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WEATHER BUREAU

TECHNICAL PAPER NO. 49

TWO- TO TEN-DAY PRECIPITATION FOR RETURN PERIODS OF 2 TO 100 YEARS IN THE CONTIGUOUS UNITED STATES

WASHINGTON, D.C.
1964

U.S. DEPARTMENT OF COMMERCE
Luther H. Hodges, *Secretary*

WEATHER BUREAU
Robert M. White, *Chief*

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Two- to Ten-Day Precipitation for Return Periods of 2 to 100 Years in the Contiguous United States

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for
Engineering Division, Soil Conservation Service, U.S. Department of Agriculture

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PREFACE

Authority.—This report was prepared for the Soil Conservation Service to provide generalized rainfall information for planning and design purposes in connection with its Watershed Protection and Flood Prevention Program (authorization: P.L. 566, 83d Congress, and as amended).

Scope.—Precipitation data for various hydrologic design problems involving areas up to 400 square miles and durations from 2 to 10 days are presented. The data consist of generalized estimates of rainfall-frequency data for return periods from 2 to 100 years.

Accuracy of results.—The degree of accuracy of the generalized estimates depicted on the rainfall-frequency maps presented in this report is believed to be adequate for practically all engineering purposes. It should be expected that somewhat greater accuracy might have been obtained had the maps been based on data from the several thousand available precipitation gages instead of from a few hundred. However, the collection and frequency analysis of rainfall data for durations up to 10 days for a few thousand gages would have been a formidable task and an extremely costly enterprise. Furthermore, the accuracy of the results obtained is much greater than indicated by the relatively small number of stations used since the approach involved the projection of the 24-hour rainfall-frequency maps of *Technical Paper No. 40* [1], which are based on data from several thousand stations. The possible greater accuracy that might have been obtained by use of data from a much larger number of gages was judged to be incommensurate with the much greater cost involved.

Acknowledgments.—The project was under the general supervision of J. L. H. Paulhus, Chief of the Cooperative Studies Section of the Office of Hydrology, W. E. Hiatt, Acting Director. L. L. Weiss assisted with the investigations. W. E. Miller and N. S. Foat supervised the collection and processing of the basic data. Drafting was supervised by C. W. Gardner. Coordination with the Soil Conservation Service was maintained through H. O. Ogrosky, Chief, Hydrology Branch, Engineering Division.

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INTRODUCTION

The "Rainfall Frequency Atlas of the United States," [1] presents generalized estimates for durations from 30 minutes to 24 hours and return periods from 1 to 100 years. The present report is an extension of that work. In a series of maps and diagrams this report provides generalized estimates of the precipitation-frequency regime of the United States for durations from 2 to 10 days and for return periods from 2 to 100 years.

A relation for obtaining 10-day values from 1- and 24-hour data was developed and was applied to the 1- and 24-hour values of [1]. Two key maps, the 2-year and 100-year 10-day maps, were then constructed. These maps, together with two key maps from the Atlas, the 2-year and 100-year 24-hour, were used with generalized duration and return-period diagrams to provide estimates for a 3300-point grid for 22 additional maps.

BASIC DATA

Summarization of data.—First, daily data from 94 stations were summarized into sequences from 1 to 10 days. The stations (encircled dots in fig. 1) were so distributed geographically as to provide a good representation of the various precipitation regimes. Their data were the basis for the conversion factors for adjusting observational-day amounts to *n*-hour amounts and for the duration- and return-period—interpolation diagrams. One- and 10-day data were then sumarized for 276 additional stations (plain dots in fig. 1). These data were used to supplement the data from the first group of 94 stations to develop the relation between 1- and 10-day amounts.

Period and length of record.—Data for the 94 stations in the first category were tabulated for the 50-year period, 1912–61, except for a few cases of missing or incomplete data. The average length of record available from all stations was 49 years. Data for the 276 stations in the second group were tabulated for the 20-year period, 1942–61. Breaks in record at a few stations necessitated tabulation of a few years of data prior to 1942 to obtain a 20-year record. In a few cases, 18 or 19 years of data were used when a 20-year record was not available. In no case, however, was less than 18 years of data used.

Station exposure.—In refined analysis of mean annual and mean seasonal rainfall data it is necessary to evaluate station exposures by methods such as double-mass-curve analysis [2]. Such methods are not appropriate for extreme values. Except for selection of stations that had had consistent exposures during the period of record used, no attempt has been made to adjust precipitation values to a standard exposure.

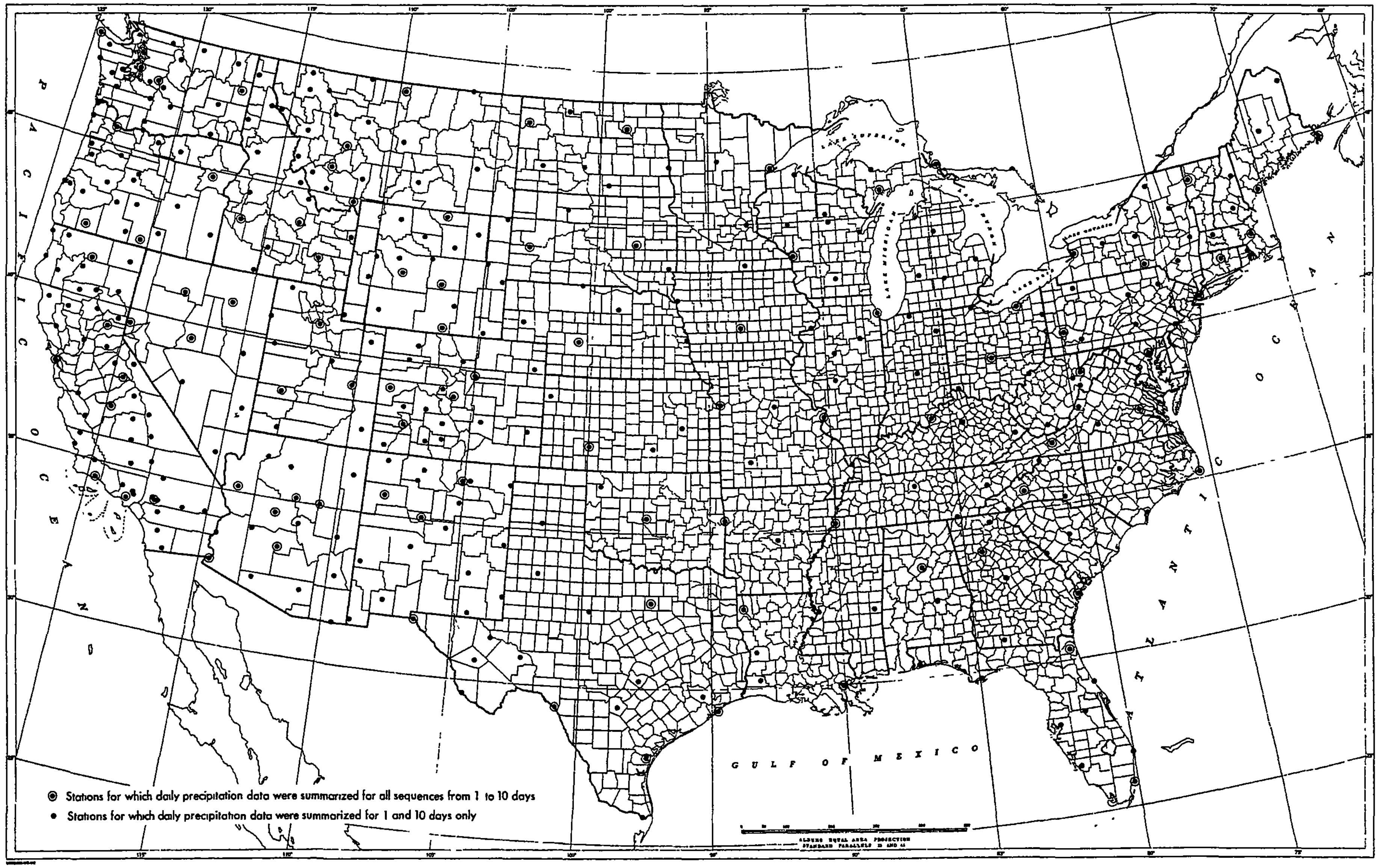

FIGURE 1.—Precipitation stations.

DURATION ANALYSIS

Observational-day vs. n-hour precipitation.—Since the basic data consisted mostly of observational-day amounts, relations had to be established between observational-day data and the corresponding n-hour amounts, i.e., the 2-observational-day to 48-hour, the 3-observational-day to 72-hour, etc. These relations are ratios of the mean of the annual series (see section on Frequency Analysis) of the n-hour precipitation to the mean of the annual series of the corresponding observational-day data. The adjustment factors are shown in table 1. The conversion factor between the observational-day and n-hour amounts is an average relationship. A graphical illustration of the quality of the relationships, based on data from 50 widely distributed stations, is shown in figure 2 for the 2-year 48-hour and 2-observational-day precipitation. Differences between amounts for the 48-hour and longer durations and the corresponding n-minute amounts are negligible.

TABLE 1.—*Empirical factors for converting observational-day amounts to the corresponding* n*-hour amounts*

Observational-day	Conversion factor to n-hour
2	1.04
3	1.03
4	1.03
5	1.02
6	1.02
7	1.02
8	1.02
9	1.01
10	1.01

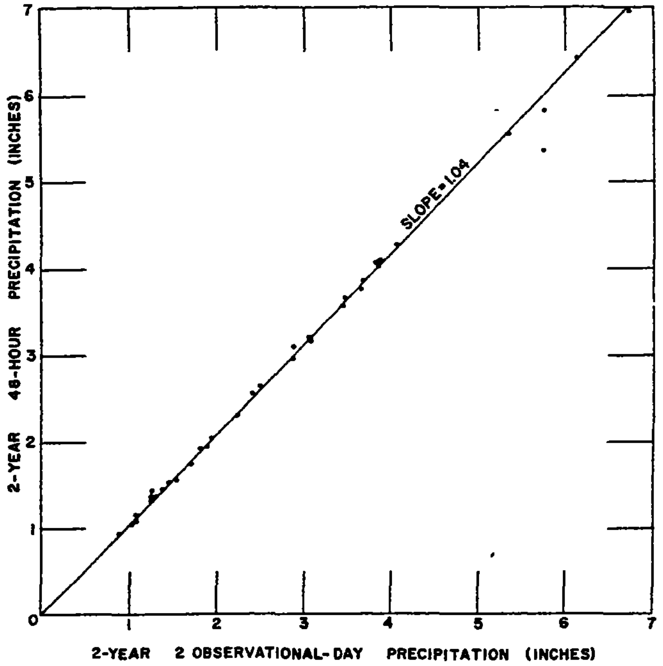

FIGURE 2.—Relation between 2-year 2-observational-day and 2-year 48-hour precipitation.

Duration-interpolation diagram.—A generalized relationship was developed for estimating precipitation for any duration between 2 and 10 days for a selected return period when the 2- and 10-day amounts for that return period are given (fig. 3). This generalization was obtained empirically from data for the 94 stations. The duration-interpolation diagram was developed using data for the 2-year return period. To use this diagram, a straightedge is laid across the values given for 2 and 10 days, and the amounts for other durations are read at the proper intersections. The quality of this relationship is illustrated in figure 4 for the 96-hour duration and 2-year return period. Tests have shown negligible differences for other return periods. The inclusion of regional variation and other parameters produced no improvement.

FREQUENCY ANALYSIS

Two types of series.—Frequency analyses of precipitation data are based on one of two types of data series. The annual series consists only of the highest value for each year. The partial-duration series recognizes that the second highest of some year occasionally exceeds the highest of some other year, and utilizes all items above a base value which is selected to yield n-items for n-years. The highest value of record, of course, is the top value of either series, but the lower values in the partial-duration series tend to be higher than those of the annual series.

The purposes served by this publication require that the results be expressed in terms of partial-duration frequencies. In order to avoid laborious processing of partial-duration data, the annual series were collected, analyzed, and the resulting statistics transformed to partial-duration statistics. Consequently, the maps of figures 12 to 35 are, in effect, based on partial-duration series data. These data may be converted to annual series data by multiplying by the factors given in table 2, which is based on data from 25 widely scattered stations. The two types of data series show no appreciable differences for return periods greater than 10 years. These conversion factors are the same as those used in [1].

TABLE 2.—*Empirical factors for converting partial-duration series to annual series*

Return period	Conversion factor
2-yr.	0.88
5-yr.	0.95
10-yr.	0.99

Frequency considerations.—Extreme values of rainfall depth form a frequency distribution which may be defined in terms of its statistical moments. Investigation of hundreds of rainfall distributions, with lengths of record ordinarily encountered in practice (usually less than 50 years) indicates that these records are too short to provide reliable statistics beyond the first and second moments. The distribution must therefore be regarded as a function of the first two moments. The 2-year value is a measure of the first moment—the central tendency of the distribution. The relationship of the 2-year to 100-year value is a measure of the second moment—the dispersion of the distribution.

Construction of return-period diagram.—The return-period diagram of figure 5 was obtained by the method described by Weiss [3]. If values for return periods between 2 and 100 years are read from the return-period diagram, then converted to annual series values by applying the factors of table 2 and plotted on either extreme or log-normal probability paper, the points will very nearly define a straight line.

Use of the return-period diagram.—The two intercepts needed for the frequency relation of figure 5 are the 2-year and 100-year values obtained from the maps of this report. Thus, given the 2- and 100-year return-period values for a particular duration, a straightedge is laid across these values on the diagram and the intermediate values are determined.

General applicability of return-period relationship.—Tests have shown that within the range of the data and the purpose of this paper, the return-period relationship is independent of duration. Comparison of this relationship with that developed for durations less than 24 hours [1] has shown only negligible differences. Studies have not disclosed any regional pattern that would improve the relationship.

Secular trend.—The use of short-record data introduces the question of possible secular trend and biased sample. Routine tests with subsamples of equal size from different periods of record for each of several stations showed no appreciable trend, indicating that the direct use of short-record data is legitimate.

ISOPLUVIAL MAPS

Relation between 2-year 24- and 240-hour amounts.—Processing of hourly data for durations in excess of 24 hours is a laborious and costly task. For this reason, it was decided to estimate rather than compute 2- to 10-day rainfalls for the majority of the stations. Relationships, using in part data already available for the shorter

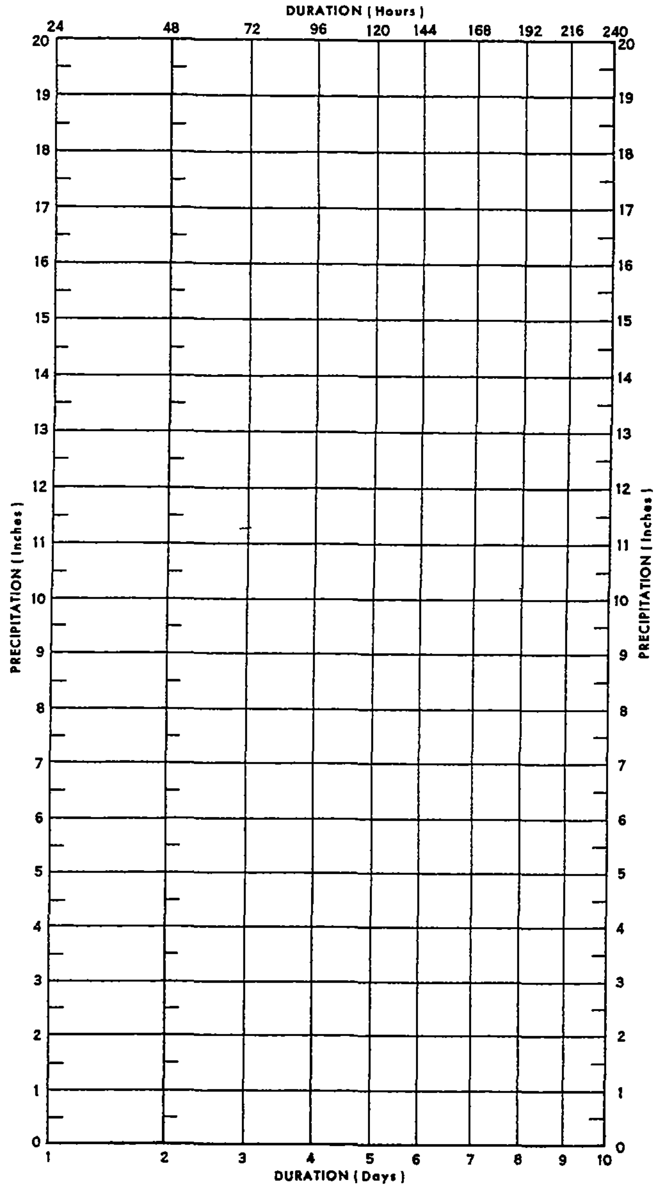

FIGURE 3.—Duration-interpolation diagram.

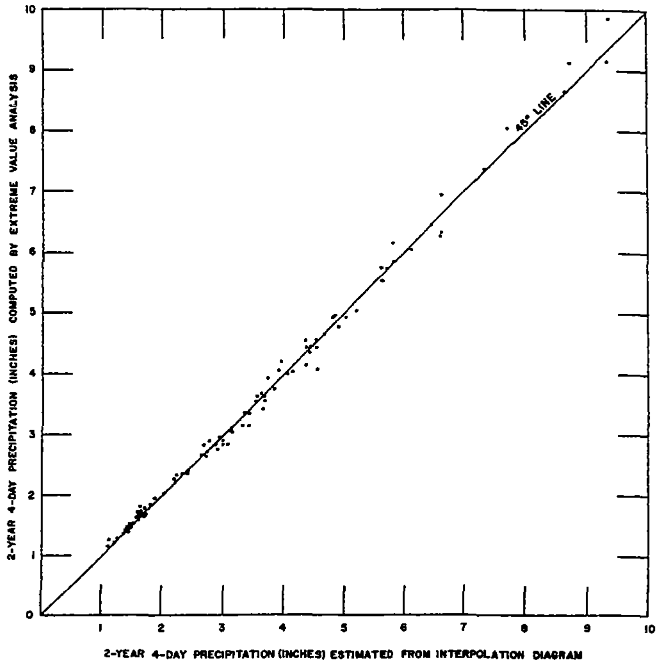

FIGURE 4.—Relation between 2-year 4-day precipitation computed by extreme value analysis and 2-year 4-day precipitation estimated from duration-interpolation diagram (fig. 3).

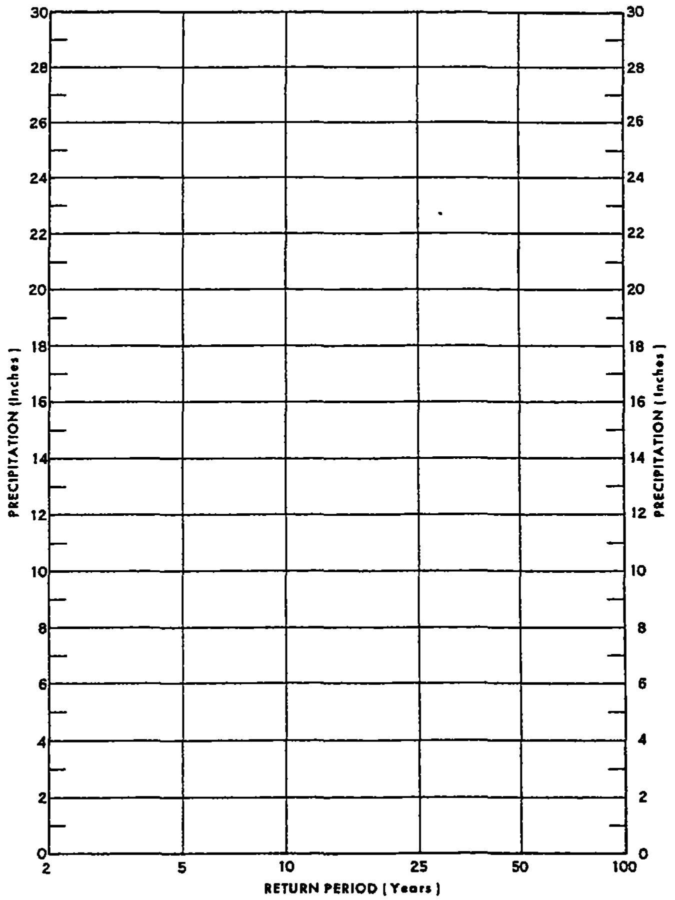

FIGURE 5.—Return-period—interpolation diagram.

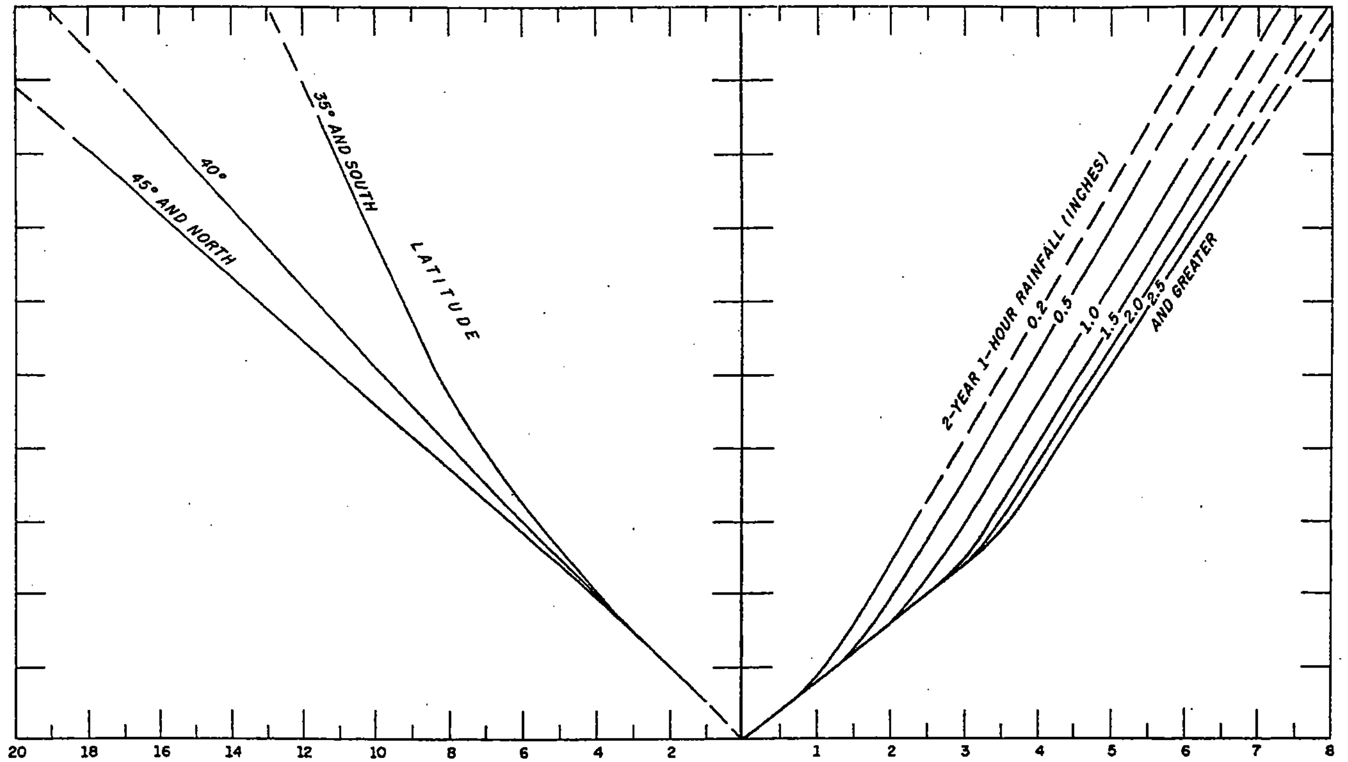

FIGURE 6.—Relation for estimating 2-year 10-day precipitation from 2-year 1- and 24-hour rainfall and latitude.

durations, were developed to estimate amounts for longer durations. Since satisfactory duration-interpolation and return-period diagrams were available, the 10-day duration was selected for development of such a relation. A total of 285 stations with hourly data provided the basic data. The parameters used to estimate the 2-year 10-day values were: (1) the 2-year 24-hour rainfall, (2) the 2-year 1-hour rainfall, and (3) latitude. The use of latitude as a parameter implies a smooth geographic variation with isopleths of departure of estimated from computed 2-year 10-day amounts parallel to the latitude circles. To test this hypothesis departures from the computed 2-year 10-day amounts were plotted on a map. The isopleths showed that, in general, there was an orderly latitudinal variation in these departures. In the development of this relationship (fig. 6) all 24- and 1-hour data were adjusted to the corresponding *n*-minute amounts. The 10-day values were adjusted to the corresponding 240-hour amounts.

Introduction of additional parameters in the relationship of figure 6 did not improve the results. Other parameters tested included elevation and mean annual number of days with precipitation greater than 0.49 in. The index of correlation between the computed and estimated amounts was 0.99, with a standard error of estimate of 0.53 in. The mean of the computed values was 5.31 in. The scatter of estimated vs. computed values is shown in figure 7.

Smoothing of isopluvial maps.—The analysis of a series of maps involves the question of how much to smooth the data. An understanding of the degree of smoothing in the analysis is necessary to the most effective use of the maps. The problem of drawing isopluvial lines through a field of data is analogous, in some important respects, to drawing regression lines on a scatter diagram. Just as an irregular regression line can be drawn to every point on a scatter diagram, so isolines may be drawn to fit every point. Such a complicated pattern of many small highs and lows would be unrealistic in most cases. There is a degree of inconsistency between smoothness and closeness of fit. Any analysis must strive for a balance between the two, sacrificing some closeness of fit for smoothness and vice versa. The maps of this report were drawn so that the standard error of estimate was commensurate with the sampling and other errors in the data and methods used.

2-year 10-day map (fig. 30).—The relationship (fig. 6) described in the preceding paragraphs, and the 2-year 1-hour and 2-year 24-hour maps of [1] were used to estimate the 2-year 10-day values for a grid of 3300 points (fig. 8). Also plotted on the map were the data for the 370 stations (fig. 1) for which 10-day data had been tabulated. On this and other similar maps all precipitation data have been adjusted by the factors of table 1 to *n*-hour amounts, i.e., the 2-day map presents 48-hour amounts, the 4-day presents 96-hour amounts, etc.

Ratio of 100-year to 2-year values.—A working map was prepared showing the 100-year to 2-year ratio for the 10-day amounts. A smooth geographical pattern was indicated. The ratio varied from about 1.8 to 3.0 with an average ratio about 2.2. The highest ratios were found in southern California and along the western slopes of the Sierra, with the lowest ratios in western Oregon and Washington.

100-year 10-day map (fig. 35).—The 100-year 10-day values were computed for the grid points of figure 8 by multiplying the values read from the 2-year 10-day map by those from the 100- to 2-year ratio map. As a further aid in the analysis of the isopluvial pattern, the 100-year 10-day values computed for the 370 stations for which data had been processed were also plotted, in addition to the grid points.

22 additional maps.—For the 22 intermediate maps required for this report, values were computed for the 3300 grid points (fig. 8). First, values were read from the 2-year 24-hour and 10-day maps and the 100-year 24-hour and 10-day maps. Then, the duration-interpolation diagram (fig. 3) and the return-period diagram (fig. 5) were used to compute amounts for the grid points. The frequency values

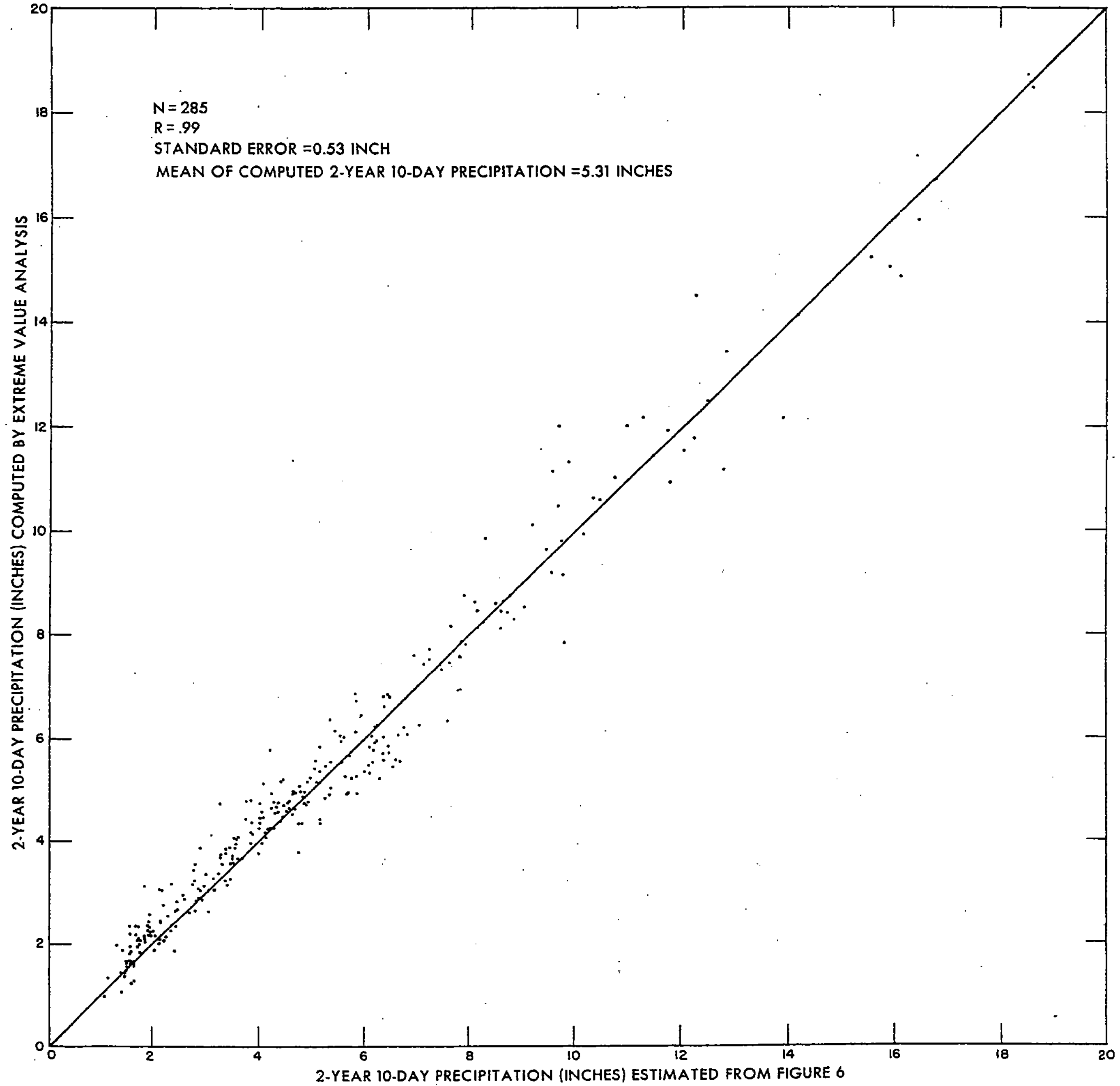

FIGURE 7.—Relation between 2-year 10-day precipitation computed by extreme value analysis and 2-year 10-day precipitation estimated from figure 6.

computed for stations for which data were processed were also plotted on each of the maps. Isolines were then drawn. Pronounced "highs" and "lows" are positioned in consistent locations on all the maps. The 24 precipitation-frequency maps are shown at the end of the text (figs. 12–35).

Reliability of results.—The term reliability is used here in the statistical sense to refer to the degree of confidence that can be placed in the accuracy of the results. The reliability is influenced by the accuracy of [1] and the accuracy of the relationships developed for this report. The accuracy of the results presented in [1] was discussed in that report. The reliability of the relationships developed may be partially assessed by reference to the various figures indicating a measure of their quality. The scatter of points in these diagrams is a result of sampling error in time and space. Sampling error in space is a result of: (1) the chance occurrence of an anomalous storm which has a disproportionate effect on the record at a station as compared with that of a nearby station, and (2) the use of station data that are not representative of the rainfall regime of the surrounding area. Similarly, sampling error in time results from the use of data for a given period that is not representative for a longer period.

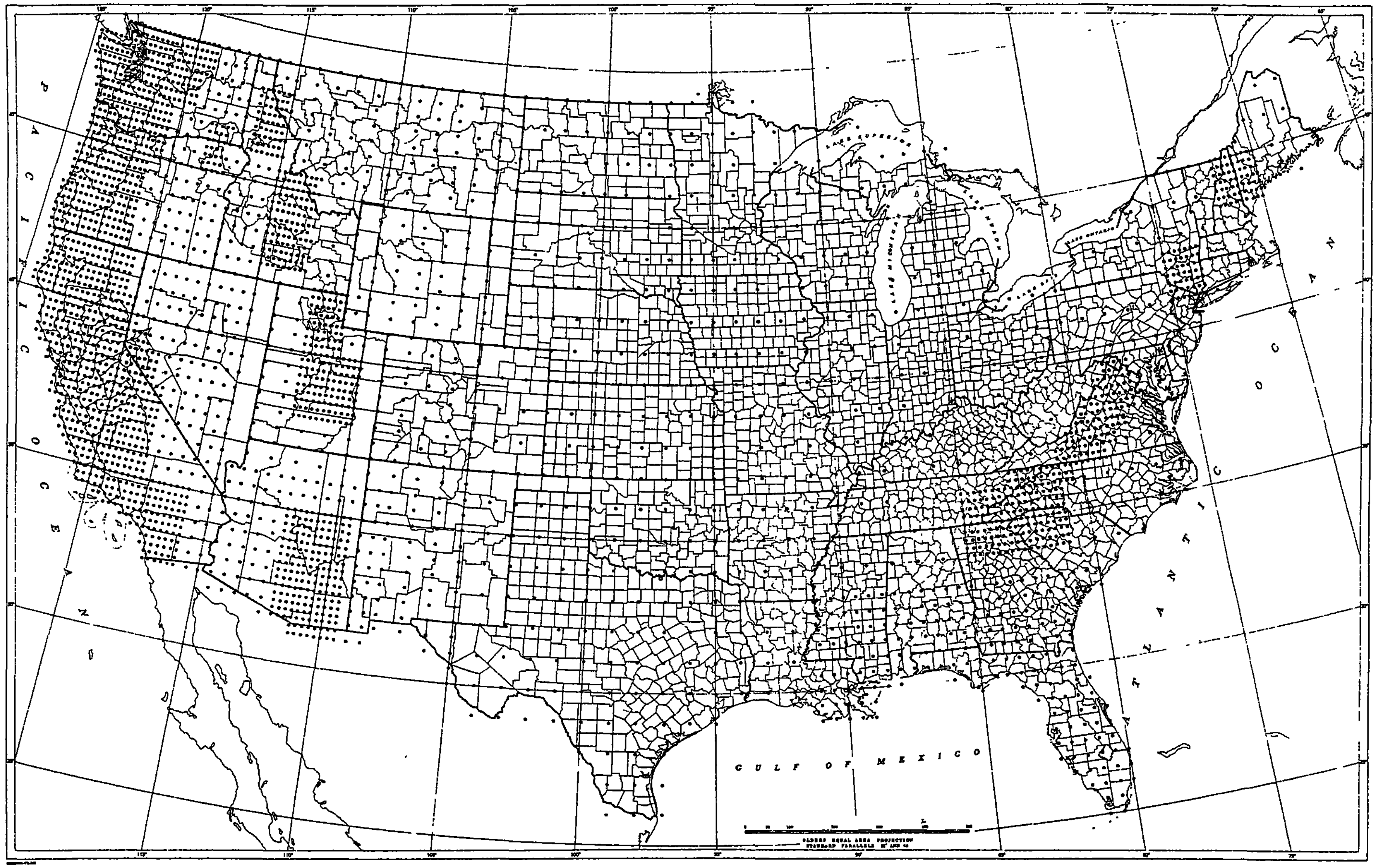

FIGURE 8.—Points for which precipitation-frequency data were computed in deriving the 22 intermediate maps from the 4 key maps, the 2-year 24-hour and 10-day and the 100-year 24-hour and 10-day.

Isoline interval.—In general, a different isoline interval was used east and west of 105° W. longitude. Within each region a dashed intermediate line was added if the isopluvials were widely separated or if the spacing of isopluvials was nonlinear to minimize the errors of interpolation. Occasionally, along the slopes of the Sierras and Cascades of California, Washington, and Oregon, it was necessary to omit an isopluvial because of the extremely steep gradient. Lows that close within the boundaries of the United States have been hatched inwardly.

Smoothing values read from the maps.—The complex patterns and steep gradients of the isopluvials combined with the difficulties of interpolation and accurate location of a specific point on a series of maps might result in inconsistencies in data read from the maps. Such inconsistencies can be minimized by fitting smooth curves to a plot of the data obtained from the maps. Figure 9 illustrates two sets of curves on logarithmic paper, one for a point (a) 39° N., 90° W. and the other (b) at 40°30′ N., 111°15′ W. Data for the 24-hour values for these curves have been taken from [1]. An alternative procedure would be to read these values from the duration-interpolation diagram (fig. 3).

In one plot in figure 9 the curve of best fit is a straight line, while in the other, a curve provides a better fit. In regions where the isopluvial pattern is relatively simple and exhibits flat gradients, minor differences in locating points have less effect on the interpolated values, and the plotted points will more clearly define a smooth set of curves. In mountainous regions complex patterns and steep gradients complicate interpolation, and the curves will be more poorly defined.

Interpolated values for a particular duration should define an almost straight line on the return-period diagram of figure 5. Also, the interpolated values for a particular return period should very nearly define a straight line on the duration-interpolation diagram of figure 3.

DEPTH-AREA RELATIONSHIPS

Introduction.—Any value read from an isopluvial map for a point is an average depth for the location, for a given return period and duration. The depth-area curve attempts to relate this average point value, for a given duration and frequency and within a given area, to the average depth over that area for the same duration and frequency. The curves of figure 10 depict the relationship for durations of 1 to 10 days and for areas up to 400 square miles, and are to be used in reducing the point values of precipitation shown on the maps of figures 12 to 35 to areal values.

Data used.—Data from 27 dense networks were used to develop the depth-area curves of figure 10. The networks, together with the total area, number of gages, number of subnetworks, and length of record are listed in table 3, and their locations are shown in figure 11. The average length of record used was 17 years. Only networks that had at least 10 years of record were considered. The denser networks were subdivided to provide additional points for the smaller areas.

Determination of area of networks.—There is no completely satisfactory method for determining the size of the area for which the precipitation measured by a particular network may be considered to be representative. The size of the area represented by a network in this study was presumed to be equal to the area of the smallest circle encompassing the network. It should not be inferred, however, that such a circle actually delineates the shape and location of the "true" representative area.

Construction of the curves.—The annual series for the period of record for each network was tabulated for the 24- and 48-hour durations, and the 2-, 5-, 10-, 25-, 50-, and 100-year values were computed. The method of computation for the percentage reduction for each network was the same as that used in [4]. These percentage reductions were then plotted on a series of charts, one for each return period, and curves were fitted by eye. The curves for the various return periods were compared, and a mean curve was drawn for each duration. The individual curves drawn for the different return periods varied by no more than about 1 percent from the mean curve, indicating that there was no need for separate curves for each return period.

The 24-hour curve showed only negligible differences from that used in previous reports [1, 4], and it was therefore decided to use the curve originally developed for those reports. For durations longer than 48 hours "cross section" at several sizes of area were taken, and the percentages for the 1-, 24-, and 48-hour values were plotted on semilogarithmic paper. A smooth curve for each size of area was then drawn through these plotted points and extrapolated to 240 hours. Data for the longer durations for a few networks were then tabulated and used to check the extrapolation.

Geographic variation.—While the area-reduction curves of figure 10 are based on networks widely scattered throughout the country, there are many large regions not represented by a network (fig. 11). In the process of constructing the curves, the data from the different networks were closely examined in an attempt to detect regional variations. None was apparent. However, it should be kept in mind that the network sampling was not adequate for delineating regional variations and that the lack of any indication of such variation is not conclusive. Pending the availability of additional dense network data, the curves of figure 10 must be considered applicable to all parts of the country.

SEASONAL VARIATION

The basic data for the precipitation-frequency maps of figures 12 to 35 show seasonal trends. Some months may contribute most of the annual series or partial series data used in the frequency analyses, while other months may contribute little or nothing. Also, the months contributing most of the series data for the shorter durations, say, one or two days, may not be the same as those contributing most of the data for the longer durations, say, nine or ten days. *Technical Paper No. 40* [1] presented a series of seasonal probability charts for 1-, 6-, and 24-hour rainfall for the region east of the Rockies. None was presented for the mountainous region to the west because of the effects of local climatic and topographic influences.

Seasonal probability curves were not derived for this report because the relatively small number of stations providing the basic data precluded the delineation of the boundaries of areas of representativeness for seasonal probability curves. Data from many more stations would have been required to depict properly the regional variations of the seasonal probability curves. It appeared that their usefulness was not commensurate with the costs of collecting and processing the additional data required for their construction.

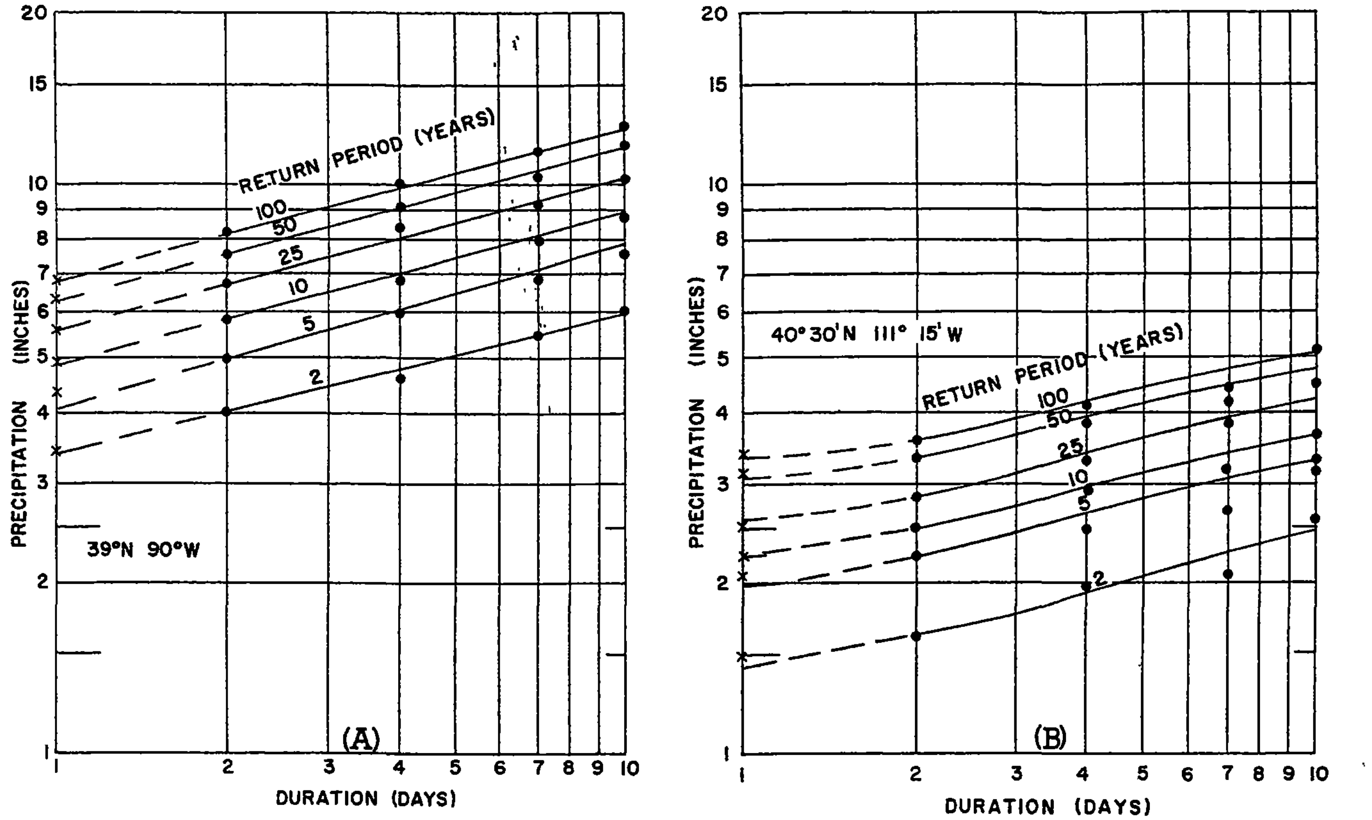

FIGURE 9.—Smoothing values read from isopluvial maps. Points are values read from maps of figures 12 to 35 for (A) 35°00′ N., 90°00′ W., and (B) 40°30′ N., 111°15′ W. The x's are values obtained from the maps of [1].

TABLE 3.—*Dense network data*

Network	Area (sq. mi.)	Total No. of gages	No. of Sub-networks	Length of record (years)
California 1	107	4	0	15
California 2	134	4	0	22
California 3	285	4	0	15
California 4	314	4	0	10
California 5	177	5	4	15
California 6	490	6	2	18
California 7	200	4	1	17
California 8	176	4	0	11
California 9	78	5	1	12
California 10	414	4	0	20
Connecticut 1	315	5	2	22
Florida 1	221	5	1	22
Georgia 1	345	4	2	15
Illinois 1	380	13	10	21
Iowa 1	63	9	7	21
Maryland 1	254	7	6	18
Missouri 1	66	5	2	14
Missouri 2	176	7	2	11
New Jersey 1	283	7	5	15
New Jersey 2	150	6	6	23
New York 1	283	4	1	18
New York 2	433	5	4	14
Ohio 1	78	4	1	19
Oregon 1	200	4	1	22
Oregon 2	330	5	0	17
Texas 1	242	4	0	19
Washington 1	380	4	0	12

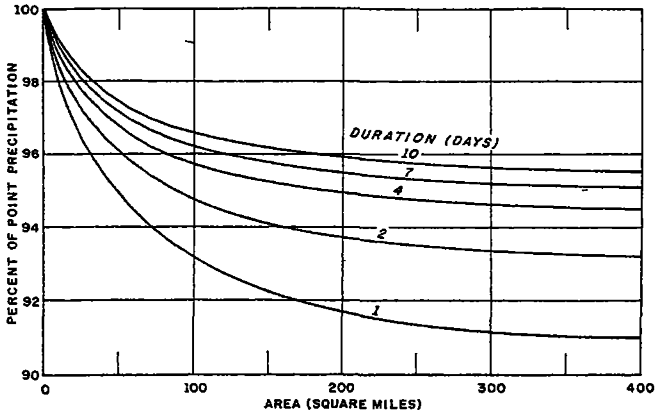

FIGURE 10.—Depth-area curves.

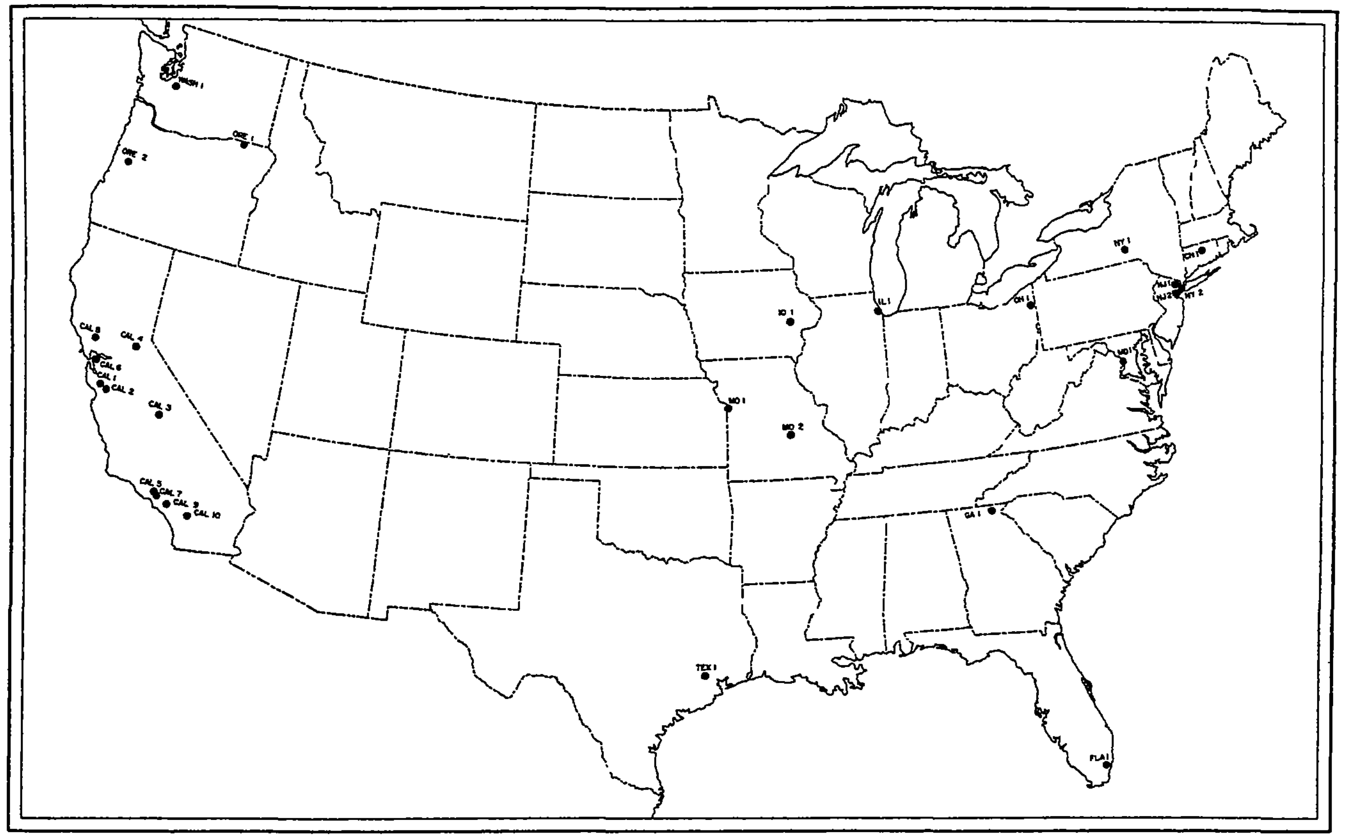

FIGURE 11.—Location of dense networks used to develop depth-area curves.

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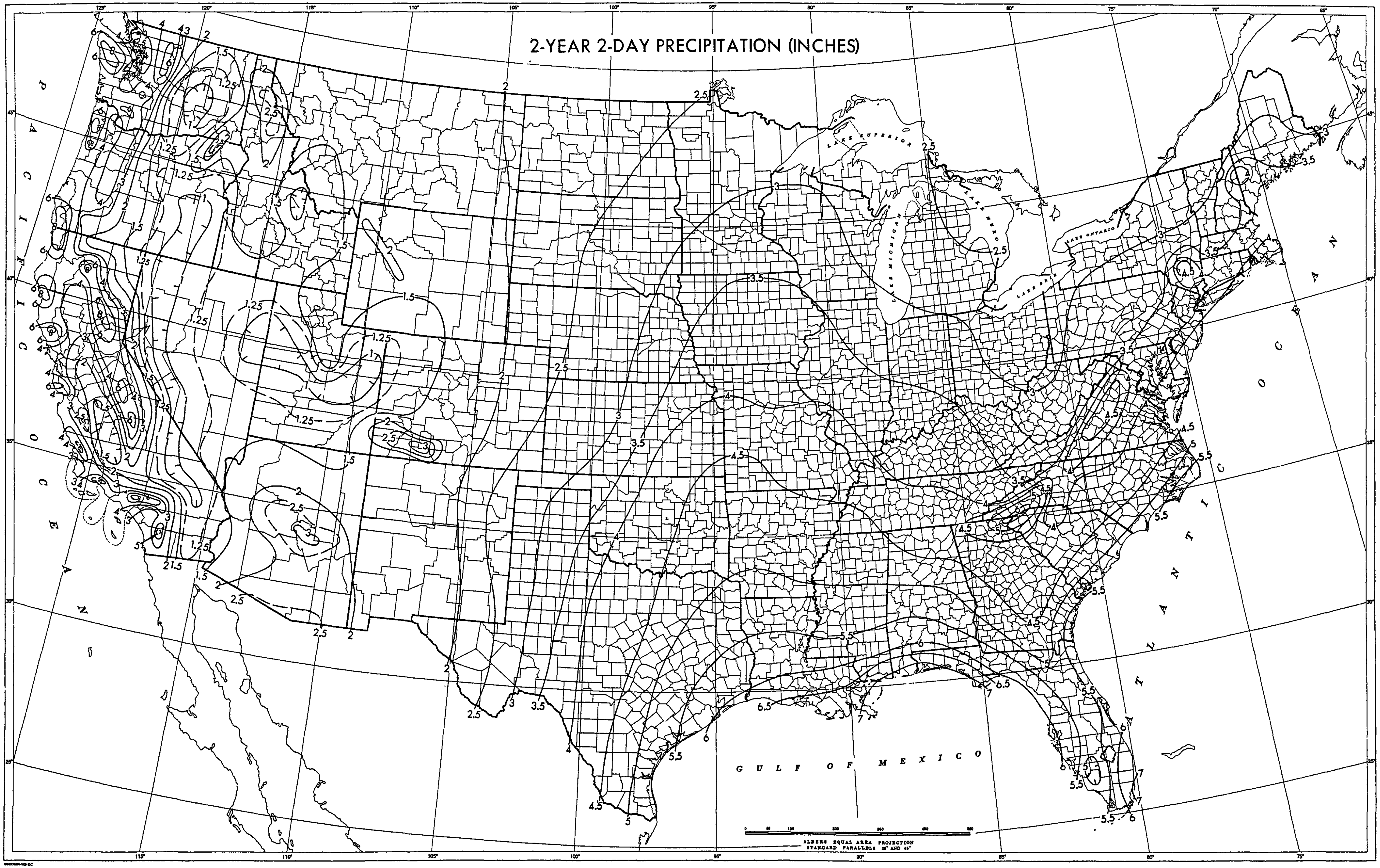
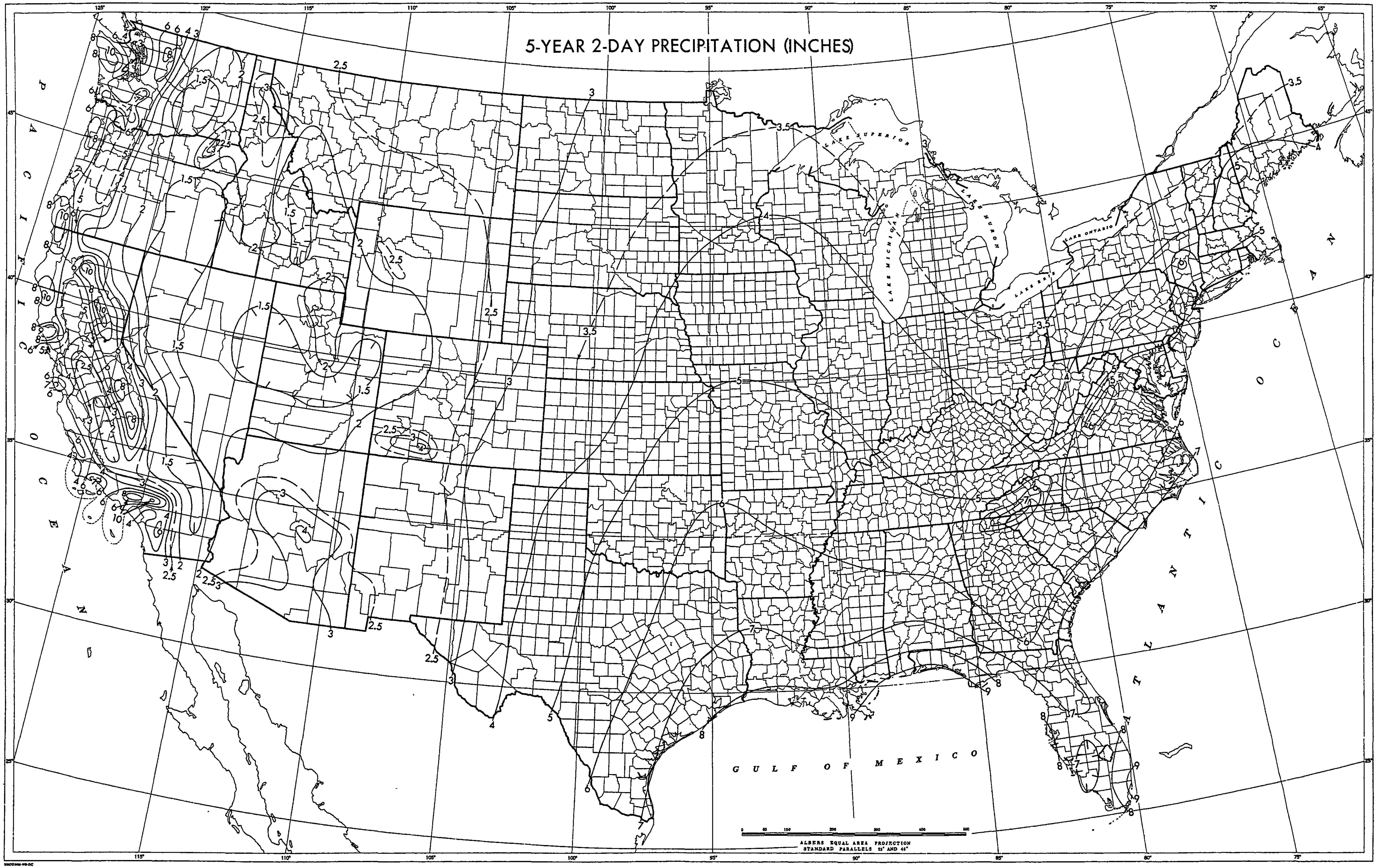


FIGURE 12.—2-year 2-day precipitation (in.).



5-YEAR 2-DAY PRECIPITATION (INCHES)

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Figure 13.—5-year 2-day precipitation (in.)

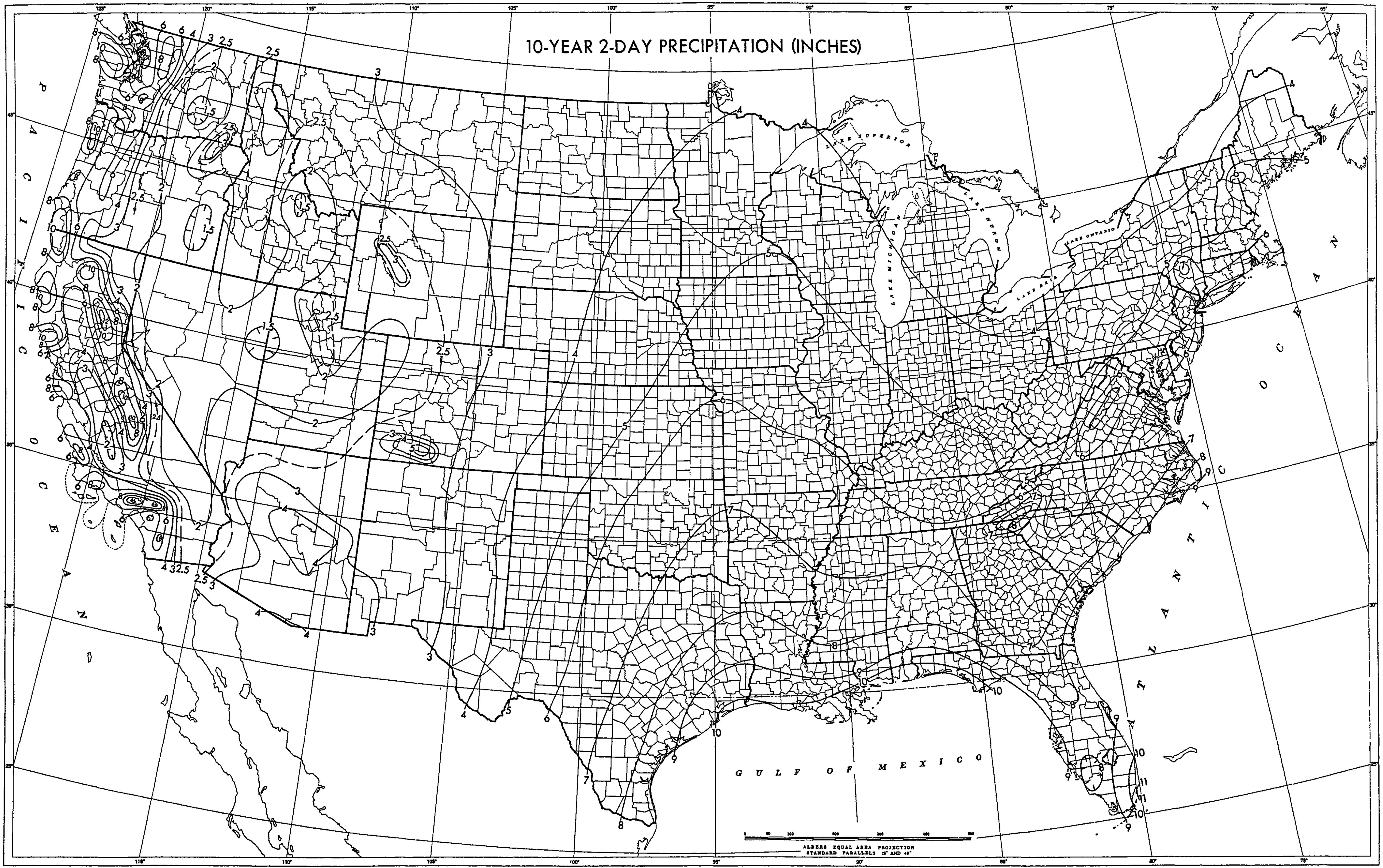

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Figure 14.—10-year 2-day precipitation (in).

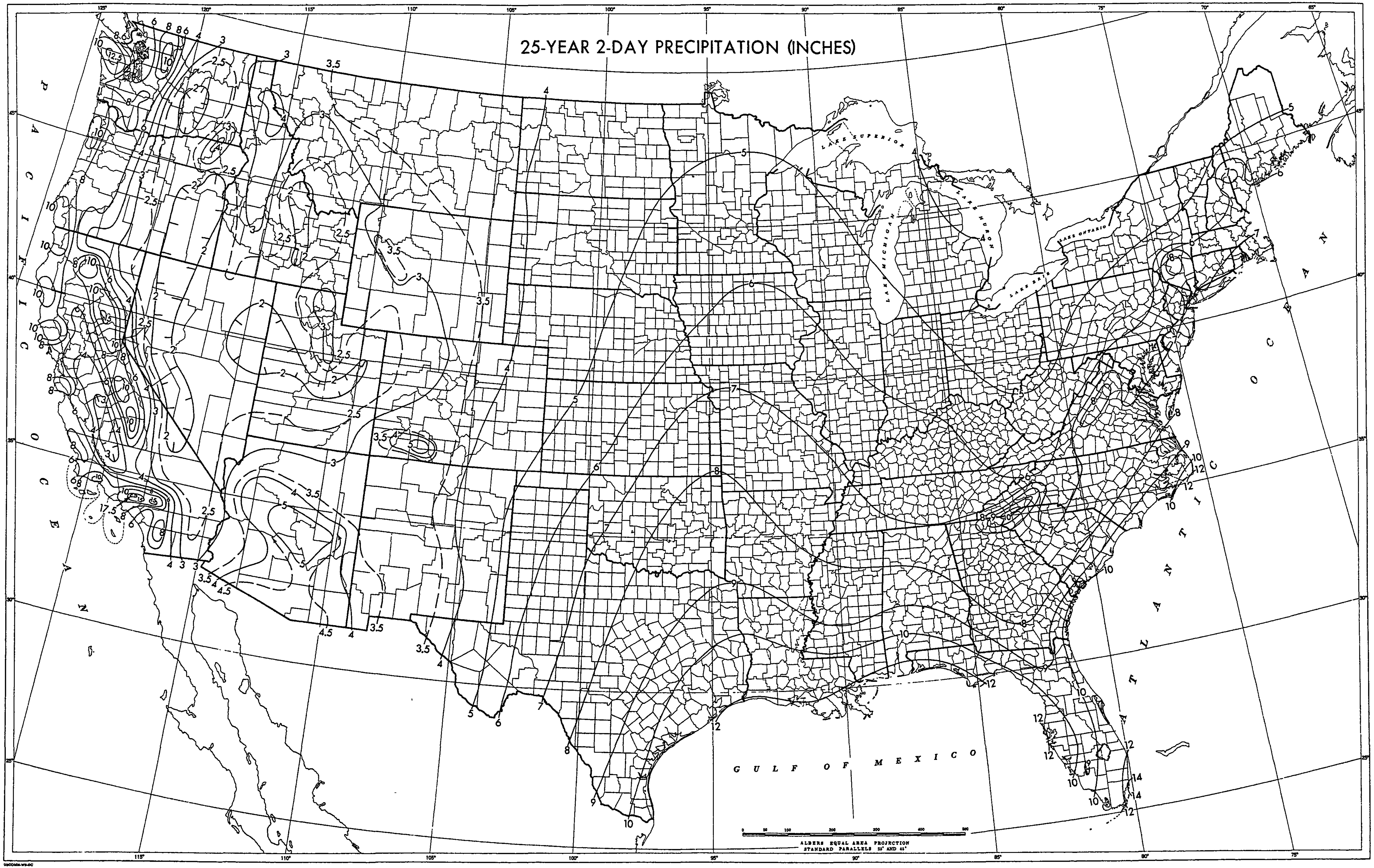

FIGURE 15.—25-year 2-day precipitation (in.).

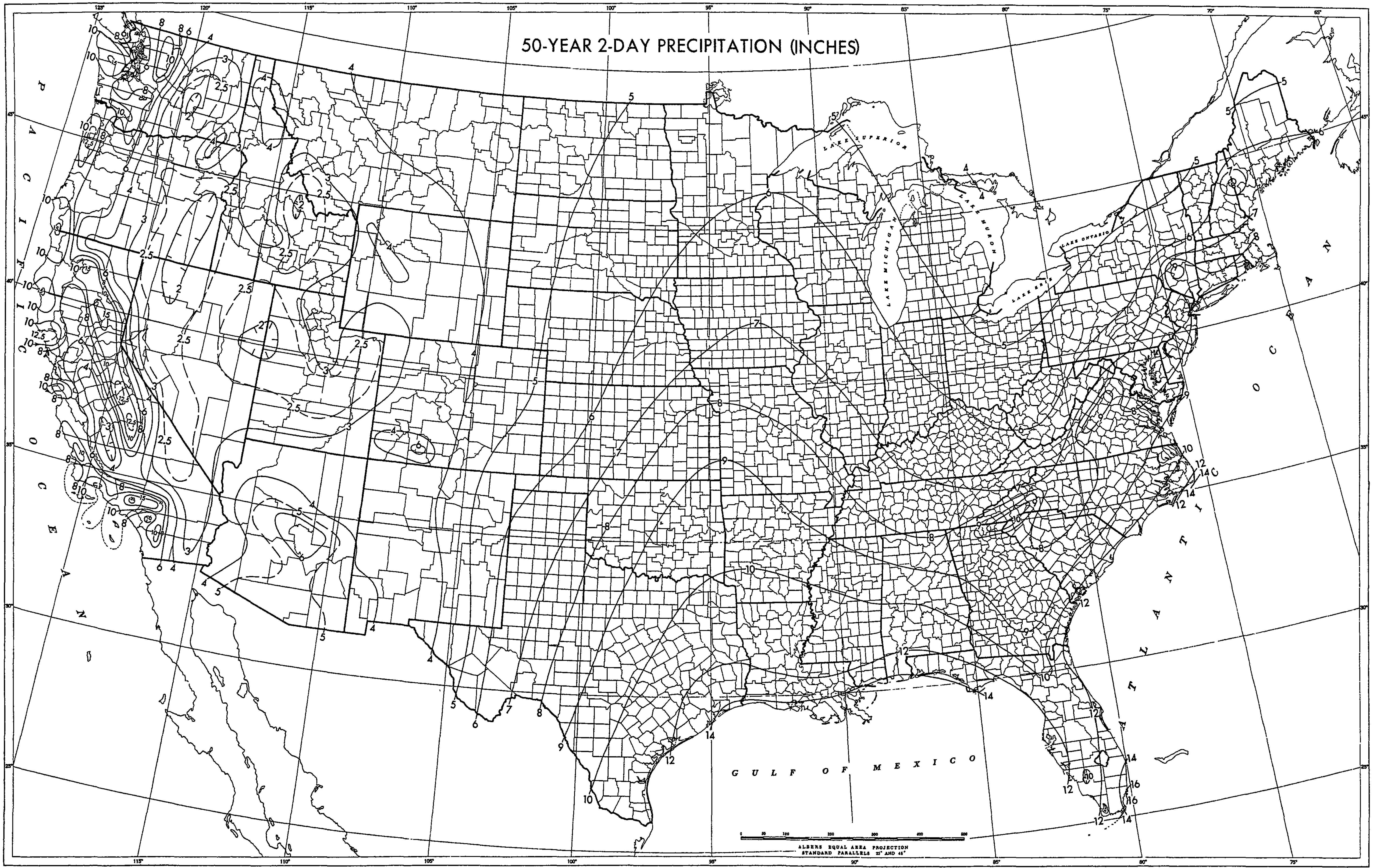

Figure 16.—50-year 2-day precipitation (in.).

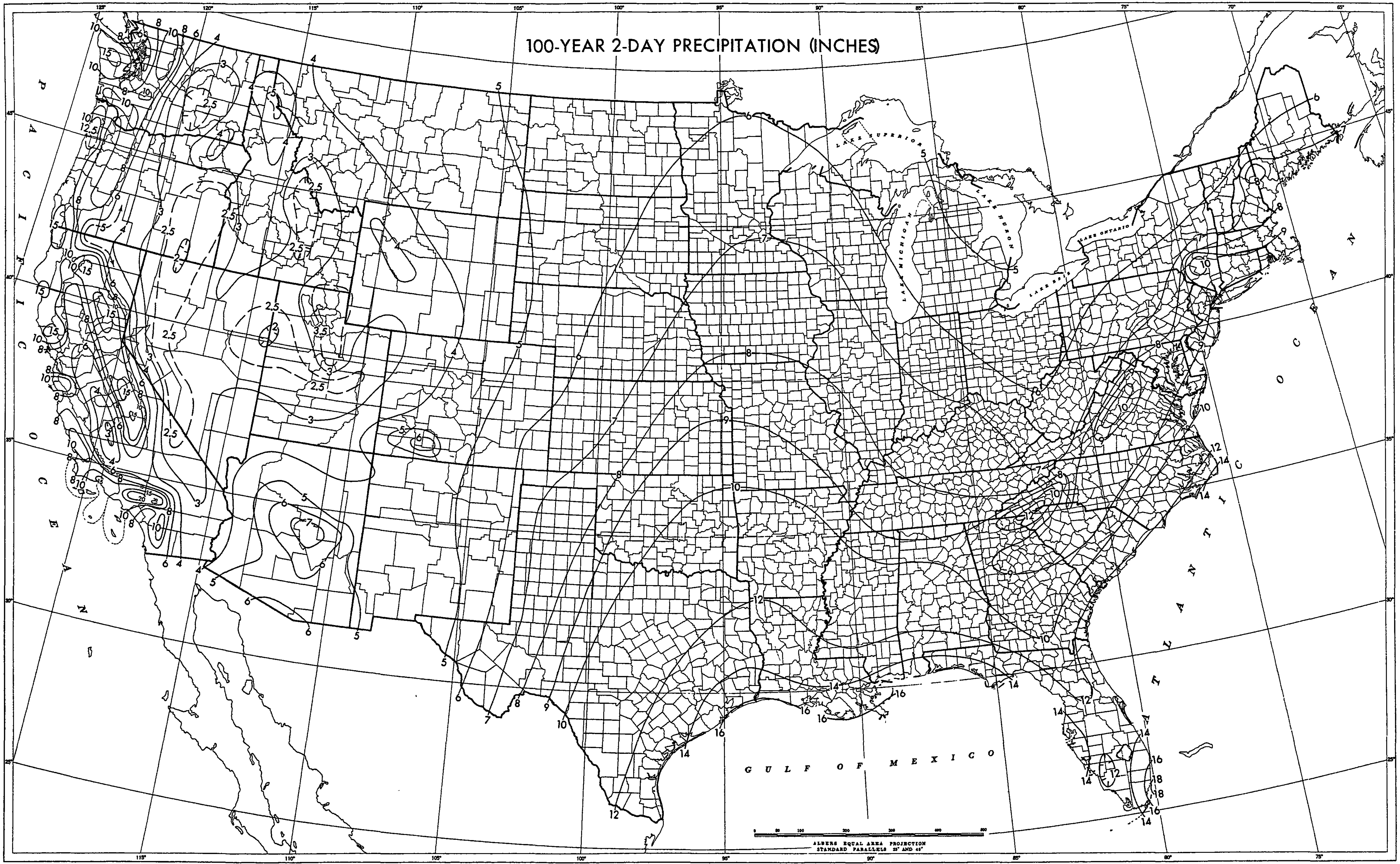

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FIGURE 17.—100-year 2-day precipitation (in.).

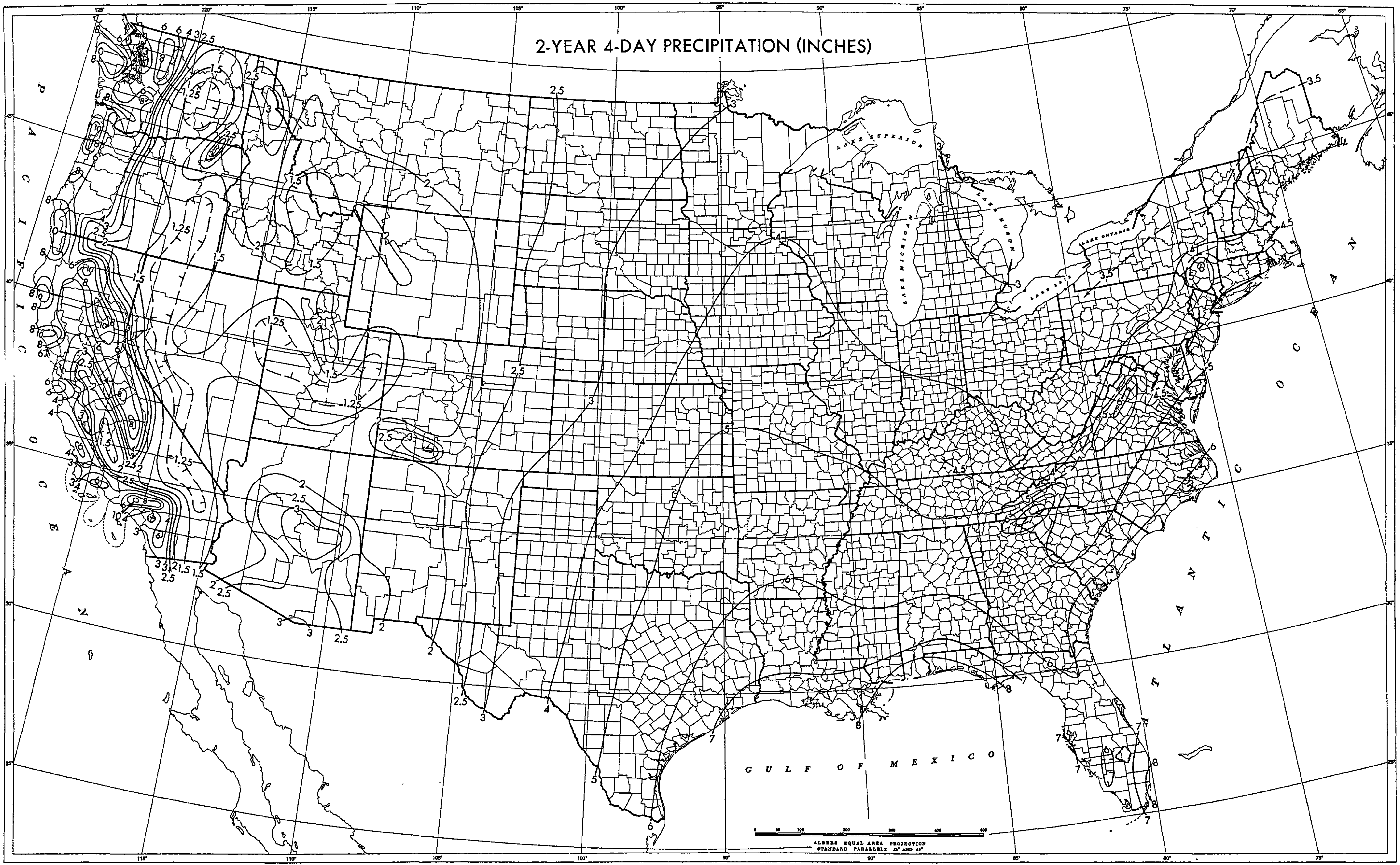

FIGURE 18.—2-year 4-day precipitation (in.).

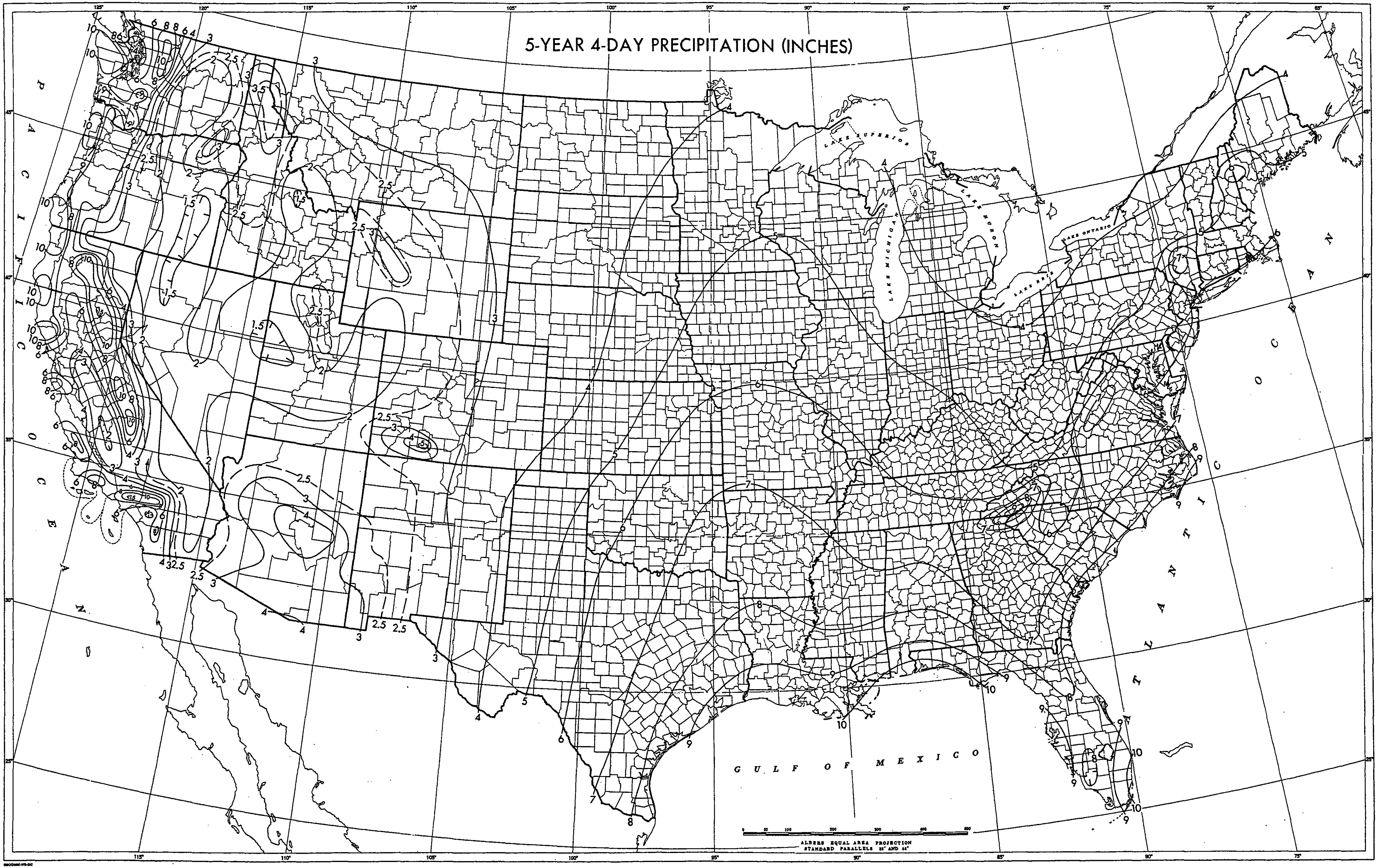

FIGURE 19.—5-year 4-day precipitation (in.).

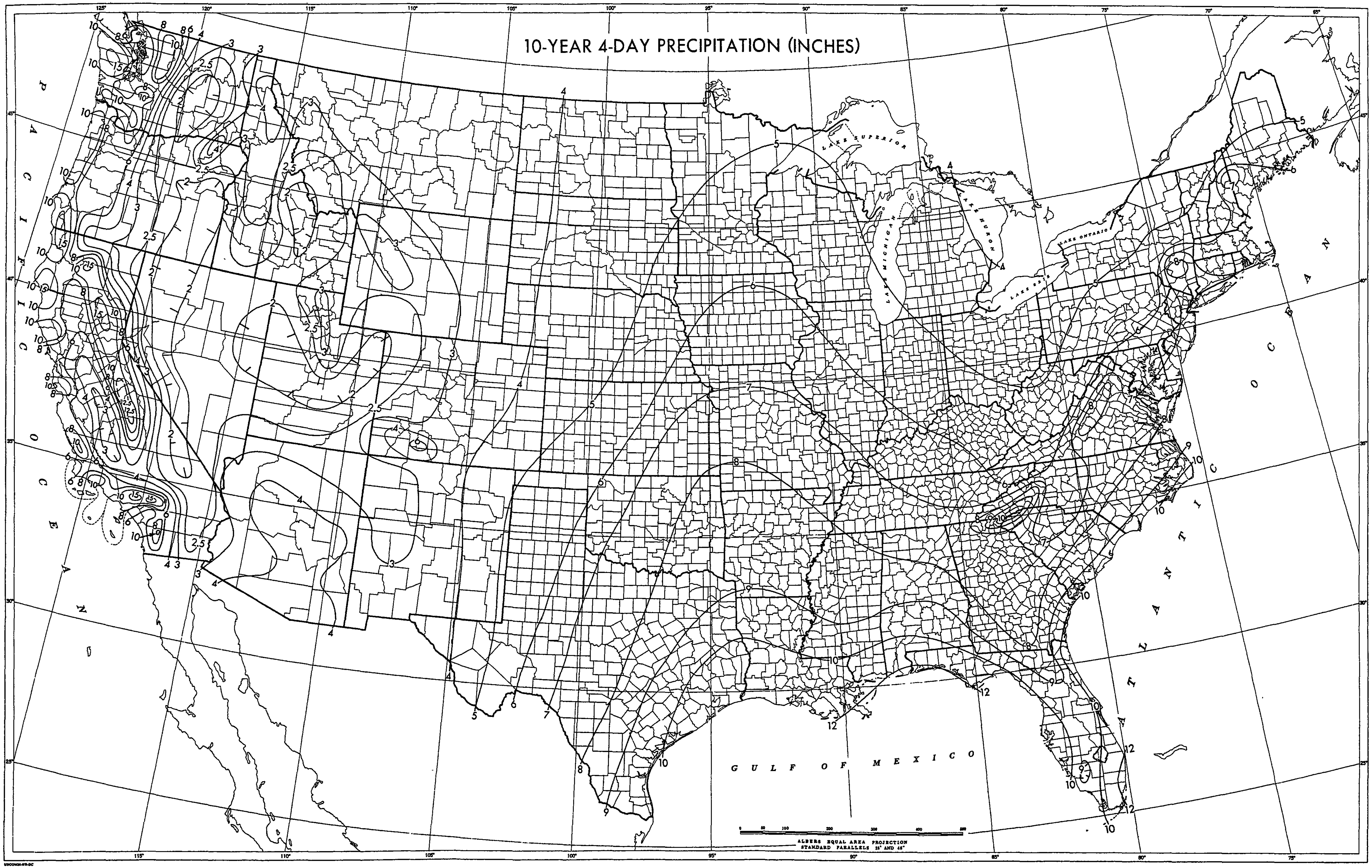

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FIGURE 20.—10-year 4-day precipitation (in.).

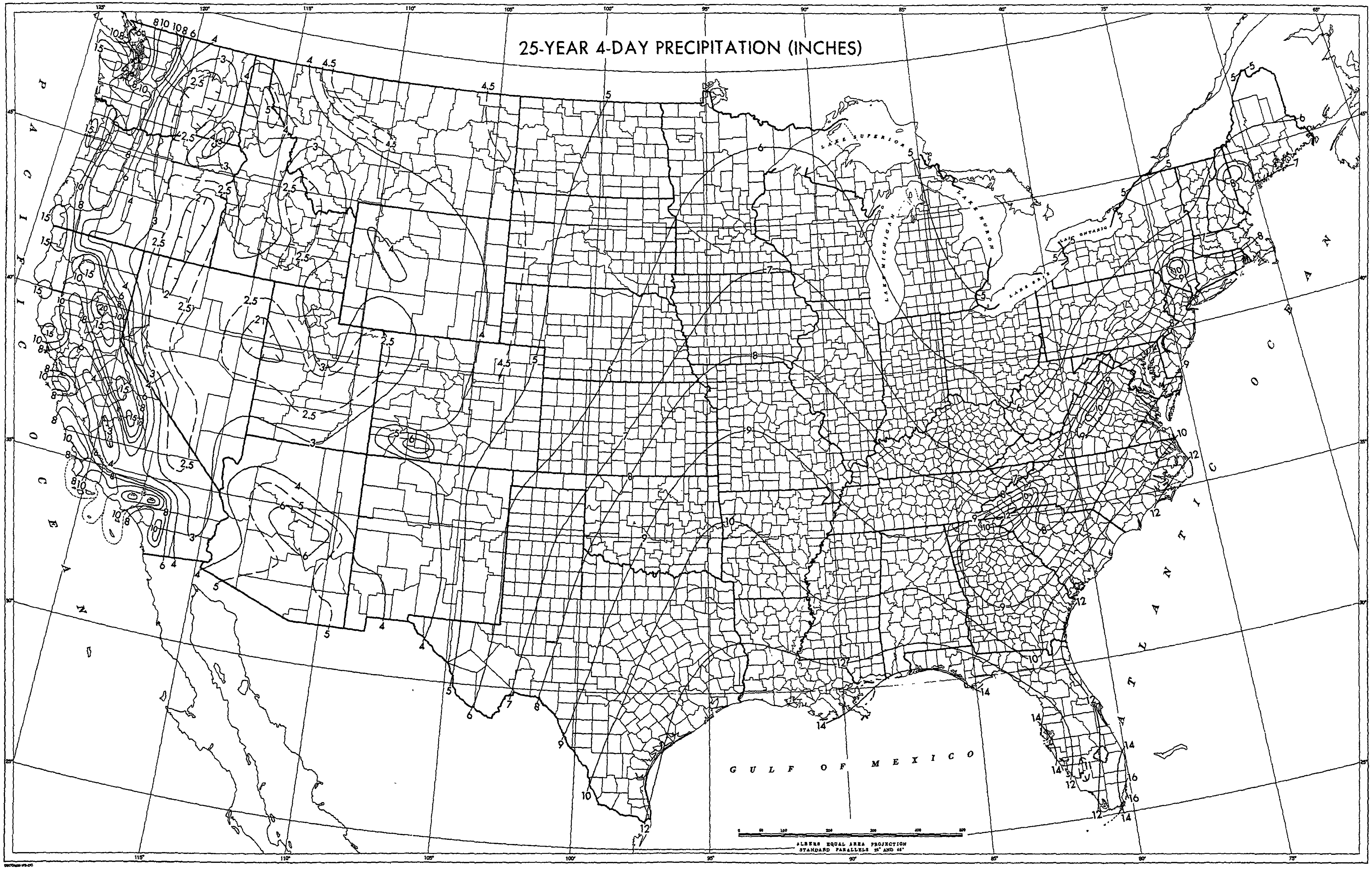

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FIGURE 21.—25-year 4-day precipitation (in.).

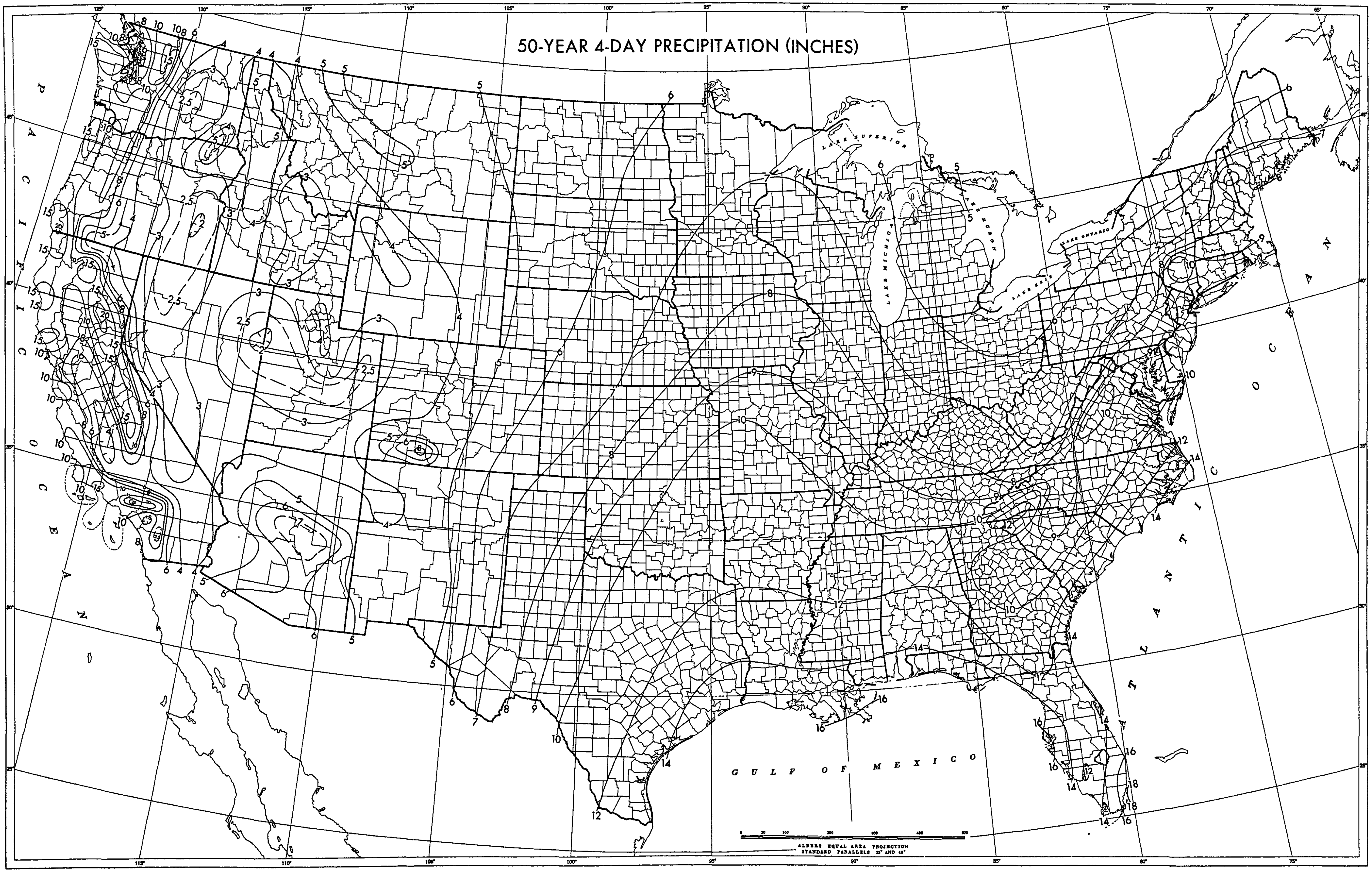

Figure 22.—50-year 4-day precipitation (in.).

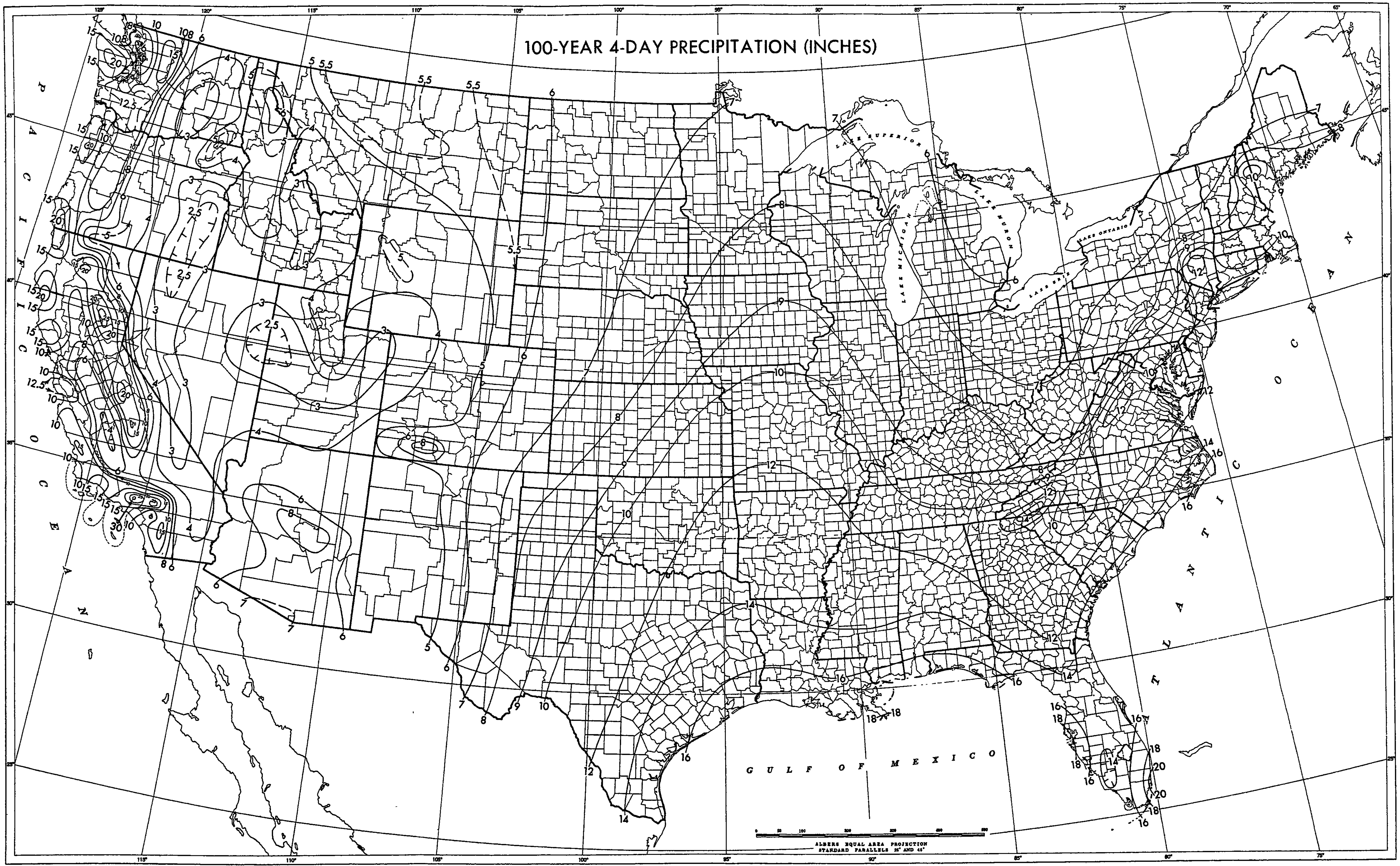

FIGURE 23.—100-year 4-day precipitation (in.).

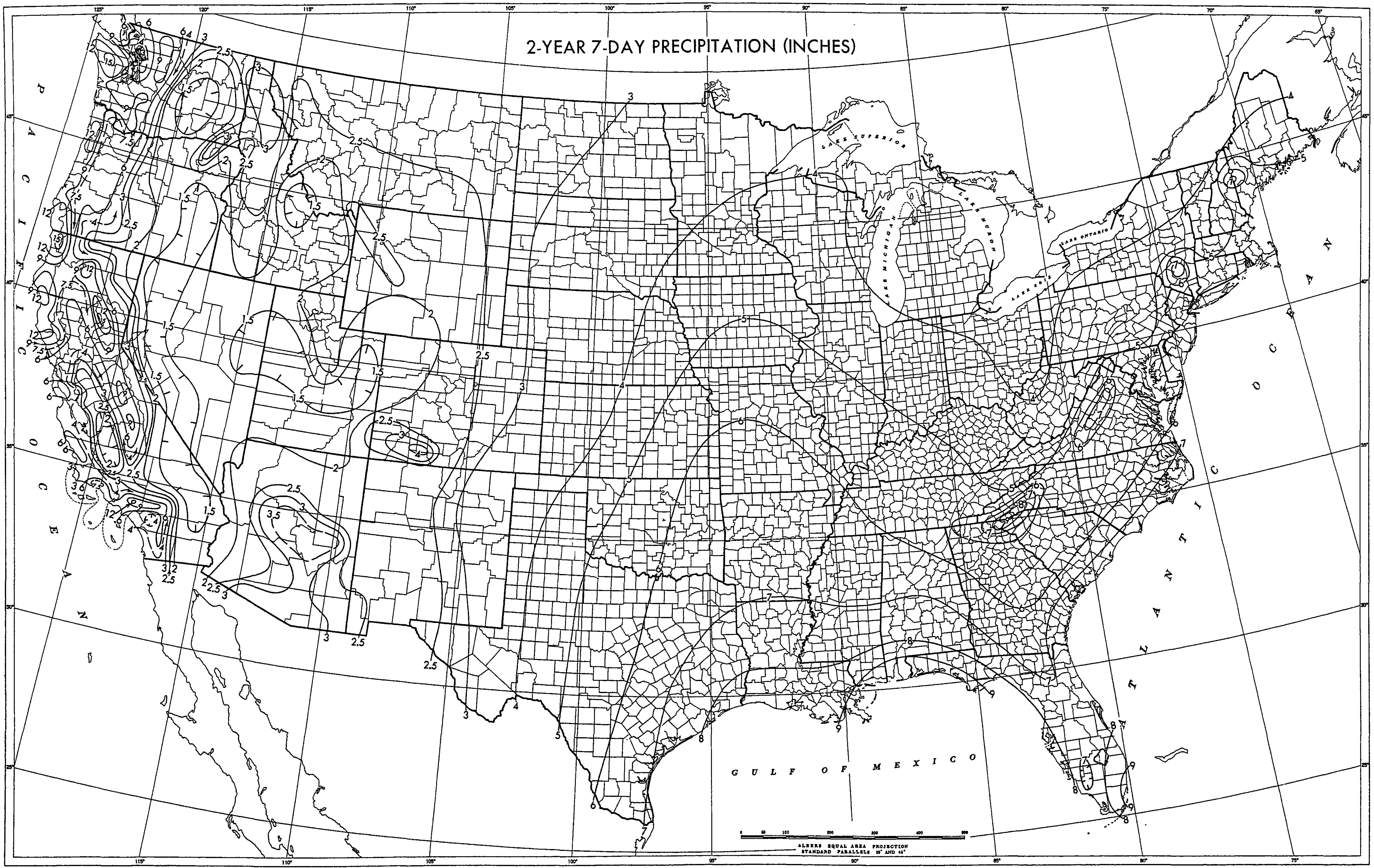

FIGURE 24.—2-year 7-day precipitation (in.).

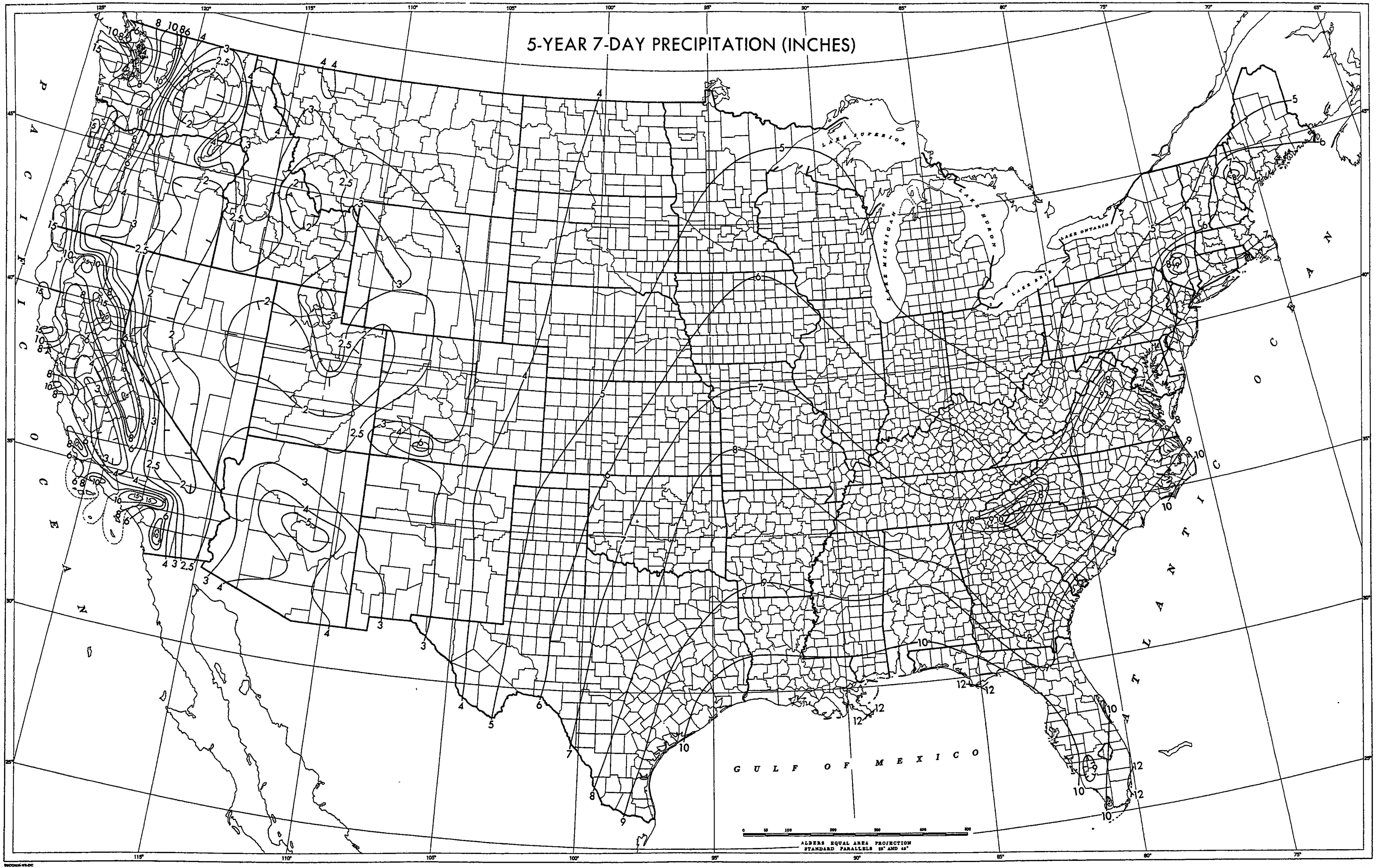

Figure 25.—5-year 7-day precipitation (in.).

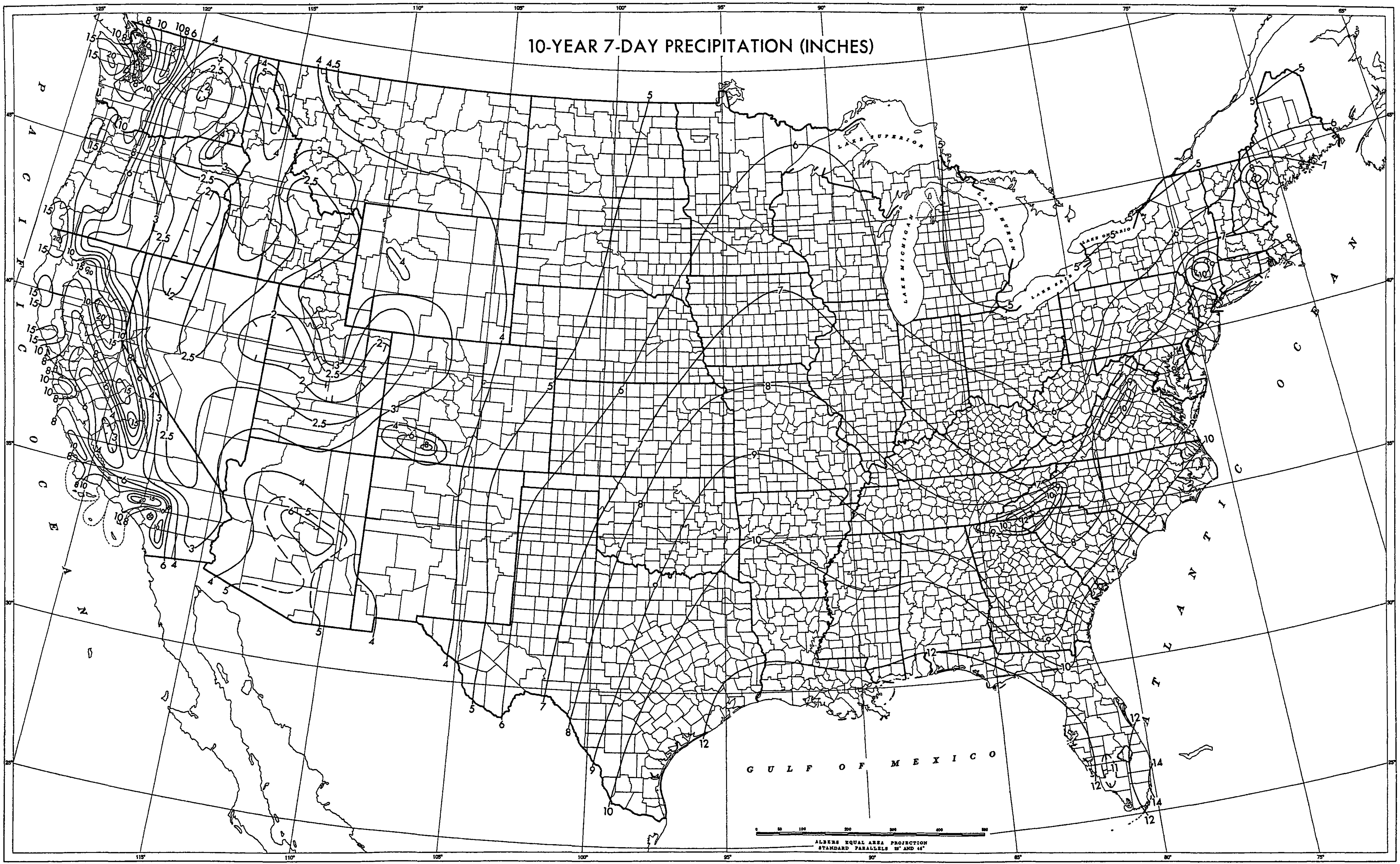

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Figure 26.—10-year 7-day precipitation (in.).

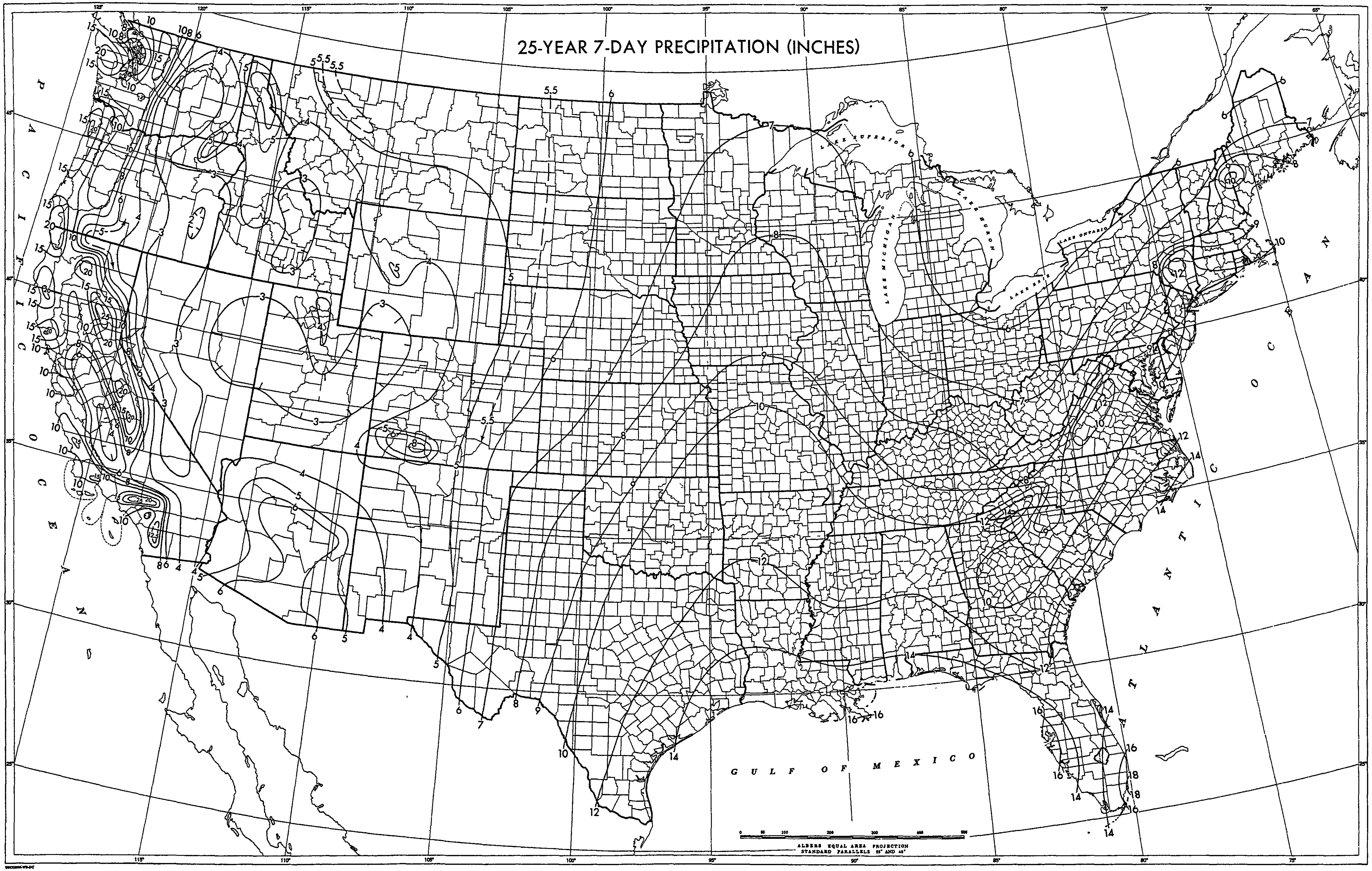

FIGURE 27.—25-year 7-day precipitation (in.).

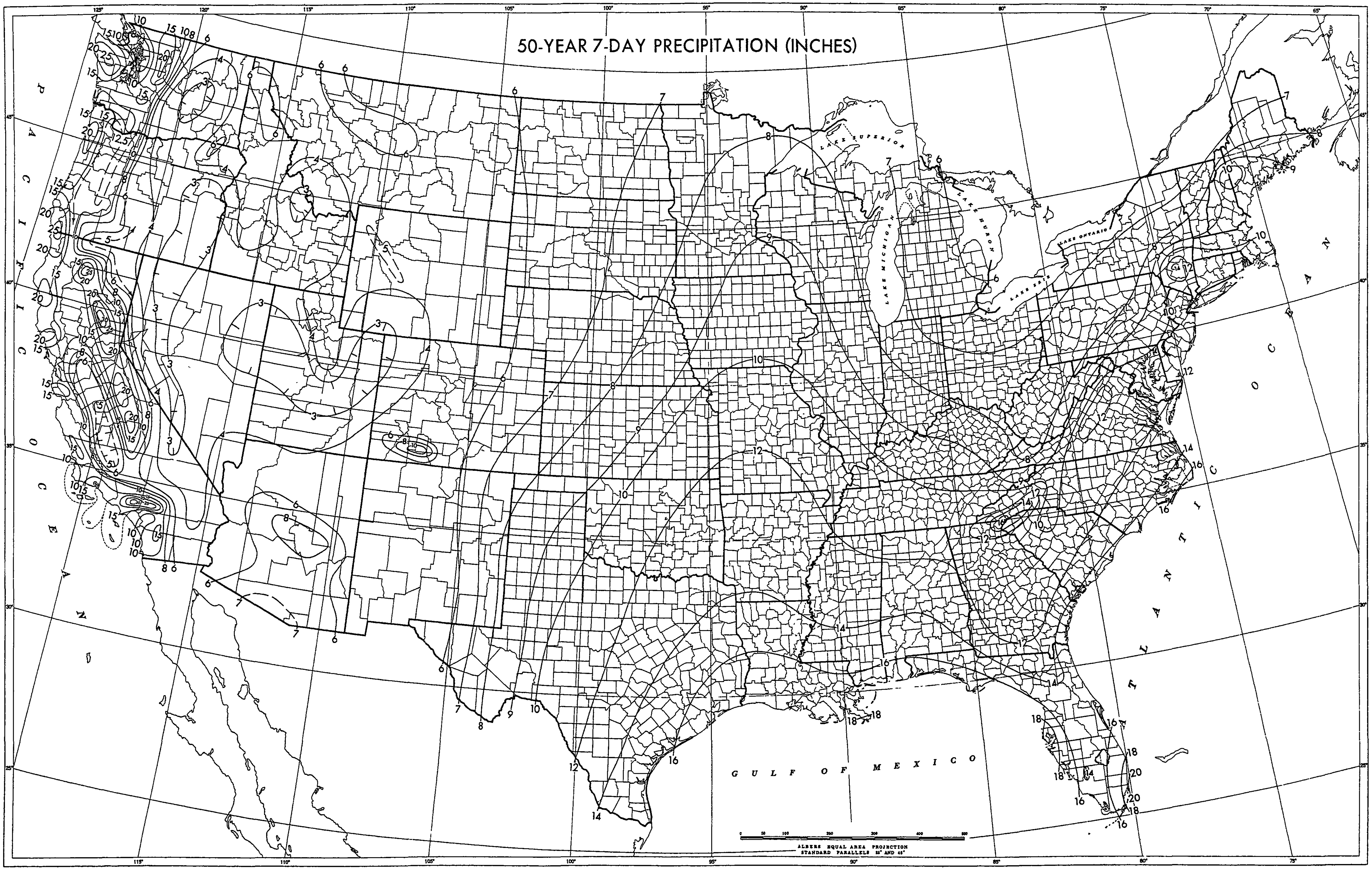

Figure 28.—50-year 7-day precipitation (in.).

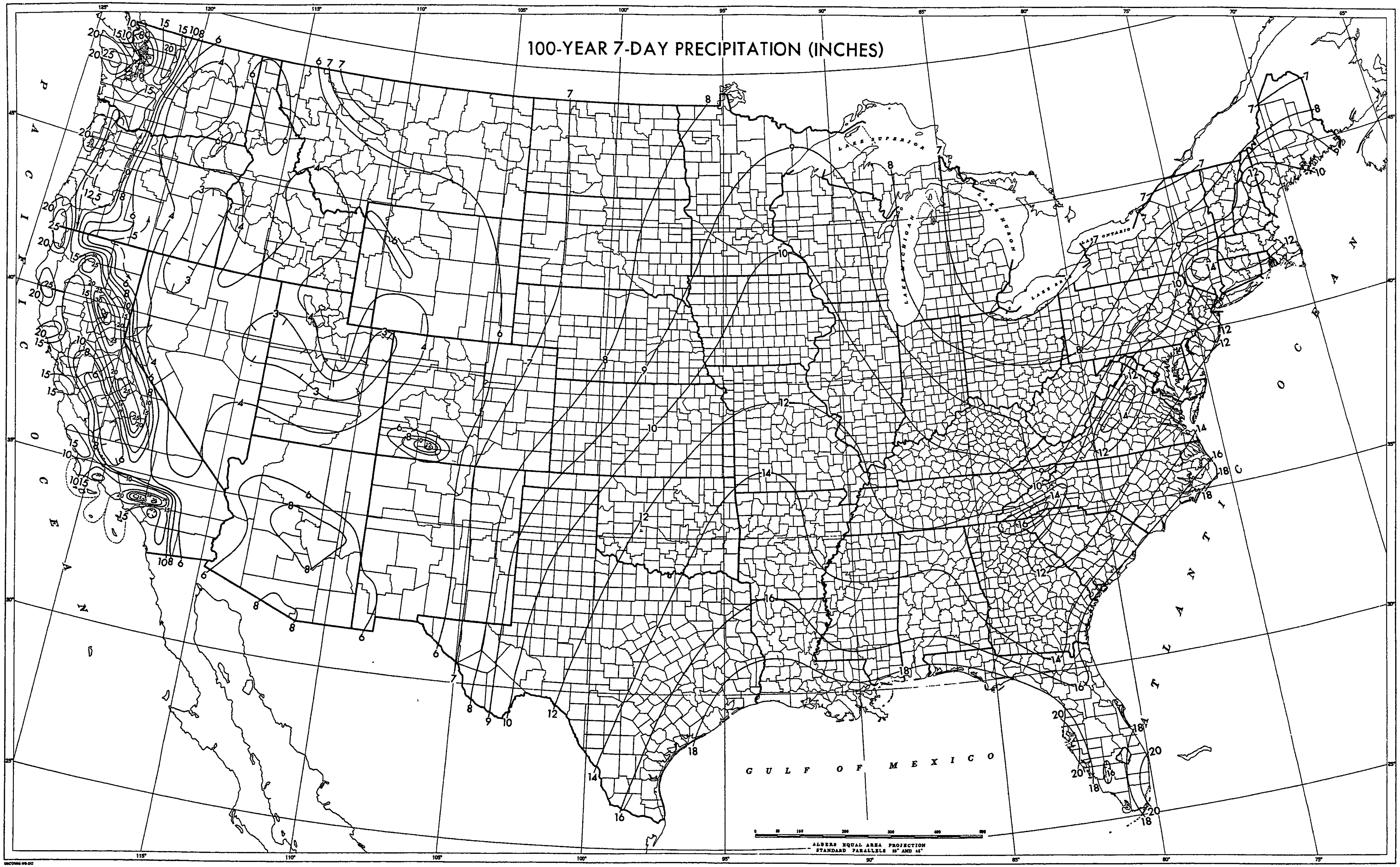

Figure 29.—100-year 7-day precipitation (in.).

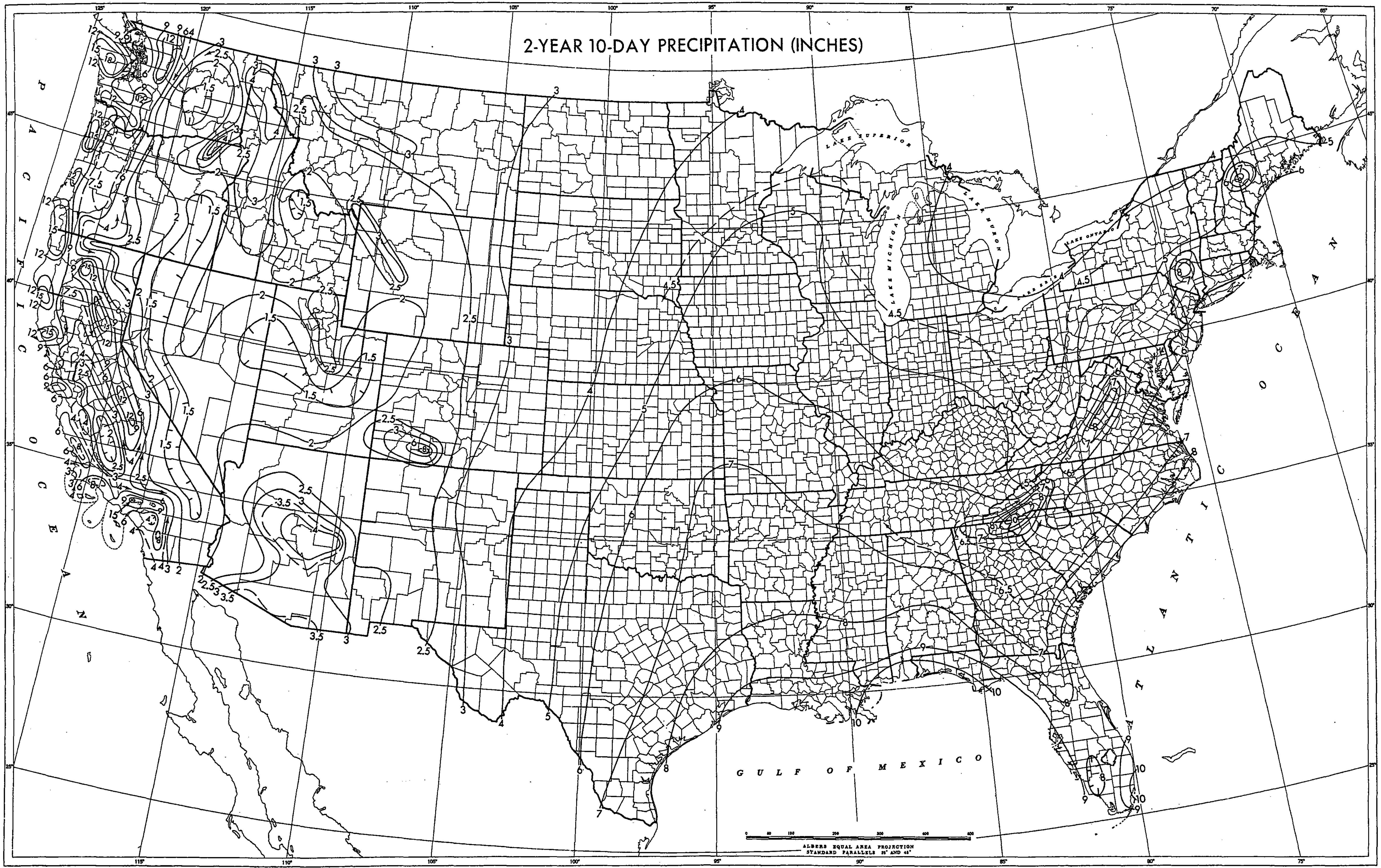

FIGURE 30.—2-year 10-day precipitation (in.).

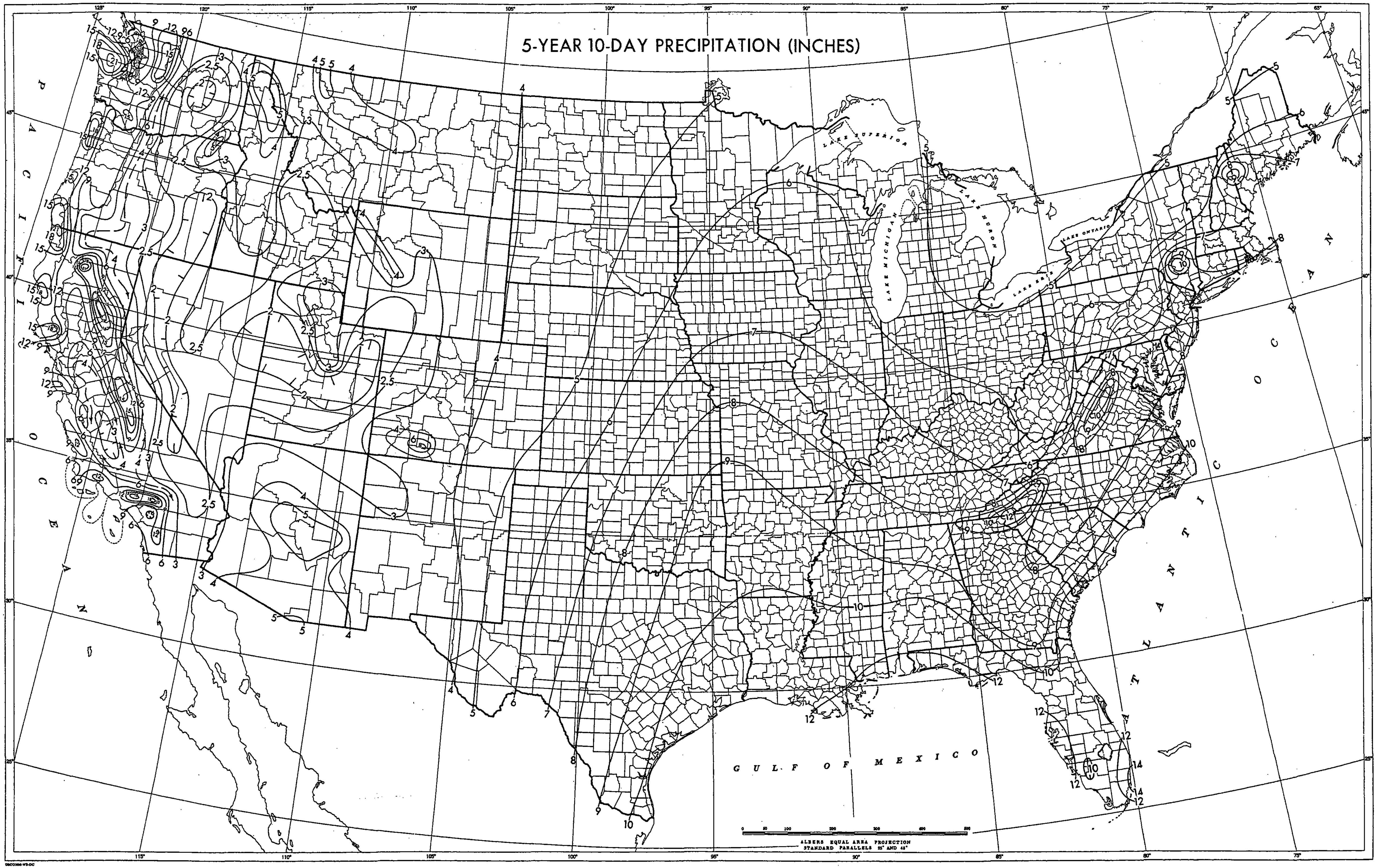

FIGURE 31.—5-year 10-day precipitation (in.).

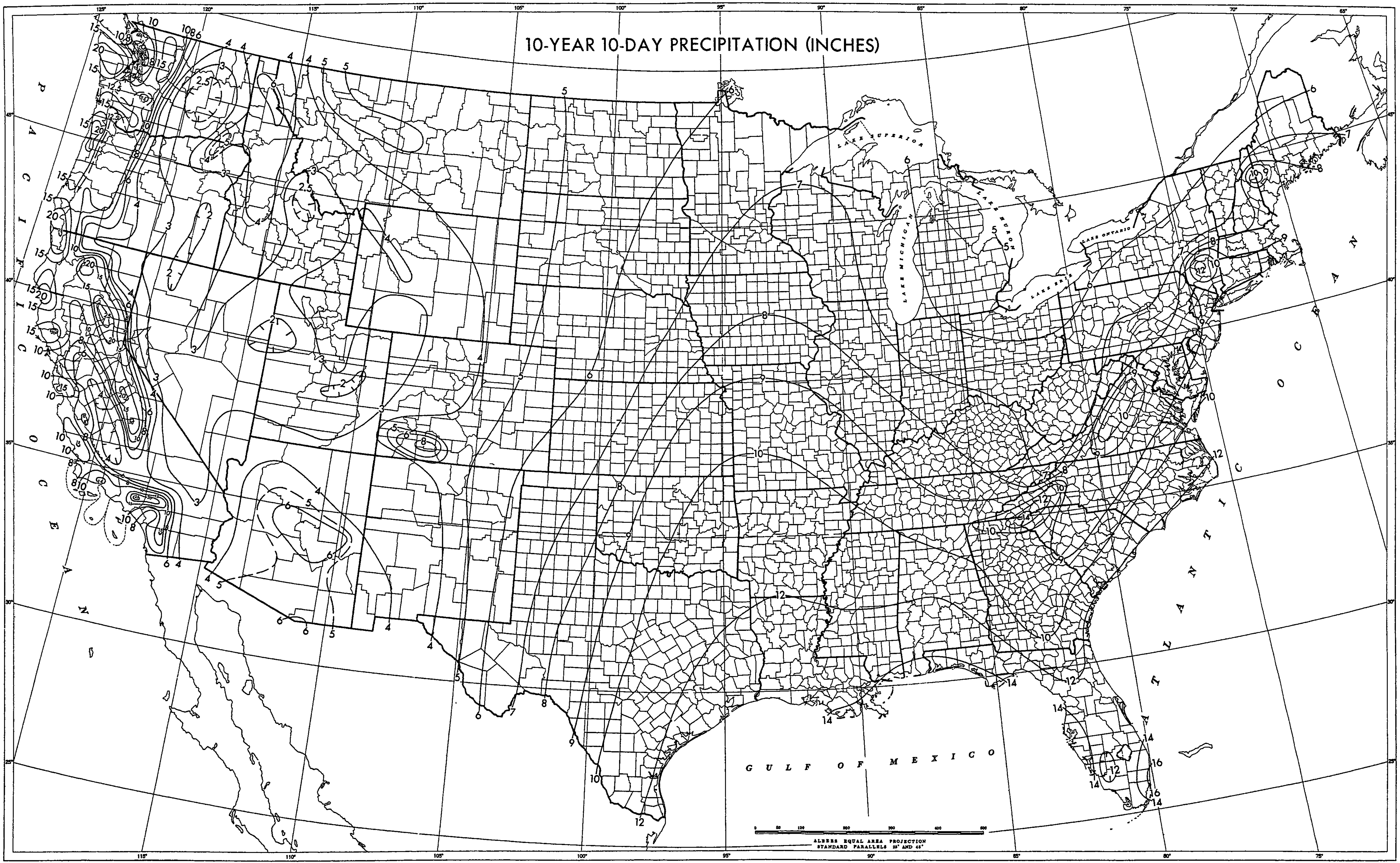

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FIGURE 32.—10-year 10-day precipitation (in.).

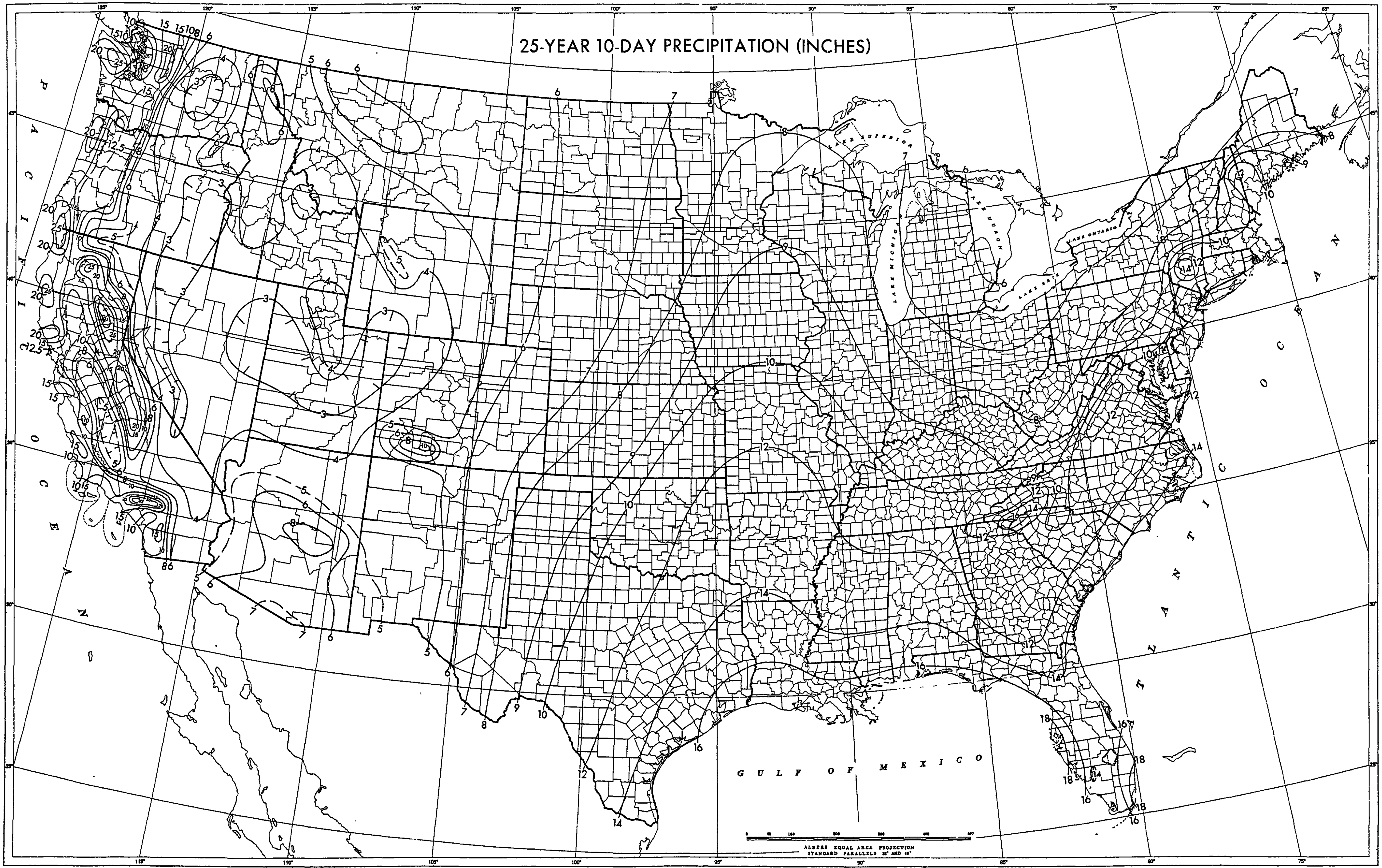

Figure 33.—25-year 10-day precipitation (in.).

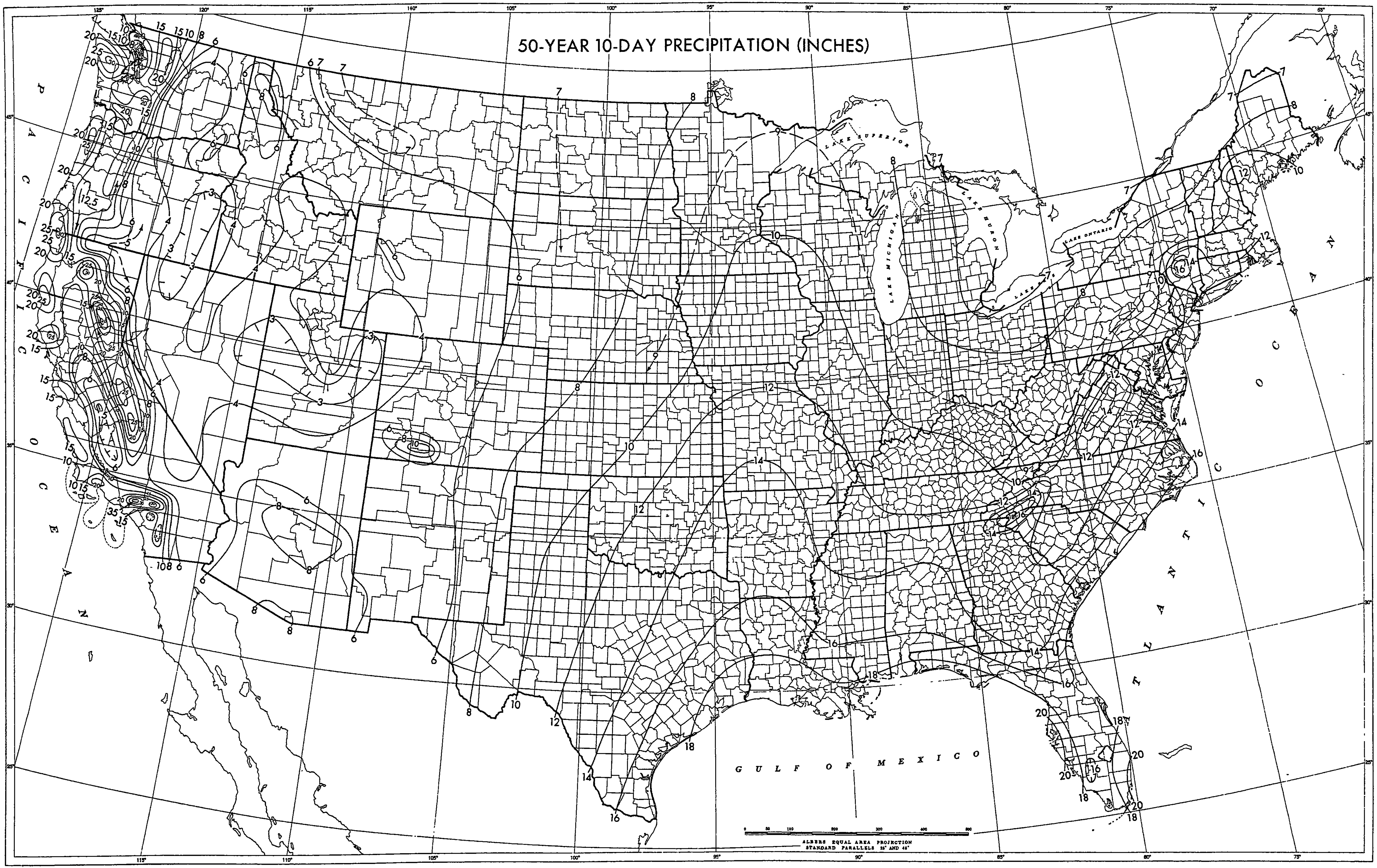

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FIGURE 34.—50-year 10-day precipitation (in.).

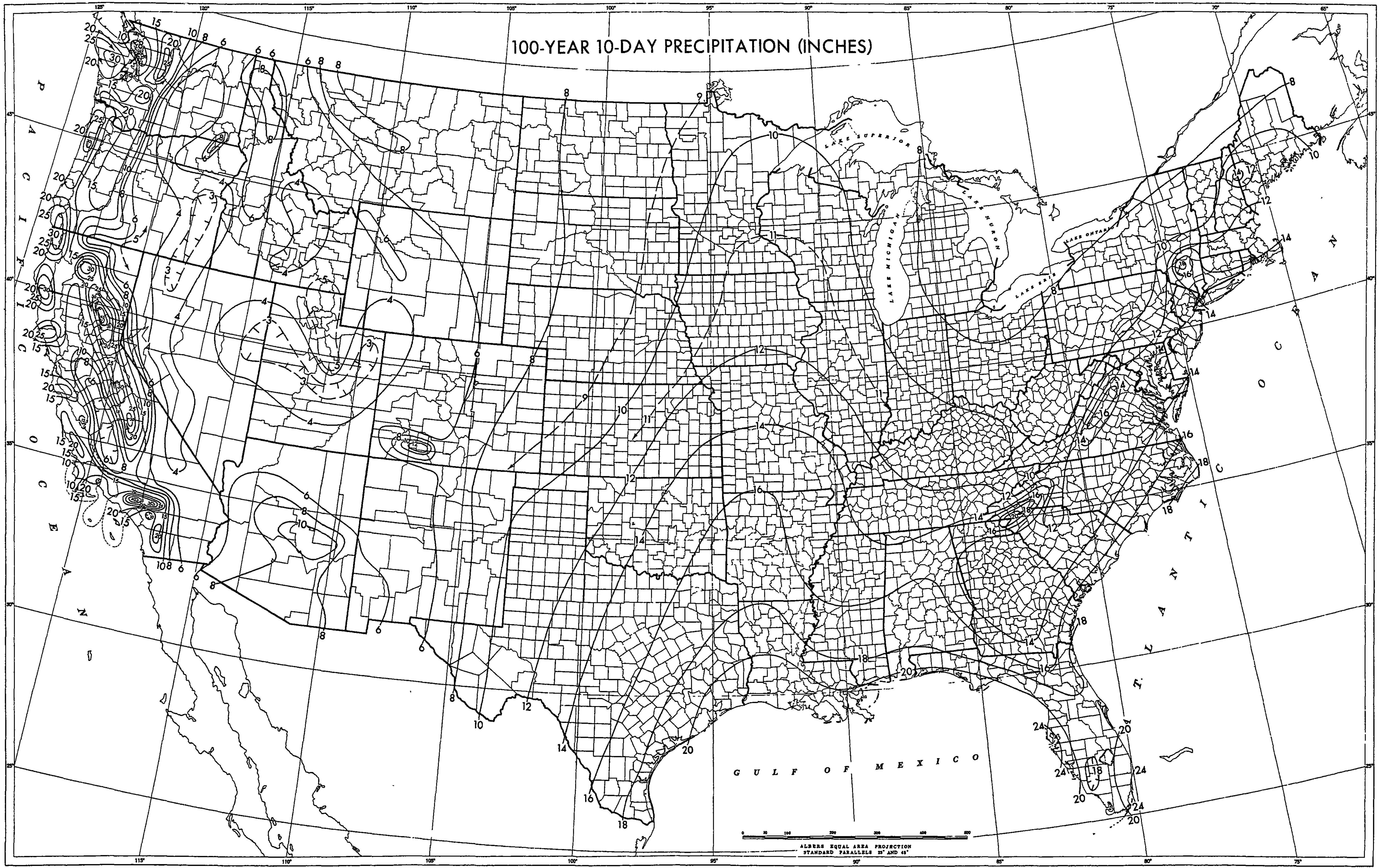

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FIGURE 35.—100-year 10-day precipitation (in.).

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