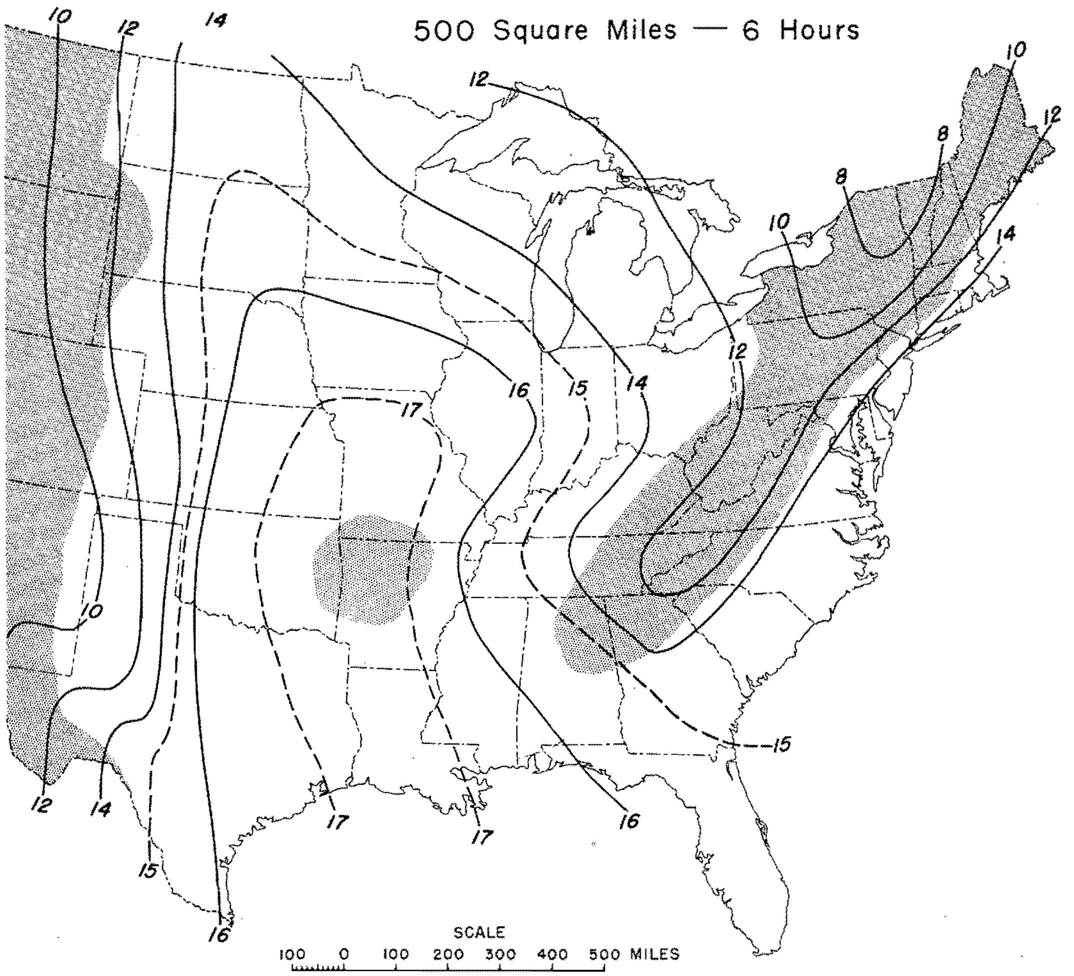
200 Square Miles — 36 Hours



THIS CHART is based on data hydrometeorologically analyzed as of April 1947. Limitations of both data and assumptions are discussed in detail in the text, which should be consulted before application of the values. Areas of least reliability are shaded.

Figure 10

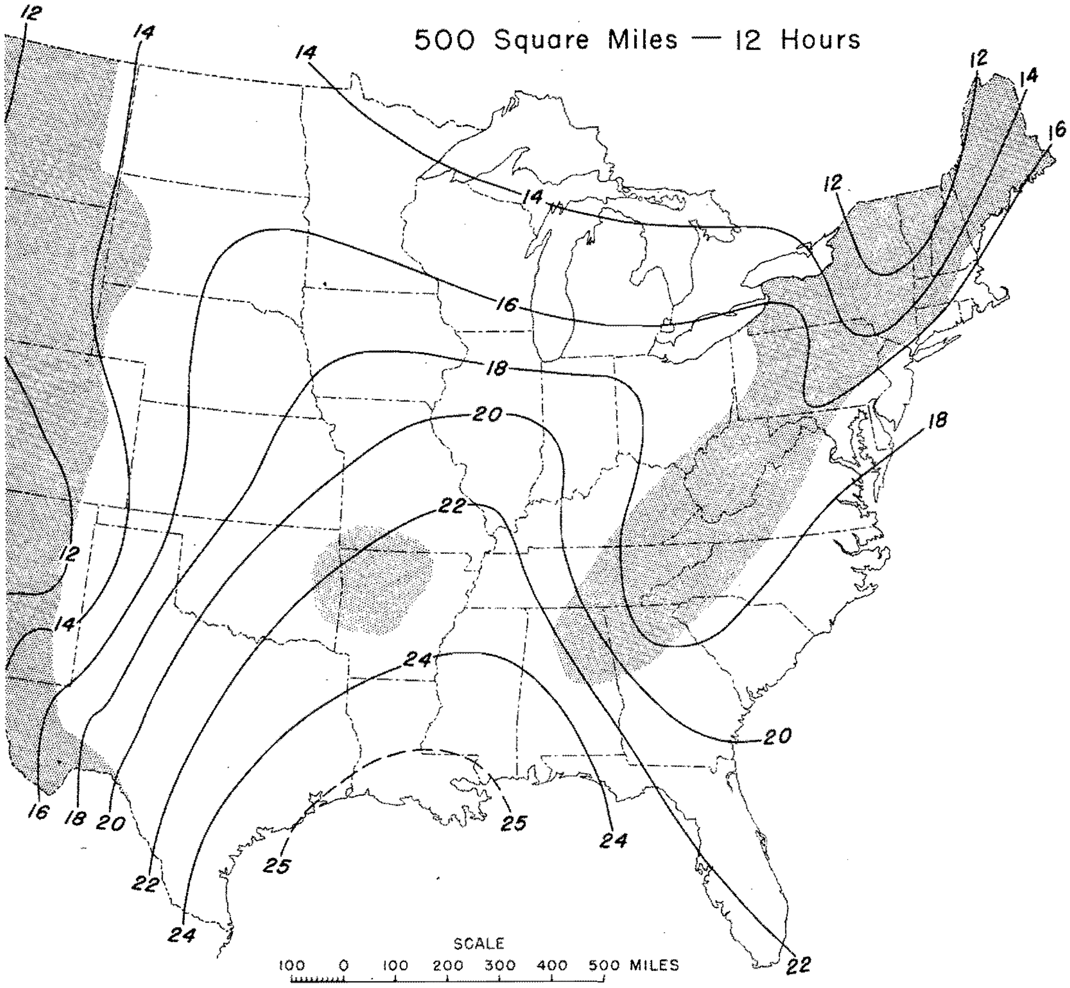
GENERALIZED ESTIMATES
MAXIMUM POSSIBLE PRECIPITATION



THIS CHART is based on data hydrometeorologically analyzed as of April 1947. Limitations of both data and assumptions are discussed in detail in the text, which should be consulted before application of the values. Areas of least reliability are shaded.

Figure 11

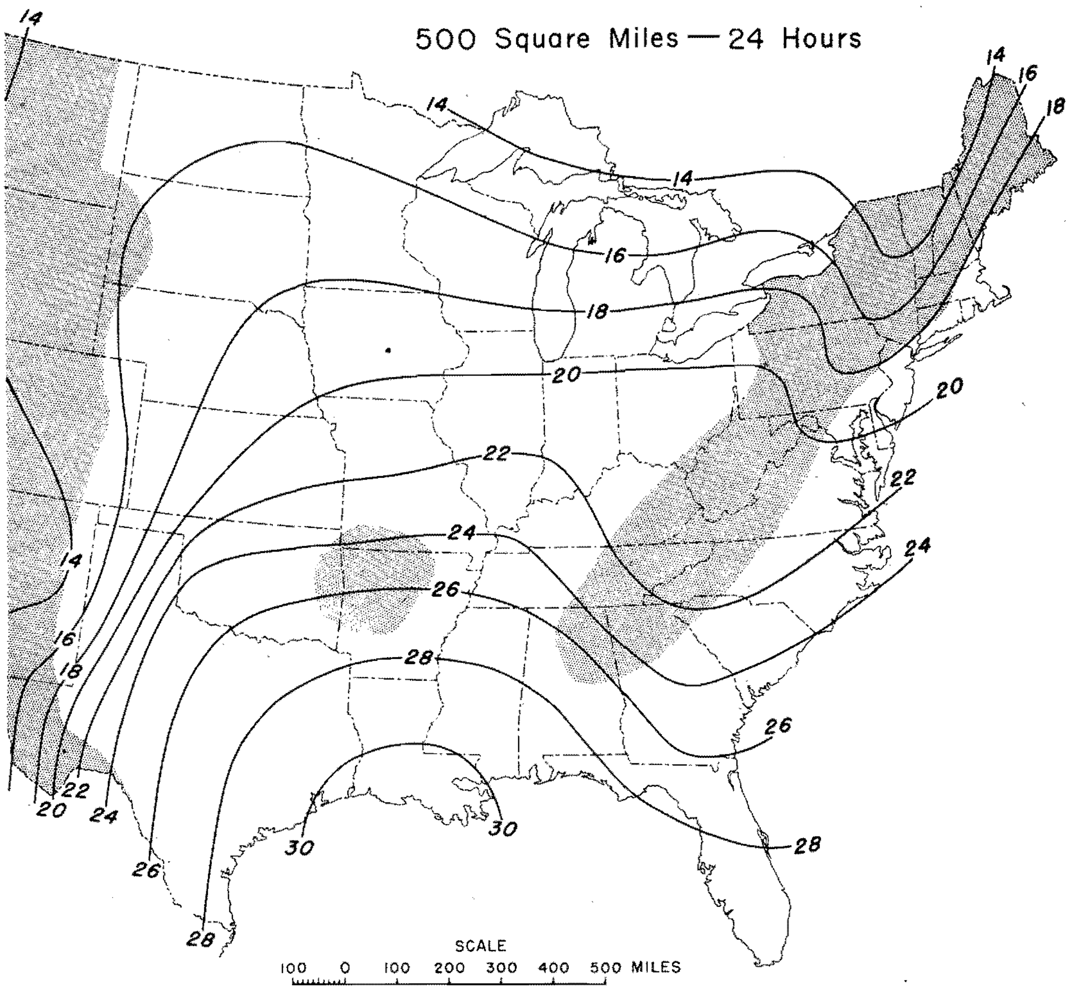
GENERALIZED ESTIMATES
MAXIMUM POSSIBLE PRECIPITATION



THIS CHART is based on data hydrometeorologically analyzed as of April 1947. Limitations of both data and assumptions are discussed in detail in the text, which should be consulted before application of the values. Areas of least reliability are shaded.

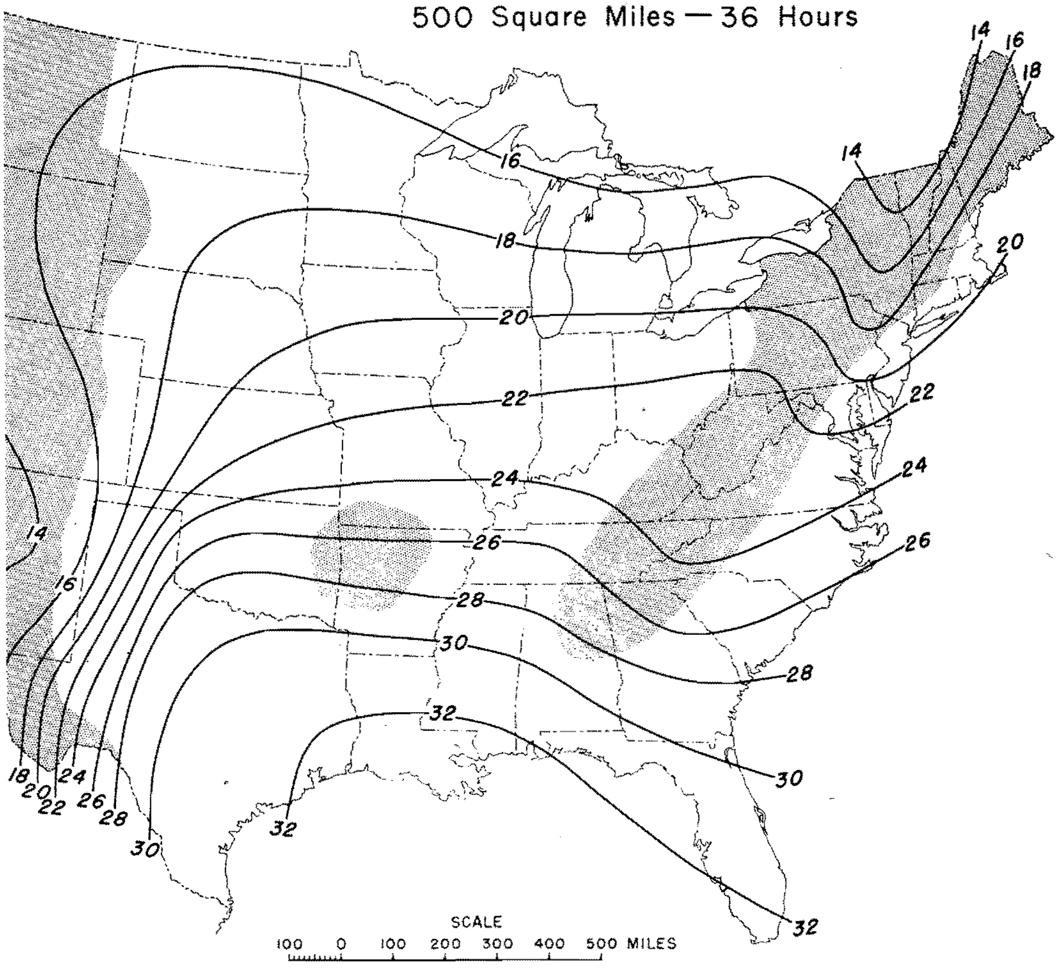
Figure 12

GENERALIZED ESTIMATES
MAXIMUM POSSIBLE PRECIPITATION



THIS CHART is based on data hydrometeorologically analyzed as of April 1947. Limitations of both data and assumptions are discussed in detail in the text, which should be consulted before application of the values. Areas of least reliability are shaded.

GENERALIZED ESTIMATES
MAXIMUM POSSIBLE PRECIPITATION

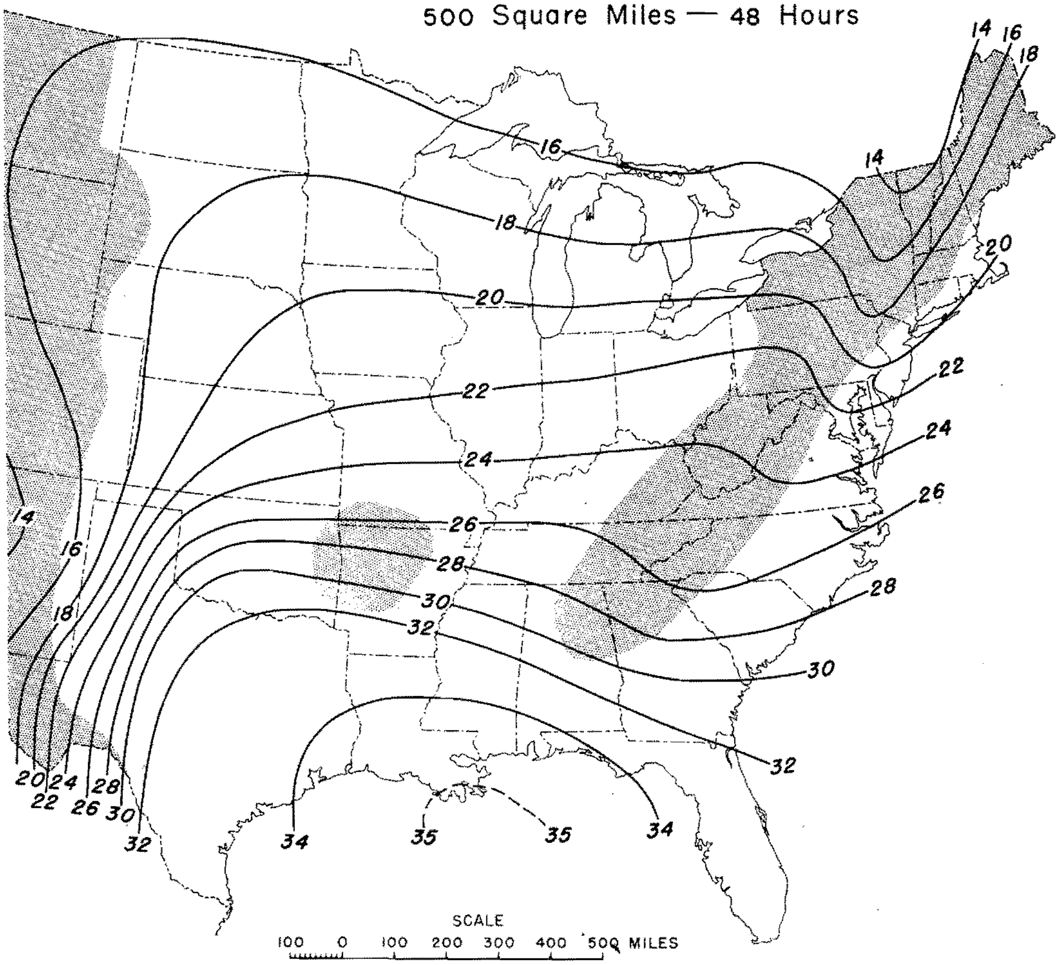


THIS CHART is based on data hydrometeorologically analyzed as of April 1947. Limitations of both data and assumptions are discussed in detail in the text, which should be consulted before application of the values. Areas of least reliability are shaded.

Figure 14

GENERALIZED ESTIMATES
MAXIMUM POSSIBLE PRECIPITATION

500 Square Miles — 48 Hours



THIS CHART is based on data hydrometeorologically analyzed as of April 1947. Limitations of both data and assumptions are discussed in detail in the text, which should be consulted before application of the values. Areas of least reliability are shaded.

Figure 15