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Climatological Probabilities of Precipitation for the Conterminous United States

SILVER SPRING, MARYLAND
DECEMBER 1967

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ESSA TECHNICAL REPORT WB-5

Climatological Probabilities of Precipitation for the Conterminous United States

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SILVER SPRING, MARYLAND
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ABSTRACT

Climatological probabilities, as represented by observed frequencies, have been generated for 6-, 12-, and 24-hour periods for 108 stations distributed over the conterminous states. A 15-year period of record was used which included the years 1949 to 1964. The results are presented in the form of plotted data with smoothed topographically dependent analyses giving seven charts for each month, for a total of 84 charts.

Seasonal and diurnal trends in the observed data are discussed briefly in terms of the synoptic and topographical influences for various regions of the country. Frequencies of precipitation occurrence are strongly influenced in a unique manner by topographic and synoptic influences, with extreme variability observed in the western states. Smooth patterns are observed in the Great Plains with the pattern further distorted by the mountains in the East. Seasonal trends in precipitation occurrence are influenced by the shifting tracks of cyclonic systems in the fall-winter-spring period, with a transition to thunderstorm precipitation during the summer months.

1. INTRODUCTION

With the continuing trend toward the expression of precipitation forecasts in probability terms, a need for a more comprehensive knowledge of climatological precipitation probabilities becomes evident. It is to fulfill this need that the present study was undertaken. Daily frequencies of precipitation occurrence on annual and monthly bases are readily available from climatological sources. Frequencies for shorter time intervals, namely, those within the diurnal period, are not generally available except for a limited number of stations for which local studies have been made. It is the purpose of this investigation to extend knowledge of precipitation probabilities to shorter time intervals for a representative number of stations throughout the United States and through these to uncover significant diurnal trends.

Background information in the form of climatological charts from recognized sources is included to summarize available information on the frequency of occurrence of precipitation. These charts include annual and monthly frequencies. Charts giving frequencies for shorter periods which have been generated by computer from a recent period of record are then presented. These frequencies are interpreted as representing climatological probabilities.

2. ANNUAL FREQUENCIES OF PRECIPITATION OCCURRENCE

Daily frequencies of occurrence of precipitation vary in space and time over the United States. This variability is illustrated on an annual basis by the frequencies of measurable precipitation given in figure 1, taken from the National Atlas [21]. As shown by this figure, the number of

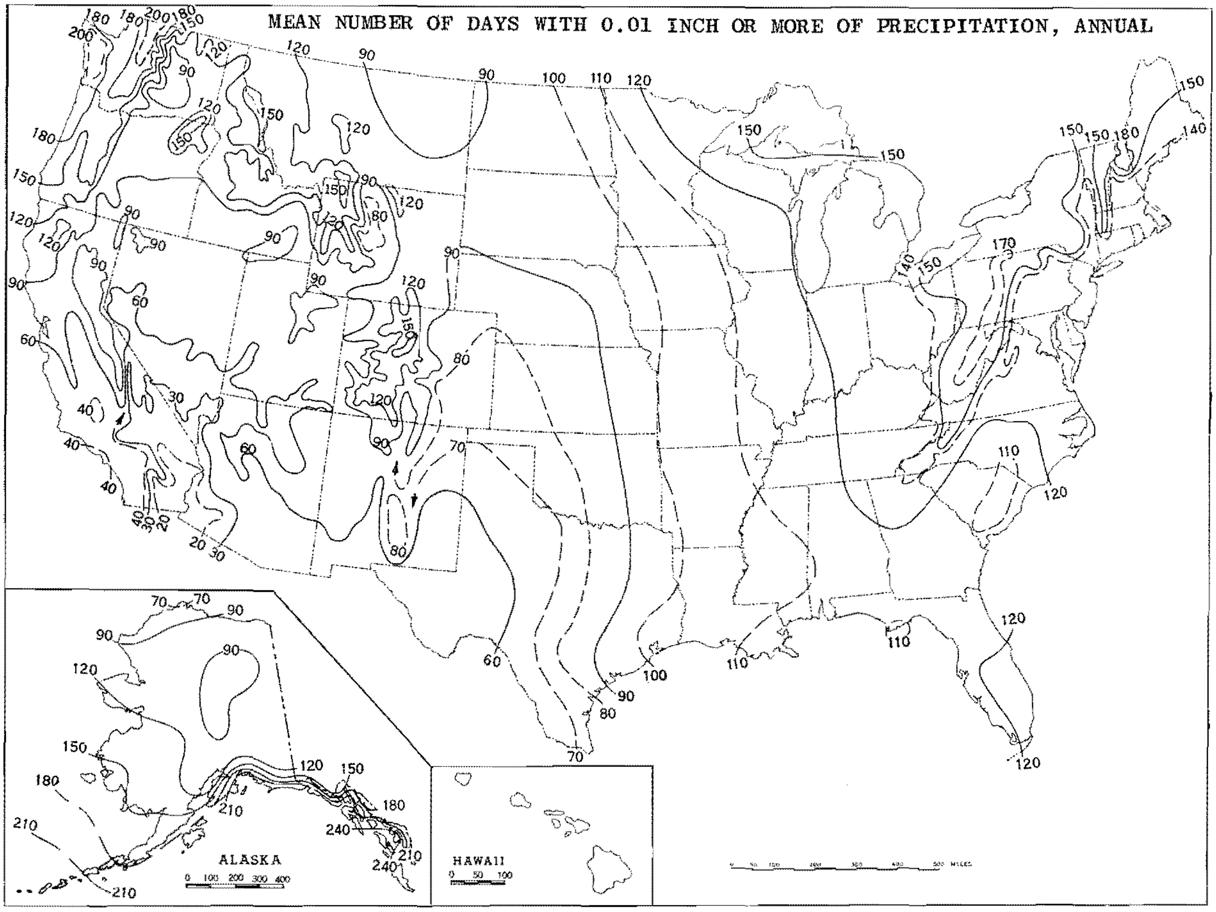


FIGURE 1.—Chart showing annual mean number of days with 0.01 inch or more of precipitation (from the National Atlas of the United States [21]).

rainy days per year ranges from over 200 in some mountain areas of the Pacific Northwest to as few as 20 in the southwestern desert region. A complex pattern of frequencies is evident in all sections of the western part of the country. A much smoother pattern is observed in the eastern half, where the number of rainy days ranges from close to 100 in the central plains to 180 locally in the mountains of the New England states.

The fact that the frequency of occurrence of precipitation is strongly influenced by topography on a long-term, broad-scale basis is clearly brought out by figure 1. The area of greatest frequency is found over the windward slopes of the mountains along the north Pacific Coast, an area which intercepts the majority of winter storms entering the country from the west. A short distance inland, in the Yakima Valley in central Washington, the frequency drops to less than half of that observed in the nearby mountains, largely as a result of the shielding effects of the mountains. High frequencies are evident over the central and northern Rockies, while areas of low frequencies are common to the east of the larger mountain ranges. A small area of low frequencies is observed in central Wyoming, and a large area lies just to the east of the Rocky Mountain chain, extending from Texas northward through the Great Plains to the Canadian border. The very low frequencies of the southwestern desert result from the shielding effects of the mountains, the distance of the area from the major storm tracks, and the predominance of anticyclonic circulation during much of the year over the adjacent Pacific Ocean.

In the central and eastern states, the relatively smooth pattern is broken up somewhat by the Appalachian Mountains but not to the extent found in the West. As in the West, the higher frequencies are observed over the western slopes of the mountains, with areas of low frequencies tending to make their appearance to the east of the mountains. This latter tendency is evident in the relatively low frequencies observed in the Carolinas. The availability of moisture from the tropical waters of the Gulf of Mexico and, to a lesser extent, from the coastal waters of the Atlantic Ocean is an important factor in increasing the frequency of precipitation in the East. However, with the highest frequencies making their appearance in the northeastern states, the major factor is, without doubt, the frequency with which storm systems move over the area. The waters of the Great Lakes show only a minor influence on precipitation frequencies when viewed on an annual basis.

It is well to point out that the areas of greatest frequencies do not necessarily coincide with the areas of greatest monthly or seasonal amounts. For a given frequency, the amount of precipitation to be expected for a specified period will depend upon the average amount received per precipitation day for the period. The average daily precipitation charts (average precipitation divided by number of days with measurable amounts) as given by the Hydrometeorological Report No. 5 [19] for the year and by months, show heavier daily amounts at more southerly latitudes and along the West Coast on an annual basis, with many modifying factors influencing the monthly values. Amounts per rainy day range from 0.1 inch in interior regions to 0.3 to 0.5 inch along the coasts and in the southern Mississippi Valley in winter, while in summer the amounts increase to 0.2 to 0.3 inch in some interior areas, but remain nearly unchanged elsewhere.

3. SEASONAL TRENDS IN PRECIPITATION OCCURRENCE

Monthly climatological statistics clearly show marked seasonal trends in the frequency of occurrence of precipitation in many parts of the country. Charts taken from the National Atlas are given in figure 2 to illustrate these trends, with the months of January, April, July, and October used to represent the four seasons. A comparison of the frequency patterns for the months of January and July highlight the areas of greatest seasonal changes. The strongest seasonal fluctuations appear in the Pacific Coast states where the dry-summer and wet-winter regimes predominate. In the states of Arizona and New Mexico, however, this trend is reversed with the well-known "monsoon" effect producing a wet period during the summer months in these states. The central and northern plains show a slight increase in precipitation frequency during the summer months. Another area of substantial increase in the occurrence of summer precipitation is located in the Florida peninsula extending westward along the Gulf Coast. In central Florida, there is shown a threefold increase in frequency and about a 50 per cent increase in the coastal areas to the west. A marked increase in the frequency of winter precipitation is observed in the Great Lakes region, but elsewhere in the eastern states the seasonal trend is of modest proportions.

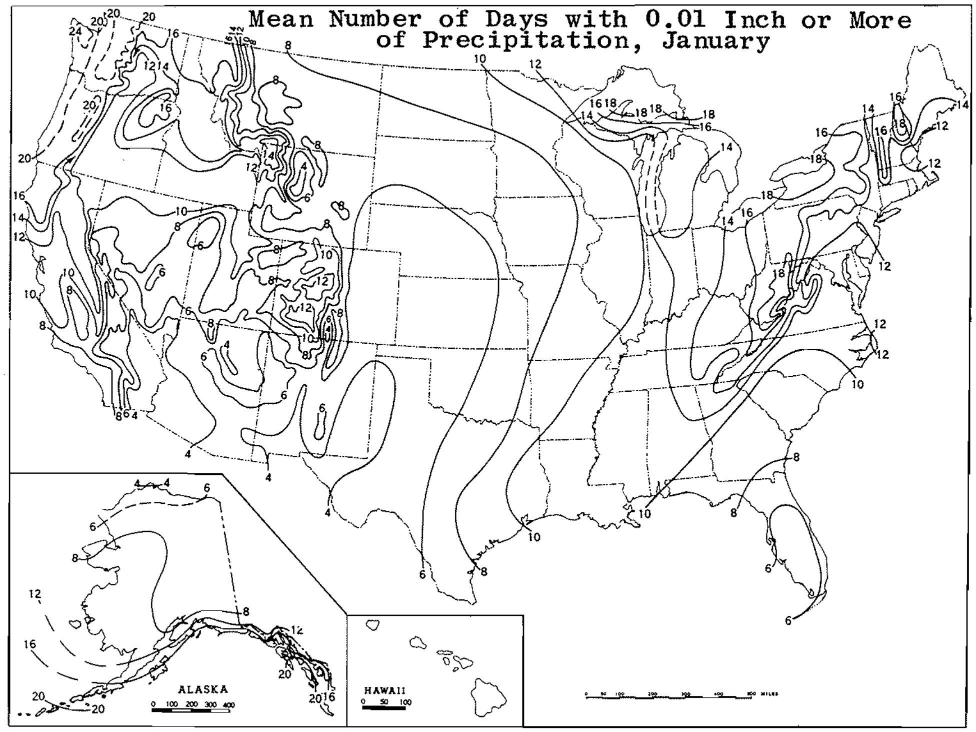
The transitional seasons of spring and fall have quite similar patterns of precipitation occurrence over most of the country, although the fall appears to have a slightly lower frequency, with frequencies reaching near minimal values in many areas. Exceptions to the low fall frequency are in the Florida peninsula, where the high frequencies of summer carry over into the fall season, and in the Great Lakes area, where the higher frequency of winter is already becoming apparent.

4. FACTORS INFLUENCING PRECIPITATION FREQUENCIES

The occurrence of precipitation for a given area of the country is a response to a combination of synoptic and topographic factors. The interaction between these factors may be quite complex, especially in mountain areas, with seasonal variations in types and frequencies of synoptic situations largely responsible for the trends in precipitation occurrence. Over much of the country during the winter season, the occurrence of precipitation is largely related to cyclones and their associated upper troughs and frontal systems. With the advent of summer, the occurrence of precipitation becomes more closely tied to an unstable atmosphere leading to thunderstorms, with squall lines an important causative factor in some northern states.

The climatology of cyclonic systems has been studied by Klein [11], who extended the work of Bowie and Weightman [4] and others in the investigation of the principal tracks, mean frequencies, and genesis of cyclones and anticyclones in the Northern Hemisphere. As shown by these studies, frequencies of occurrence of cyclones are found to reach maximum and minimum values at different times of the year in different parts of the country. Cyclonic systems affecting the north Pacific Coast have their greatest frequency in the winter months and a minimum in the summer season. In the intermountain region, the greatest frequency is in the spring with a minimum in July, while in the Great Plains there appears to be a maximum of occurrence in spring and early summer and a minimum in the fall. In the vicinity of the Great Lakes, an area experiencing a high frequency of

(a)



(b)

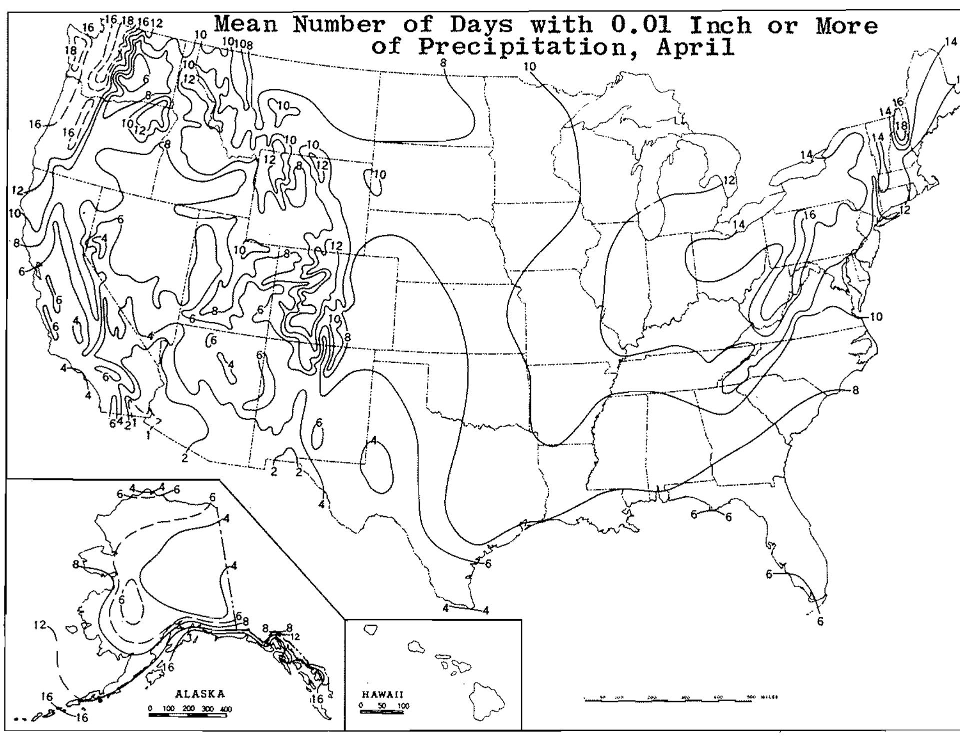
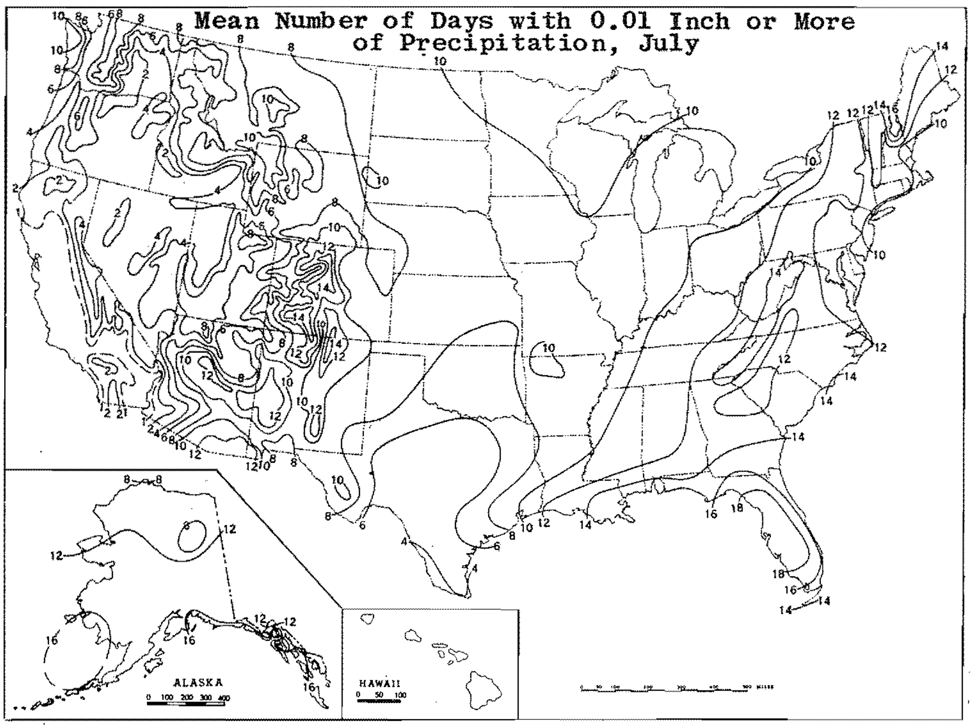


FIGURE 2.—Charts showing monthly mean number of days with 0.01 inch or more of precipitation for four months representing the four seasons (from the National Atlas of the United States /‾21_/).

(c)



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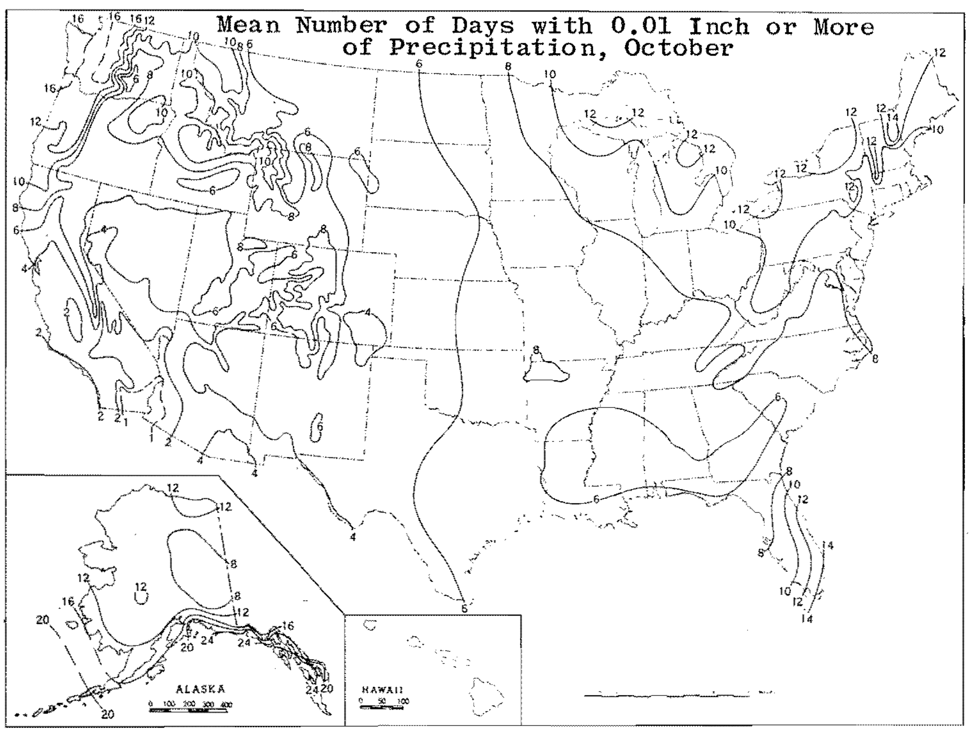

(Figure 2, continued)

cyclonic activity, a maximum frequency exists in the winter months with a minimum in summer and early fall. The principal tracks of cyclones affecting the weather over the country reach their farthest southward position in February, and are farthest north in August. Cyclones which enter the area from the west in winter or form over the western states tend to move eastward or northeastward toward the Great Lakes region and then northeastward through the St. Lawrence Valley. An especially active area of cyclogenesis is found off the central Atlantic Coast in late winter and spring with the lows, thus formed, moving toward the northeast.

In addition to seasonal variations in cyclonic frequencies in different parts of the country, the distribution of precipitation in relation to the systems themselves varies with geographic area. In a study relating present weather to the circulation patterns at 700 mb., Klein et al. [12] show that the optimum area for precipitation during the winter occurs well to the east of the 700-mb. trough in the eastern part of the country, and nearer the trough in western and southern sections. In a study dealing with closed lows at 700 mb., Jorgensen et al. [9] show the distribution of amounts and frequencies of precipitation as related to these systems during the winter in the intermountain region of the West. In a subsequent study covering the same area, Jorgensen et al. [10] have examined the frequency of precipitation for individual stations and find that the precipitation associated with 700-mb. low-pressure centers is strongly influenced in a unique manner by the surrounding local and broad-scale topographic features.

With the movement to a more northerly latitude of the cyclone tracks during spring, and with increasing insolation, the occurrence of thunderstorms takes on an increasingly important role in increasing precipitation frequency in many sections of the country. Monthly thunderstorm frequency, as shown by Hydrometeorological Report No. 5 [19], averages 2 or less over most of the conterminous states during the winter months. In March, thunderstorm frequency begins to increase, especially in the lower Mississippi Valley, with the area of increasing activity gradually spreading northwestward and expanding. By June, an area having a frequency of 10 thunderstorms per month has become established over and to the east of the Central Rockies, while the frequency has increased along the Gulf Coast to 12 and in west-central Florida to 16. During July and August, the monthly frequency of thunderstorms has reached a maximum in most sections of the country, with maxima of 18 centered in northern New Mexico and northeastern Arizona, and 20 along the west coast of central Florida. The frequency of occurrence drops off sharply in September, and by October and November the number is not significantly greater than for the winter months. During the fall months, cyclonic systems once more begin to become reestablished as the predominant cause of precipitation.

5. CLIMATOLOGICAL PROBABILITIES FOR 6-, 12-, AND 24-HOUR PERIODS

The climatological frequencies of precipitation, and from these the climatological probabilities, can be derived for shorter time periods for greater operational usefulness. In general, the term "probability" is used when denoting operational use of the derived results and "frequency" when dealing with accumulated climatological data. Monthly frequencies can readily be modified to give average daily or 24-hour climatological probabilities for the given month. In order to obtain probabilities for 6- and 12-hour periods, however, it is necessary to examine the actual frequencies of occurrence for the shorter periods. The manner in which climatological probabilities are obtained for individual stations for the 6-, 12-, and 24-hour periods and the preparation of the final charts are described in the following subsections.

Source of Data

The basic data source for this study is a compilation of 15 years of record, September 1949 to August 1964, made available by the National Weather Records Center, Asheville, N. C., and computer processed by the Techniques Development Laboratory in Suitland, Md., into frequency of occurrence during the periods of time selected. For the 15 years chosen, there were records available for 108 stations which met the necessary criteria for computer processing. These were the same stations and the same period of record used in an earlier study by the Techniques Development Laboratory of temperature prediction, and were chosen to give a good coverage of large population centers [13]. An example of a computer printout is given in figure 3. Data for a number of western stations were worked up by Miles [16] for about the same period of record and were available for comparative purposes. The literature dealing with precipitation probabilities at various individual stations was not used as a source of data for incorporation into this study.

Method of Construction of Charts

The charts given in the Appendix, with 7 charts for each month, present the data for individual

PRECIP. PROBABILITIES BASED ON 15 YEARS OF, DECEMBER DATA   ALL TIMES G. M. T.

CITY NAME	6 HOUR PROBABILITIES 01 TO 06	07 TO 12	13 TO 18	19 TO 24	12 HOUR PROBABILITIES 01 TO 12	13 TO 24	24 HOUR PROBABILITY 01 TO 24
ALBANY, NEW YORK	0.17	0.17	0.16	0.18	0.23	0.23	0.36
ALBUQUERQUE, N.M.	0.04	0.06	0.04	0.04	0.08	0.07	0.10
AMARILLO, TEXAS	0.05	0.06	0.05	0.04	0.08	0.06	0.11
APALACHICOLA, FLA.	0.09	0.11	0.11	0.10	0.14	0.17	0.25
ATLANTA, GEORGIA	0.14	0.17	0.18	0.17	0.22	0.25	0.33
AGUSTA, GEORGIA	0.11	0.15	0.14	0.14	0.18	0.19	0.27
BAKERSFIELD, CALIF	0.04	0.06	0.05	0.06	0.08	0.09	0.13
BILLINGS, MONTANA	0.08	0.09	0.09	0.07	0.12	0.13	0.18
BINGHAMTON, N.Y.	0.23	0.26	0.26	0.24	0.35	0.36	0.54
BIRMINGHAM, ALA.	0.16	0.17	0.15	0.16	0.22	0.23	0.33
BISMARCK, N.D.	0.11	0.10	0.11	0.09	0.17	0.15	0.25
BOISE, IDAHO	0.13	0.16	0.17	0.15	0.23	0.24	0.35
BOSTON, MASS.	0.17	0.18	0.16	0.16	0.23	0.22	0.33
BROWNSVILLE, TEXAS	0.08	0.11	0.11	0.06	0.13	0.14	0.20
BUFFALO, NEW YORK	0.27	0.34	0.37	0.28	0.44	0.46	0.63
BURLINGTON, VT.	0.20	0.22	0.21	0.22	0.30	0.30	0.45
BURNS, OREGON	0.14	0.17	0.18	0.12	0.24	0.23	0.34
CARIBOU, MAINE	0.22	0.22	0.21	0.21	0.29	0.30	0.43
CASPER, WYOMING	0.07	0.09	0.07	0.05	0.12	0.10	0.18
CHARLESTON, S.C.	0.10	0.12	0.12	0.13	0.17	0.18	0.27
CHARLOTTE, N.C.	0.13	0.16	0.14	0.12	0.20	0.20	0.29
CHICAGO, ILLINOIS	0.16	0.16	0.15	0.17	0.22	0.23	0.35
CINCINNATI, OHIO	0.17	0.21	0.18	0.17	0.26	0.24	0.37
CLEVELAND. OHIO	0.22	0.28	0.28	0.24	0.36	0.37	0.52
COLUMBUS, OHIO	0.17	0.19	0.21	0.16	0.26	0.25	0.37
DENVER, COLORADO	0.05	0.06	0.06	0.06	0.08	0.09	0.13
DES MOINES, IOWA	0.09	0.10	0.11	0.09	0.15	0.14	0.22
DETROIT, MICHIGAN	0.17	0.20	0.20	0.18	0.26	0.29	0.41
DODGE CITY, KANSAS	0.05	0.04	0.03	0.04	0.06	0.05	0.09
DULUTH, MINNESOTA	0.15	0.21	0.15	0.13	0.26	0.20	0.35
EL PASO, TEXAS	0.02	0.04	0.05	0.03	0.05	0.06	0.08
ELY, NEVADA	0.08	0.07	0.08	0.06	0.11	0.11	0.17
EUREKA, CALIF.	0.27	0.29	0.30	0.29	0.36	0.38	0.48
FARGO, N.C.	0.10	0.13	0.09	0.09	0.17	0.13	0.24
FORT SMITH, ARK.	0.09	0.10	0.10	0.09	0.12	0.14	0.19
FORT WORTH, TEXAS	0.07	0.10	0.11	0.08	0.12	0.14	0.18
FRESNO, CALIF.	0.10	0.10	0.11	0.08	0.14	0.14	0.20
GND JUNCTION,COLO.	0.08	0.08	0.07	0.07	0.13	0.11	0.19
GND RAPIDS, MICH.	0.25	0.29	0.23	0.21	0.37	0.31	0.48
GREAT FALLS, MONT.	0.11	0.12	0.09	0.11	0.16	0.14	0.22
GREEN BAY, WISC.	0.14	0.16	0.14	0.11	0.22	0.18	0.31
HARTFORD, CONN.	0.18	0.16	0.15	0.16	0.24	0.21	0.34
HOUSTON, TEXAS	0.11	0.14	0.17	0.15	0.17	0.23	0.29
HUNTINGTON, W. VA.	0.15	0.20	0.22	0.17	0.25	0.27	0.37
HURON, S. DAKOTA	0.07	0.09	0.08	0.09	0.13	0.13	0.21
INDIANAPOLIS, IND.	0.17	0.19	0.19	0.20	0.26	0.27	0.37
INTR. FALLS, MINN.	0.15	0.23	0.17	0.15	0.28	0.24	0.40
JACKSON,MISS.	0.15	0.16	0.15	0.16	0.23	0.22	0.34
JACKSONVILLE, FLA.	0.08	0.09	0.09	0.11	0.13	0.15	0.23
KANSAS CITY, MO.	0.09	0.09	0.09	0.09	0.12	0.13	0.18
KNOXVILLE. TENN.	0.16	0.20	0.17	0.16	0.25	0.24	0.35
LANDER, WYOMING	0.06	0.07	0.06	0.05	0.10	0.08	0.12
LAS VEGAS. NEVADA	0.03	0.04	0.02	0.02	0.05	0.03	0.06
LITTLE ROCK, ARK.	0.14	0.14	0.16	0.14	0.20	0.20	0.28

FIGURE 3.—Example of portion of machine printout for the month of December showing computed values for seven time periods.

stations for 6-, 12-, and 24-hour periods for each of the twelve months, and the analyses based on these data. However, the stations are not spaced closely enough to show the variability known to exist, especially in the mountain areas, and the analysis makes interpolation estimates between stations based on a generalized topographical map, seasonal wind charts, and supplementary charts of the type given in figure 2 of monthly precipitation frequencies for each month of the year. The assumption is made that the analysis giving the frequency of occurrence of precipitation for the 24-hour periods will be similar to that giving the monthly frequency of precipitation for the same month. However, for the shorter periods involving 6- and 12-hour periods, diurnal influences can change the analyzed patterns significantly. Even though an attempt has been made to bring the various factors into play in making the final analyses, the patterns must still be used with caution when interpolating between known station values. Many local factors affecting precipitation occurrence cannot be taken into account in a study of this nature, and where possible, individual station data should be obtained and analyzed to give local precipitation frequencies (probabilities).

In making the analyses, the processed data were plotted on charts showing general topographic features. This permitted a more accurate placing of areas of higher probabilities on the windward slopes of mountains, as well as the "rain shadow" to the leeward side. Isolines were drawn to each 10 per cent probability of occurrence except where the spacing or amount of detail made the use of each 5 per cent or 20 per cent more appropriate. Smoothing was used in some cases to better portray the pattern. As can be seen, the 24-hour period analyses show a pattern similar to the monthly precipitation frequencies, e.g., comparing chart 1 - 7 in the Appendix with figure 2(a), and the 6- and 12-hour patterns are in general similar to the 24-hour pattern for each month, except for diurnal variations in some regions during certain seasons. Data stations in mountain localities are usually situated at the lower elevations, and thus are not representative of some of the surrounding elevated terrain. Estimated values for the higher elevations are, of necessity, rather crude and are to be taken only to establish the general pattern in the region.

6. COMPARISON OF THE PROBABILITIES FOR DIFFERING TIME PERIODS

The periods of this study are based on observation periods in sequence: and, as has been pointed out in previous works, the probability of precipitation for combined periods will not correspond to the number calculated on the basis of independent probability. The persistency of rainy periods becomes evident; or, as exhibited here, the periods often "straddle" the observational periods, and the precipitation thus has a degree of apparent recurrence.

The relationship between the probabilities of precipitation occurrence for various time periods of varying lengths can be illustrated by an example. At Little Rock, Ark., the probability of precipitation occurrence for a 24-hour period in January is 31 per cent. The average 12-hour probability is 21.5 per cent, or 69 per cent of the 24-hour value. The average 6-hour probability is 15.8 per cent, or 73 per cent of the 12-hour value and 51 per cent of the 24-hour probability. As can be seen, the probabilities for two consecutive 6-hour periods and for two consecutive 12-hour periods cannot be added to give the respective 12- and 24-hour probabilities.

7. DISCUSSION OF PROBABILITIES BY REGIONS

In the following subsections, the more significant seasonal and diurnal variations in climatological precipitation probabilities are examined for various sections of the country. A number of references will be indicated describing studies of individual stations within the regions, but no attemp has been made to compile a comprehensive bibliography of studies related to the investigation of climatological probabilities of precipitation.

Florida Peninsula

Florida has the distinction of recording the highest annual number of thunderstorm days of all the conterminous states. All sections of the state record at least 70 thunderstorm days on an annual basis, with the number increasing to 90 along the west-central coast. A majority of the thunderstorms are observed during the summer months, and the greatest diurnal variability in precipitation frequency occurs during this period. The variation in the 6-hour precipitation frequencies illustrates the diurnal changes. The frequency of occurrence is greatest from 18-24Z, with precipitation occurring during 24 per cent (average of the six Florida stations) of the periods in June, and least during the 06-12Z period, when only 8.7 per cent of the periods report precipitation. The average frequency for the 6-hour periods for June is 62 per cent of the average 12-hour frequency, and the average 12-hour frequency is 62 per cent of the average 24-hour frequency. This variability is attributed to the occurrence of afternoon thunderstorms and to the absence of other precipitation-producing mechanisms during this season. The spatial distribution in summer shows the effect of the prevailing easterly winds, with convective precipitation increasing after a sufficient trajectory over the warm land. In winter, when precipitation is caused most frequently by fronts and cyclonic storms, Florida is affected less often than the section immediately to the north; and, consequently, the frequency of occurrence tends to be lower in Florida.

Gulf Coast and Southeastern States

The frequency of thunderstorm occurrence along the Gulf Coast takes on a seasonal and diurnal pattern similar to that for the Florida peninsula, but with somewhat lower frequencies, and with frequencies decreasing inland into the lower Mississippi Valley. In summer, a decreasing frequency of thunderstorms inland from the Gulf and Atlantic Coasts and an increase in orographically induced precipitation in the Appalachian Mountains gives a semblance of a dry area extending from east central Texas into the Carolinas.

With the advent of winter and the southward displacement of the principal cyclone tracks, an area of heavier precipitation appears from Louisiana northeastward to the western slopes of the Appalachians. Due to the heavier amounts of precipitation which tend to occur at lower latitudes, the associated frequency distribution does not show as much variability as the quantitative pattern. There is a greater frequency of occurrence on the windward (western) slopes of the Appalachians compared to the areas nearer the Gulf Coast and just to the east of the mountains.

Studies of hourly frequency and intensity of rainfall at New Orleans by McDonald [14] and at Mobile by Armstrong [2] show a distribution typical of the Gulf Coast region. In winter little diurnal change is observed; but, from April until October, there is a maximum frequency during the period from 18-24Z with a peak at 20-21Z. The maximum value of the diurnal difference is found in July when at mid-afternoon the frequency is five times greater than for a like period at night, with the period 07-08Z in July having the lowest frequency of the year.

Northeastern States and Eastern Great Lakes Region

The frequency of precipitation in this section is variable. Lakes, mountains, and proximity to the ocean all show substantial influences on the local frequency. For example, Maine encompasses two differing climatic regimes; one on the coast, the other inland. The frequency of precipitation is greater inland with lower frequencies along the coast. The frequency of precipitation occurrence, in general, over most of this section is fairly even on a seasonal basis, with somewhat higher frequencies in winter than in the early fall. These are due to a smaller number of cyclonic storms during the fall as a result of the shift of the primary track northward into Canada.

The major influence of the Great Lakes is felt mostly within 25 miles of the lakes. In the early summer, the lakes tend to cool and stabilize the atmosphere to decrease precipitation; and in the early winter, they produce a maximum local effect by providing heat and moisture to increase precipitation.

Central States

In this area, the distinguishing feature is the steady decline in the frequency of occurrence from the Appalachian Mountains westward to the Rocky Mountains, with the lowest values in the southwestern section. The most frequent precipitation, though in light amounts, is observed in the northeastern area; and heavier rates of fall are common in the southeastern portion.

The climatic regime in this section, particularly in the western part, is one of dry winters and relatively wet summers. Over much of the western area, the winter minimum in frequency of occurrence is about 50 per cent of the summer maximum. The eastern portion shows a more even seasonal pattern with a tendency for lower values in the fall.

The frequencies vary diurnally in this area, mostly in relation to convectively produced summer thunderstorms [1]. The greatest variation occurs in the summer months, with minimum frequencies occurring during the 06-12Z period and maximum frequencies during the afternoon and evening. An exception to this timing occurs in the area of maximum nocturnal thunderstorms which is centered in eastern Kansas in July and August. In this area the diurnal frequency reaches its maximum during the 06-12Z period [15, 19, 20, 23].

Intermountain States

This section has the most varied precipitation pattern in the conterminous states. This variability is induced, as noted earlier, by the mountainous terrain. On an annual basis, the frequencies of precipitation decrease from north to south, reaching their lowest values in southwestern Arizona.

The seasonal change in precipitation is featured by a dry summer and wet winter in contrast to the central states and Rocky Mountain areas, where summer is the wet period. In the southern portion, the period from April to June is the driest part of the year, with a subsequent shift northward so that the dry period occurs in July and August. In Arizona and New Mexico, the dry period is interrupted, as mentioned earlier, in July when the "monsoon" influx of moisture from the Gulf of Mexico produces favorable conditions for thunderstorms [5, 8]. In winter, precipitation is associated with cyclonic circulation which increases with the shift southward of the principal and secondary storm tracks. Precipitation is generally more frequent when a large upper-level trough exists in the region and cyclonic storms move into the area from the Pacific, with often more than one storm in succession. The deeper storms are seen to produce a more widespread precipitation area [10].

A diurnal variation is caused by thunderstorms in summer. During the period of minimum thunderstorm activity, frequencies of precipitation are very low with locations such as Salt Lake City having a 2 per cent frequency from 12 to 18Z. In winter, variations are small from period to period with a maximum tending to occur from 06 to 12Z.

Pacific Coast States

The seasonal change in frequency of precipitation is large with trends similar to those observed in the intermountain region. The climatological regime consists of a wet winter and dry summer, with the dry minimum occurring in the northern part later in the summer than in the southern part. The change from the higher frequencies occurring in the winter to the lower frequencies in summer, and the reverse in the fall, is notable for its steady trend. In contrast, the dry period in Arizona and New Mexico is interrupted in July by the appearance of numerous thunderstorms. The large Pacific High pressure center affects the area, averaging farthest north in position and reaching a maximum extent in mid-summer with a heat low in the southwestern area. Both of these features tend to inhibit the occurrence of precipitation. The western coastal strip has the lowest thunderstorm frequency of any area in the country.

In winter, cyclones have their highest frequency of occurrence in this region as the mean storm tracks shift southward during the fall and early winter. The highest frequencies of precipitation in the conterminous states, as already observed, occur over the western slopes of the Coast Range in Oregon and Washington. Frequencies decrease toward the south until parts of southeastern California are included in the driest parts of the country.

Diurnal variations are mostly small throughout this region during all seasons [7]. In Portland and Seattle, a small increase is seen in the period 06 to 12Z, and slightly lower precipitation frequencies occur in the 18 to 24Z period.

ACKNOWLEDGMENTS

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APPENDIX

CHARTS GIVING 6-, 12-, AND 24-HOUR CLIMATOLOGICAL PROBABILITIES

The charts making up this Appendix are given on pages 13 through 60. These show plotted data and analyses for 6-, 12-, and 24-hour climatological probabilities for each of the twelve months. In making the analyses, the data were plotted on charts showing general topographic features. This permitted a more accurate placing of areas of higher probabilities on the windward slopes of the mountains as well as the "rain shadow" to the leeward side. Isolines are drawn to each 10 per cent probability of occurrence except where the spacing or amount of detail made the use of each 5 per cent or 20 per cent interval more appropriate.

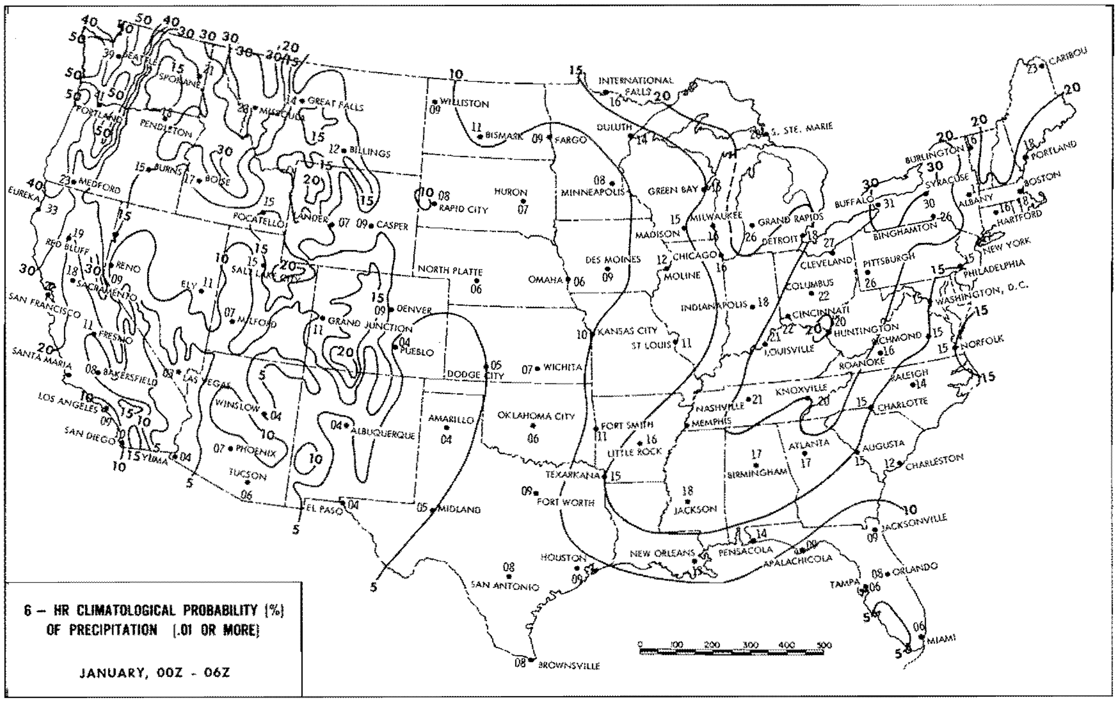
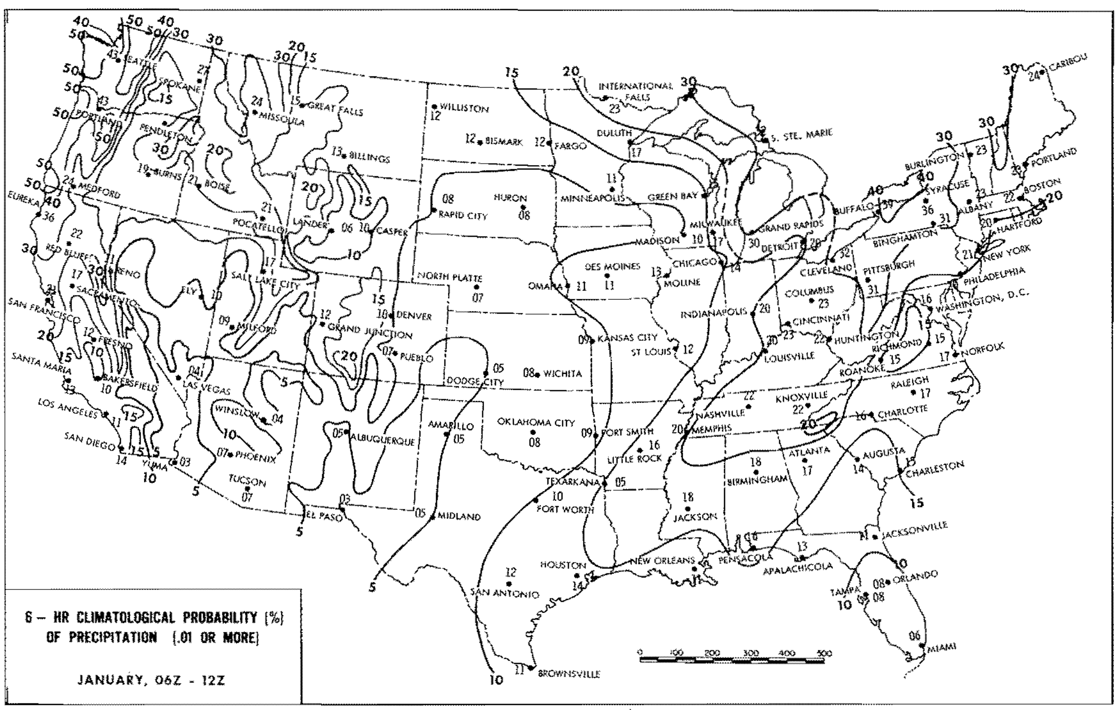


Chart 1 - 1



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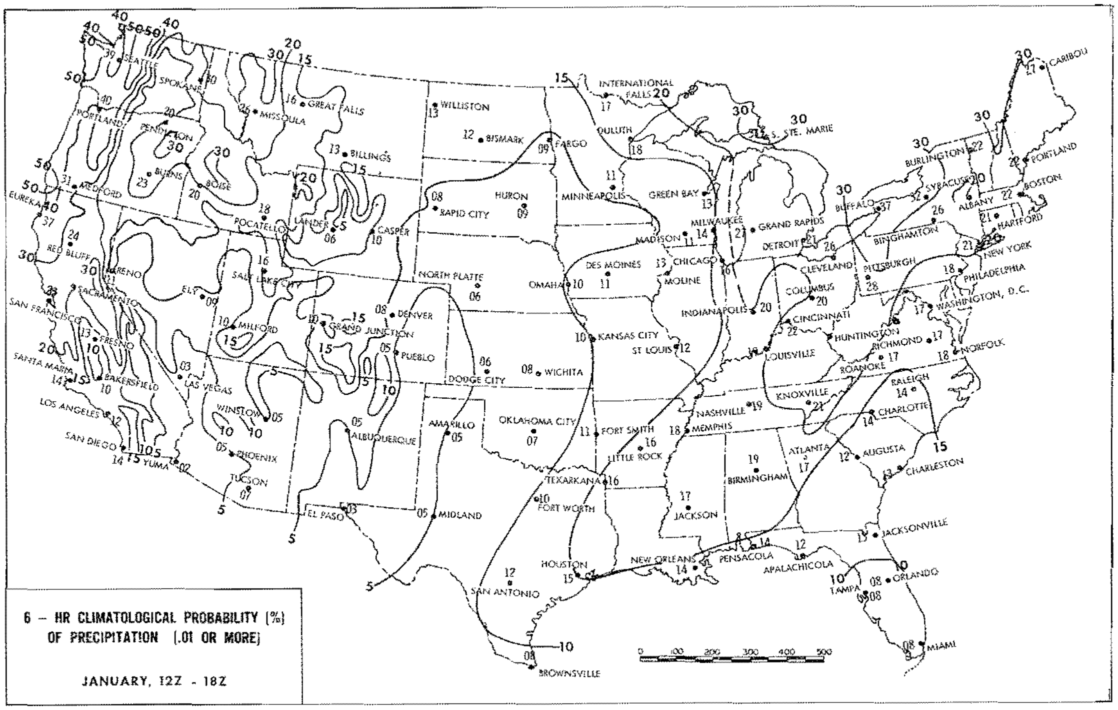

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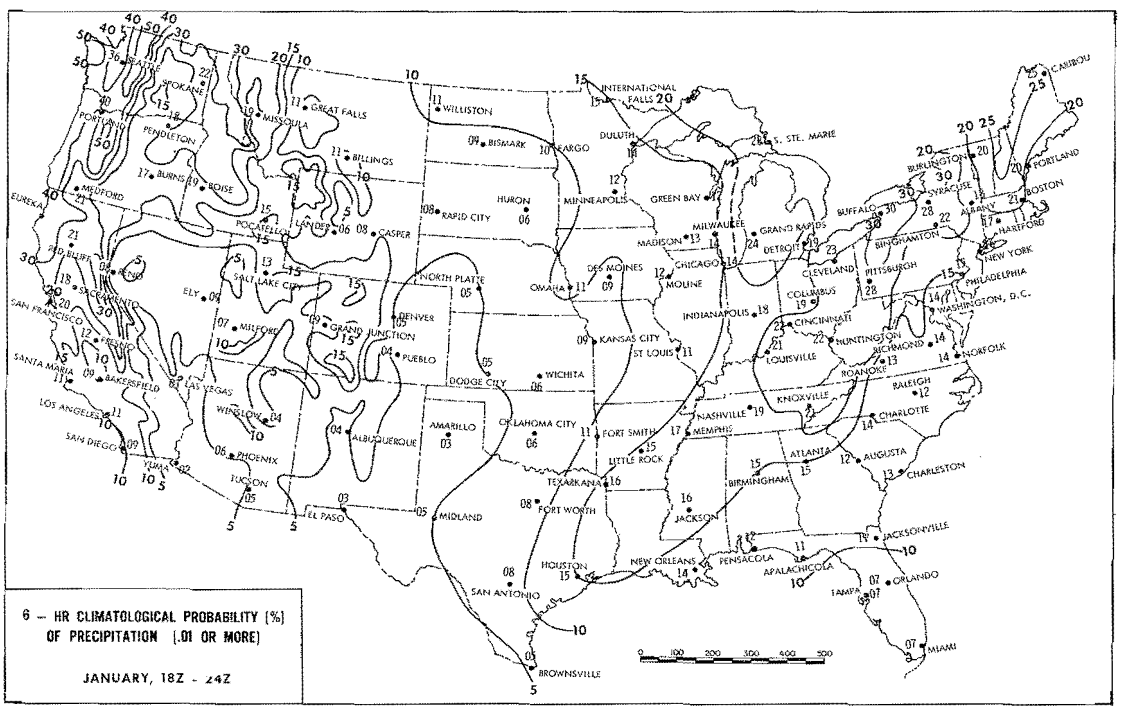

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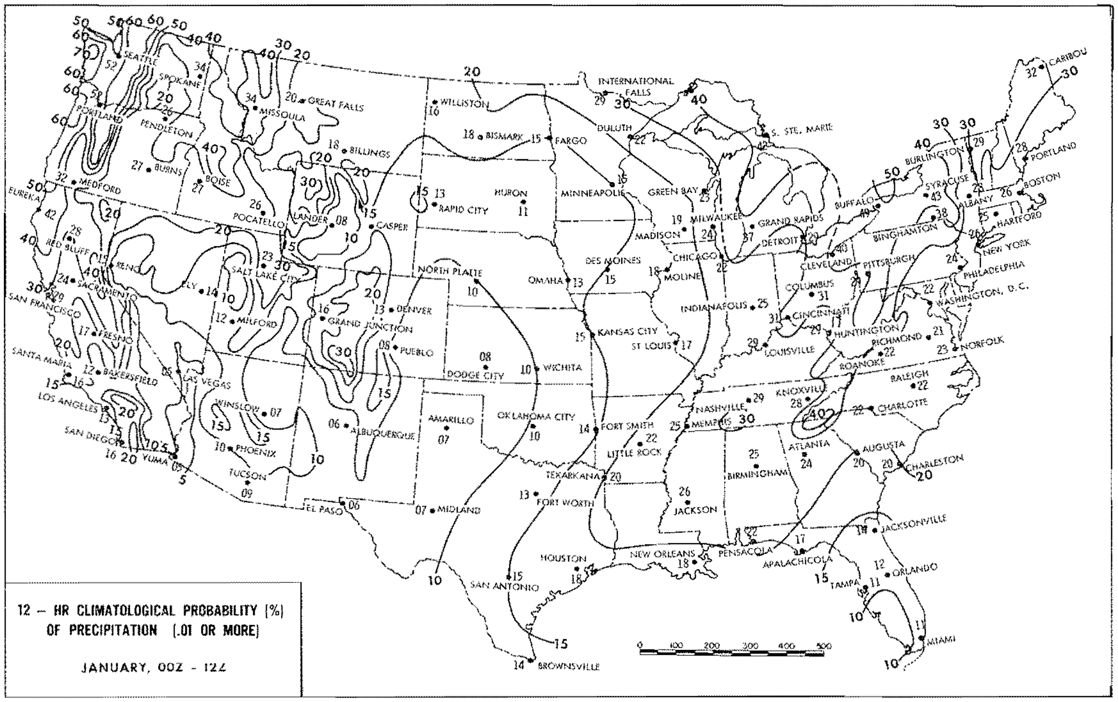
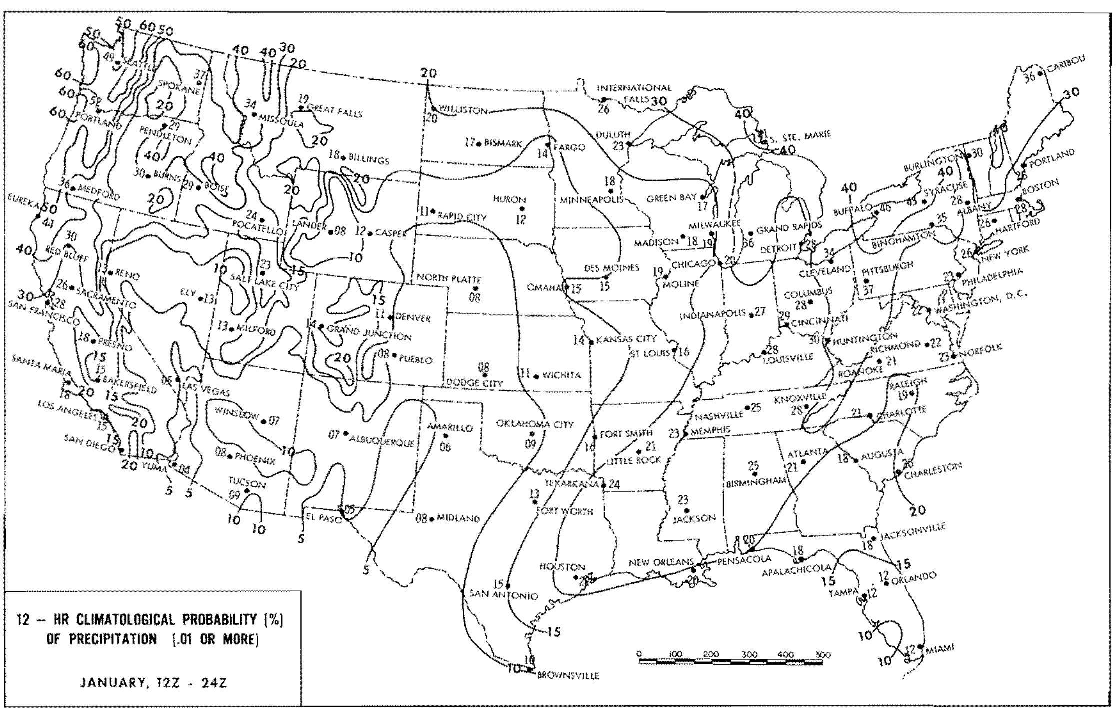


12 – HR CLIMATOLOGICAL PROBABILITY (%) OF PRECIPITATION (.01 OR MORE)

JANUARY, 00Z - 12Z

Chart 1 - 5



12 – HR CLIMATOLOGICAL PROBABILITY (%) OF PRECIPITATION (.01 OR MORE)

JANUARY, 12Z - 24Z

Chart 1 - 6

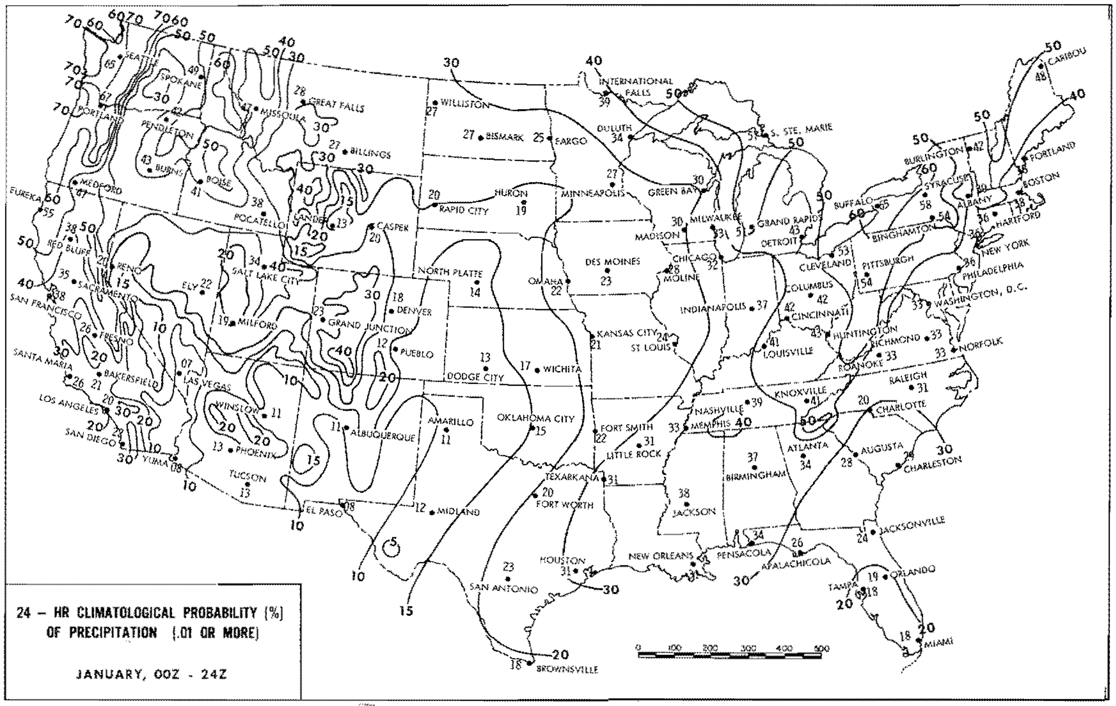
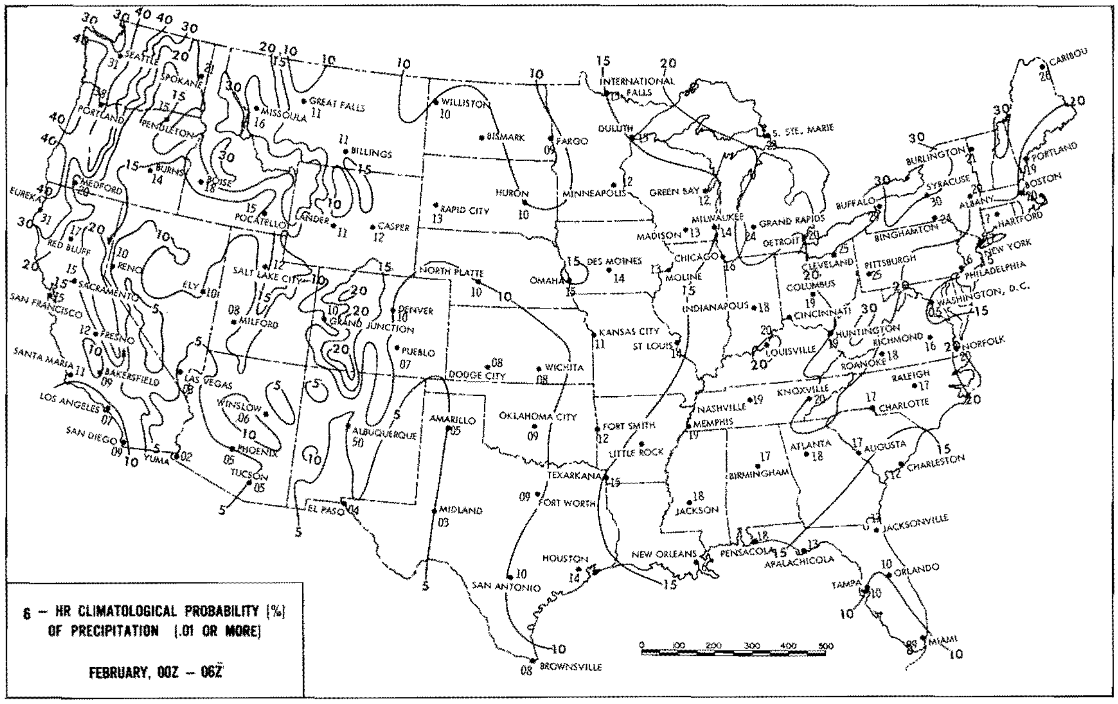

24 – HR CLIMATOLOGICAL PROBABILITY (%)
OF PRECIPITATION (.01 OR MORE)
JANUARY, 00Z - 24Z
SEATTLE
SPOKANE
PORTLAND
PENDLETON
MISSOULA
GREAT FALLS
BILLINGS
WILLISTON
BISMARCK
FARGO
INTERNATIONAL FALLS
DULUTH
S. STE. MARIE
CARIBOU
BURLINGTON
PORTLAND
BOSTON
SYRACUSE
ALBANY
HARTFORD
BUFFALO
BINGHAMTON
NEW YORK
PHILADELPHIA
WASHINGTON, D.C.
NORFOLK
RICHMOND
ROANOKE
RALEIGH
CHARLOTTE
CHARLESTON
AUGUSTA
JACKSONVILLE
ORLANDO
TAMPA
MIAMI
APALACHICOLA
PENSACOLA
NEW ORLEANS
ATLANTA
BIRMINGHAM
KNOXVILLE
NASHVILLE
MEMPHIS
JACKSON
LITTLE ROCK
FORT SMITH
TEXARKANA
FORT WORTH
HOUSTON
SAN ANTONIO
BROWNSVILLE
MIDLAND
EL PASO
AMARILLO
OKLAHOMA CITY
WICHITA
DODGE CITY
KANSAS CITY
ST LOUIS
LOUISVILLE
CINCINNATI
HUNTINGTON
COLUMBUS
PITTSBURGH
CLEVELAND
DETROIT
GRAND RAPIDS
MILWAUKEE
GREEN BAY
MADISON
CHICAGO
MOLINE
INDIANAPOLIS
DES MOINES
OMAHA
MINNEAPOLIS
HURON
RAPID CITY
NORTH PLATTE
DENVER
PUEBLO
GRAND JUNCTION
CASPER
LANDER
POCATELLO
SALT LAKE CITY
MILFORD
ELY
RENO
BOISE
BURNS
MEDFORD
EUREKA
RED BLUFF
SACRAMENTO
SAN FRANCISCO
FRESNO
SANTA MARIA
BAKERSFIELD
LAS VEGAS
LOS ANGELES
SAN DIEGO
YUMA
PHOENIX
TUCSON
WINSLOW
ALBUQUERQUE

Chart 1 - 7



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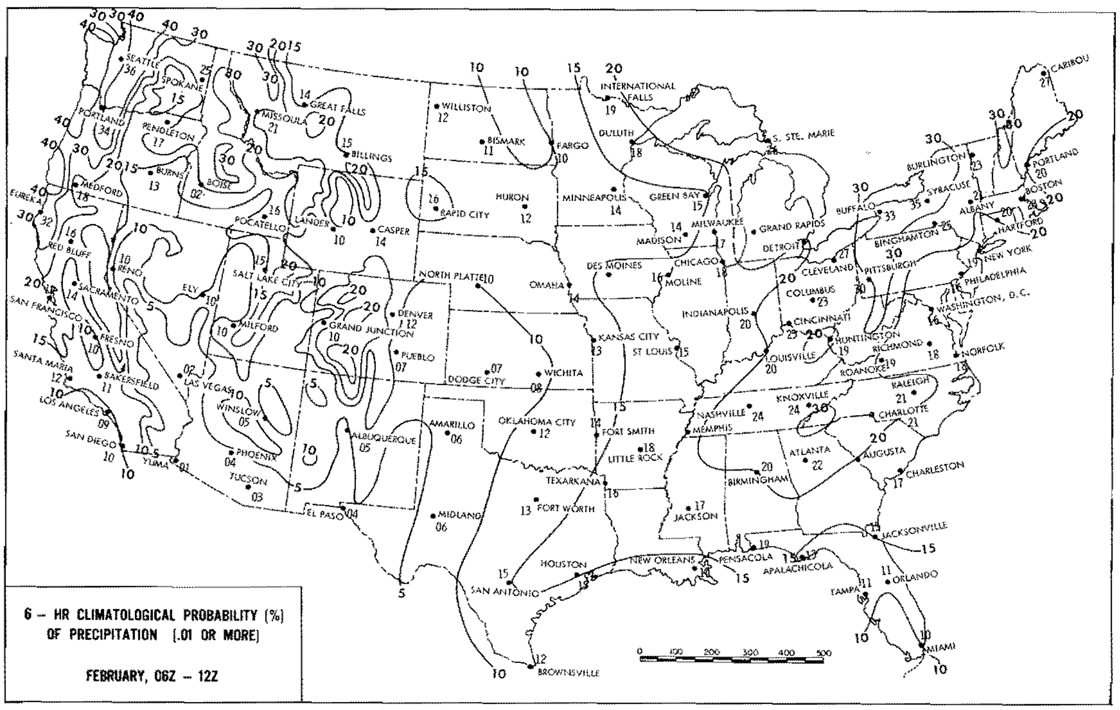

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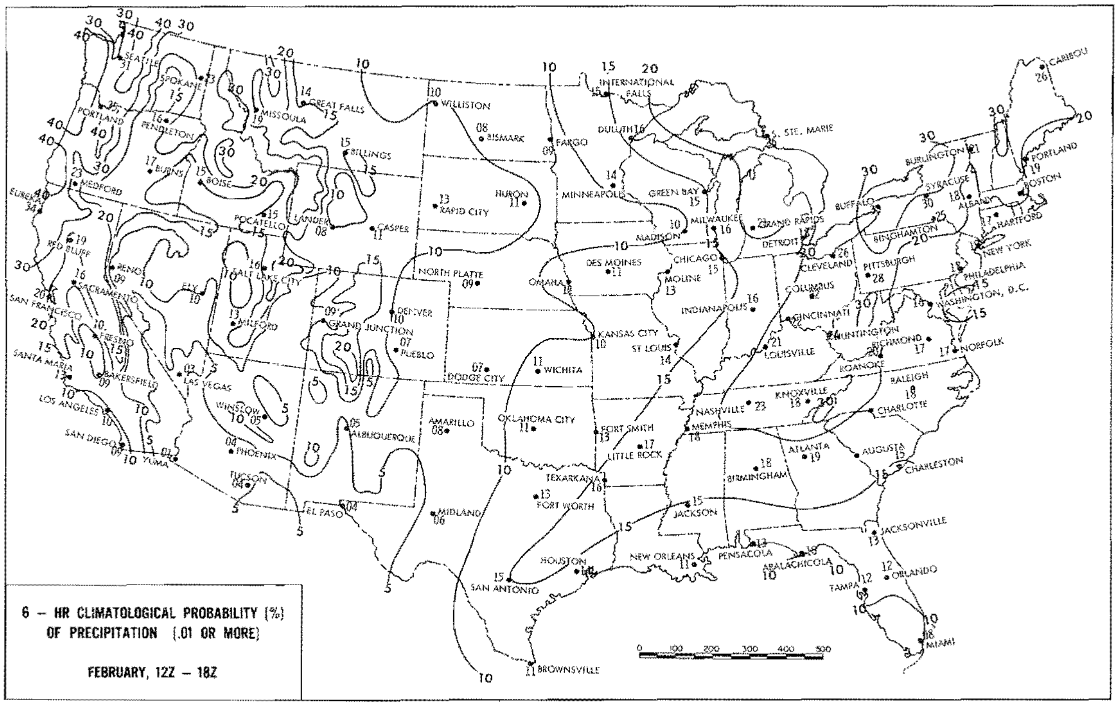

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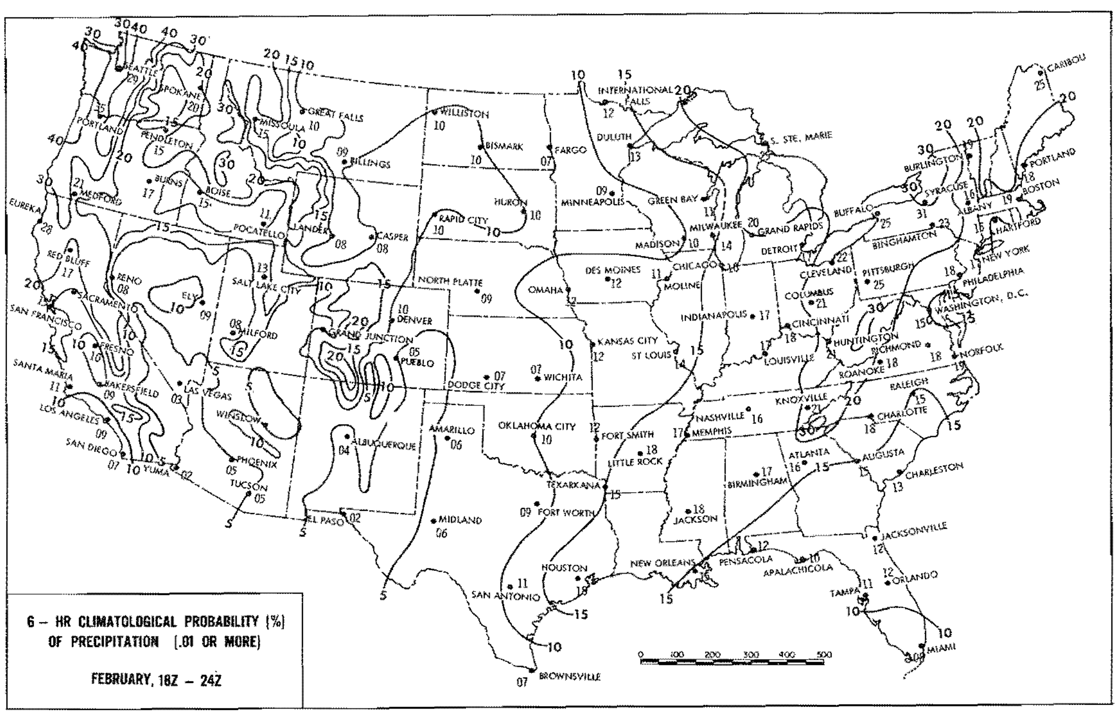

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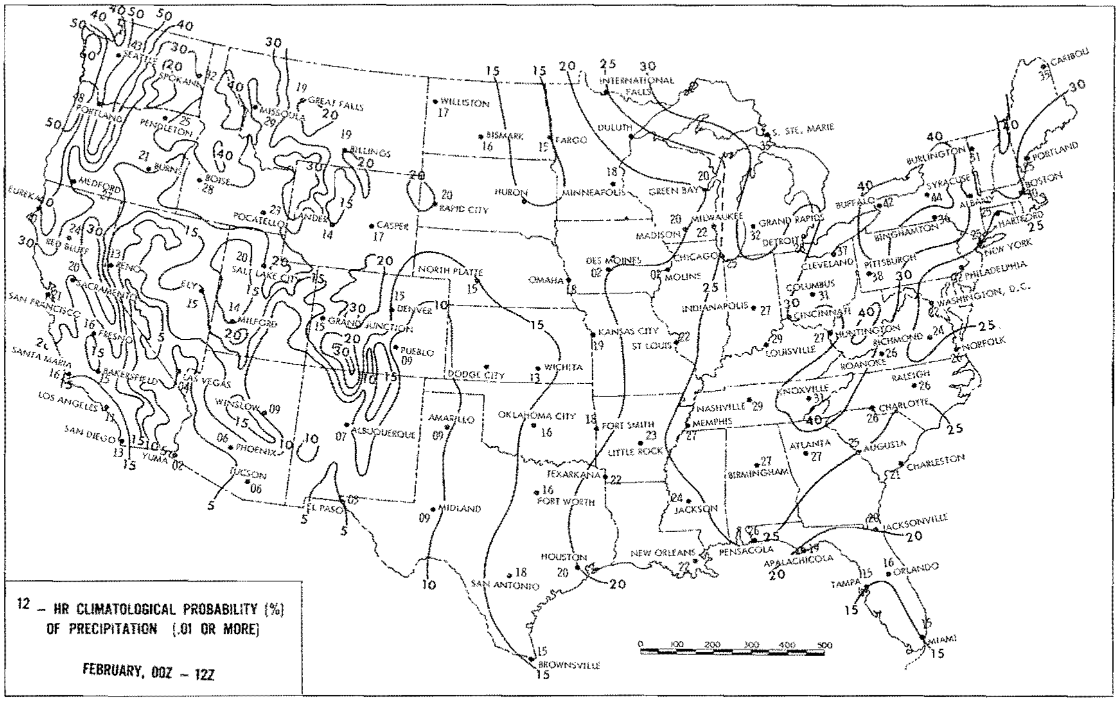
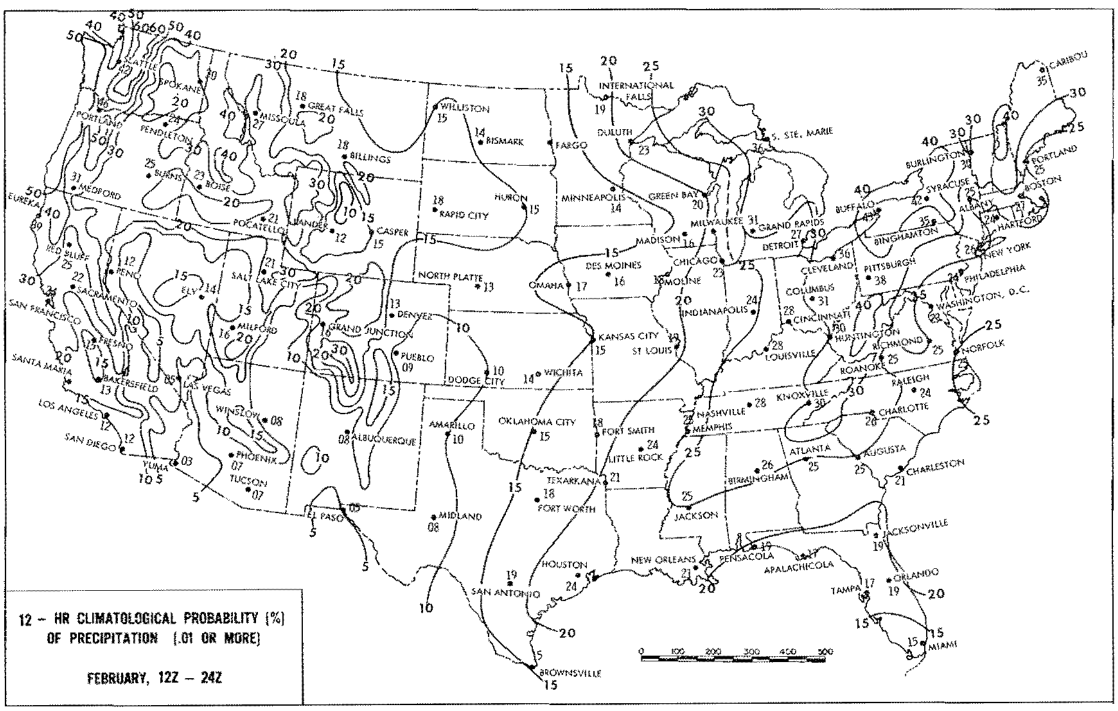


12 – HR CLIMATOLOGICAL PROBABILITY (%) OF PRECIPITATION (.01 OR MORE)

FEBRUARY, 00Z – 12Z

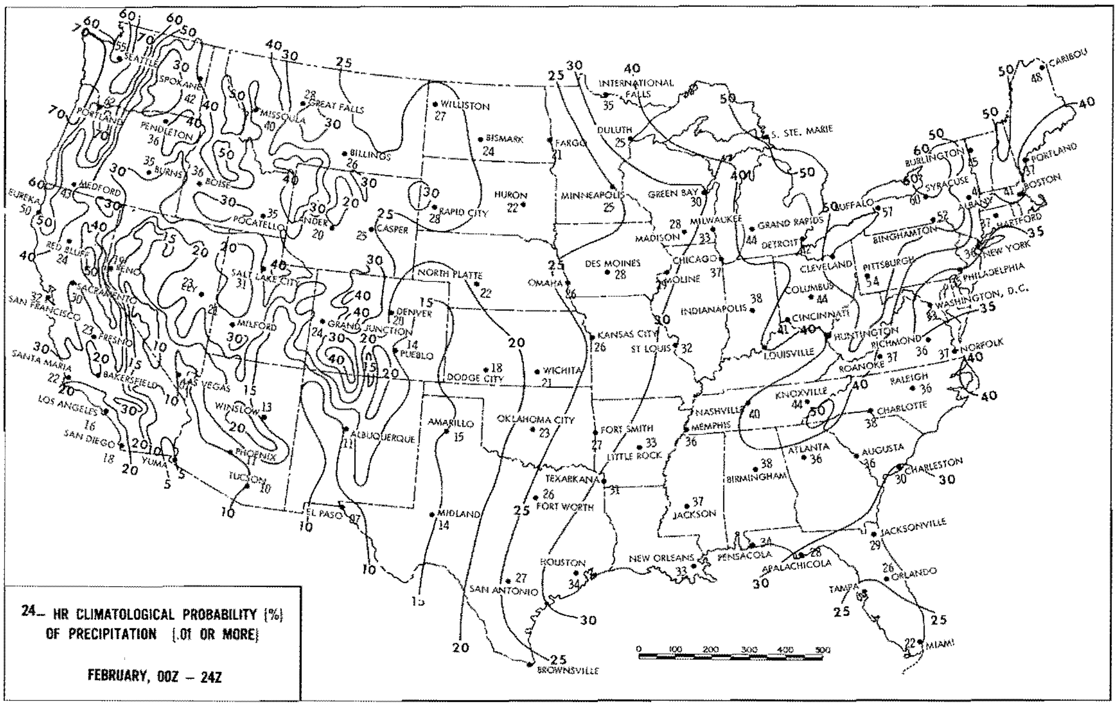
Chart 2 - 5



12 – HR CLIMATOLOGICAL PROBABILITY (%) OF PRECIPITATION (.01 OR MORE)

FEBRUARY, 12Z – 24Z

Chart 2 - 6


24– HR CLIMATOLOGICAL PROBABILITY (%) OF PRECIPITATION (.01 OR MORE)
FEBRUARY, 00Z – 24Z
0 100 200 300 400 500
SEATTLE
SPOKANE
PORTLAND
PENDLETON
BURNS
BOISE
MEDFORD
EUREKA
RED BLUFF
RENO
SACRAMENTO
SAN FRANCISCO
FRESNO
SANTA MARIA
BAKERSFIELD
LOS ANGELES
SAN DIEGO
YUMA
LAS VEGAS
ELY
MILFORD
SALT LAKE CITY
POCATELLO
MISSOULA
GREAT FALLS
BILLINGS
LANDER
CASPER
WINSLOW
PHOENIX
TUCSON
EL PASO
ALBUQUERQUE
GRAND JUNCTION
DENVER
PUEBLO
WILLISTON
BISMARK
RAPID CITY
HURON
NORTH PLATTE
DODGE CITY
AMARILLO
MIDLAND
SAN ANTONIO
BROWNSVILLE
FARGO
MINNEAPOLIS
OMAHA
DES MOINES
WICHITA
OKLAHOMA CITY
FORT WORTH
HOUSTON
TEXARKANA
FORT SMITH
LITTLE ROCK
KANSAS CITY
ST LOUIS
INTERNATIONAL FALLS
DULUTH
GREEN BAY
MADISON
MILWAUKEE
CHICAGO
MOLINE
INDIANAPOLIS
LOUISVILLE
NASHVILLE
MEMPHIS
JACKSON
NEW ORLEANS
BIRMINGHAM
ATLANTA
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S. STE. MARIE
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DETROIT
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PITTSBURGH
BUFFALO
BINGHAMTON
SYRACUSE
BURLINGTON
ALBANY
HARTFORD
BOSTON
PORTLAND
CARIBOU
NEW YORK
PHILADELPHIA
WASHINGTON, D.C.
RICHMOND
NORFOLK
ROANOKE
RALEIGH
CHARLOTTE
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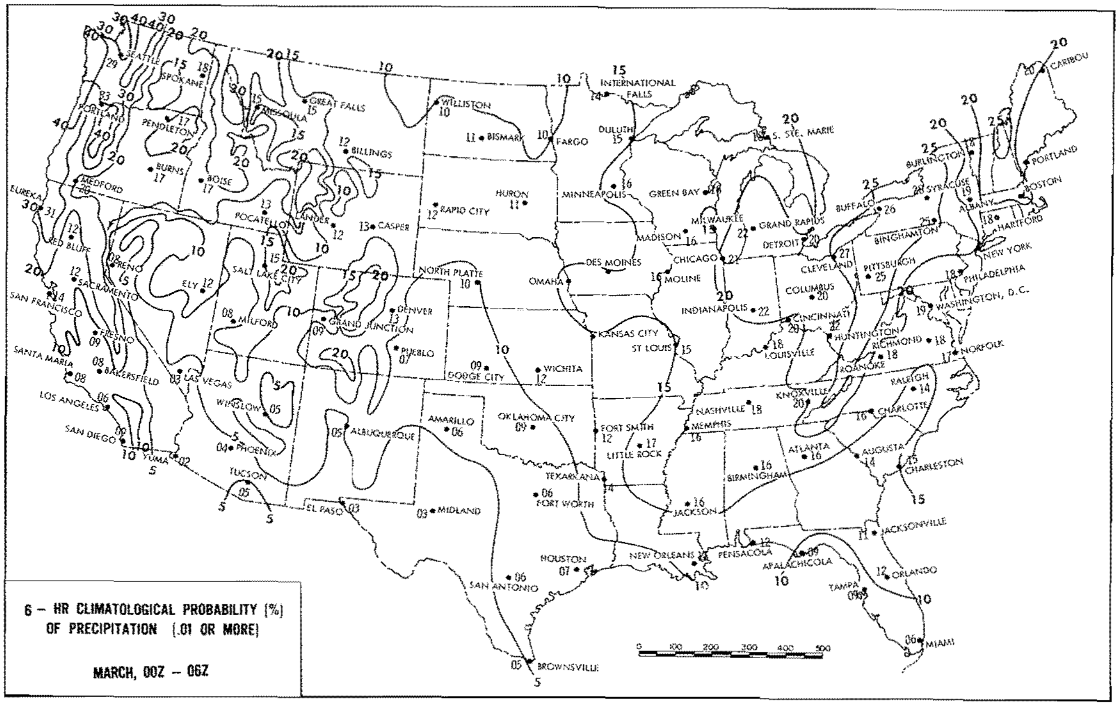
JACKSONVILLE
PENSACOLA
APALACHICOLA
ORLANDO
TAMPA
MIAMI

Chart 2 - 7



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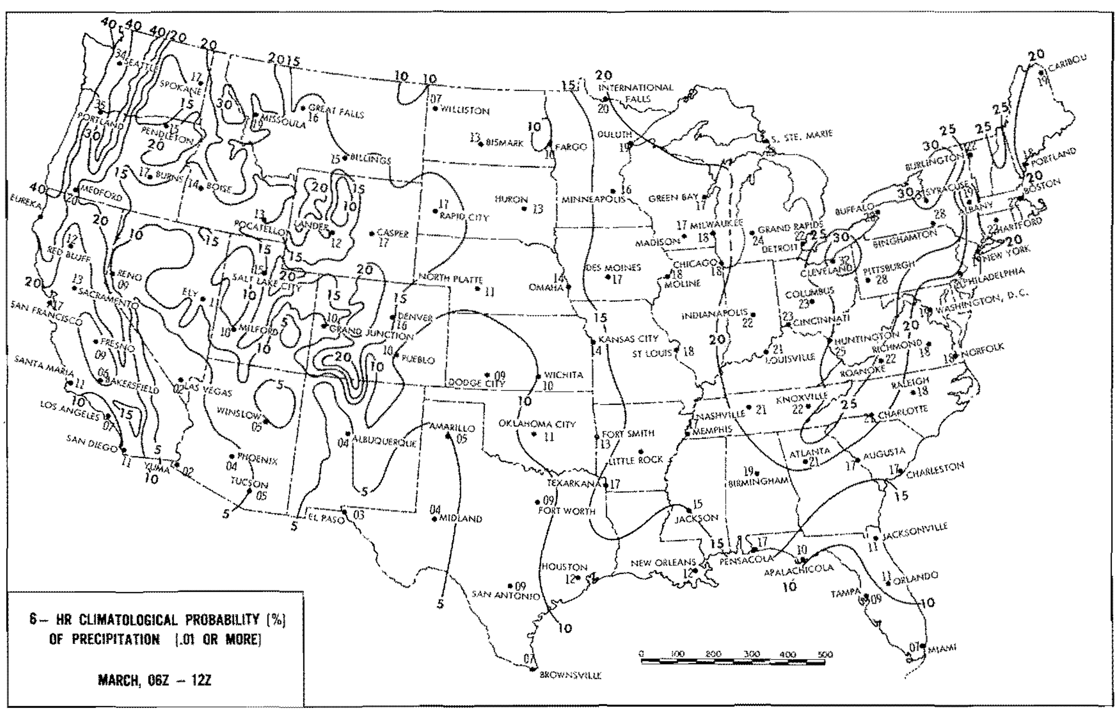

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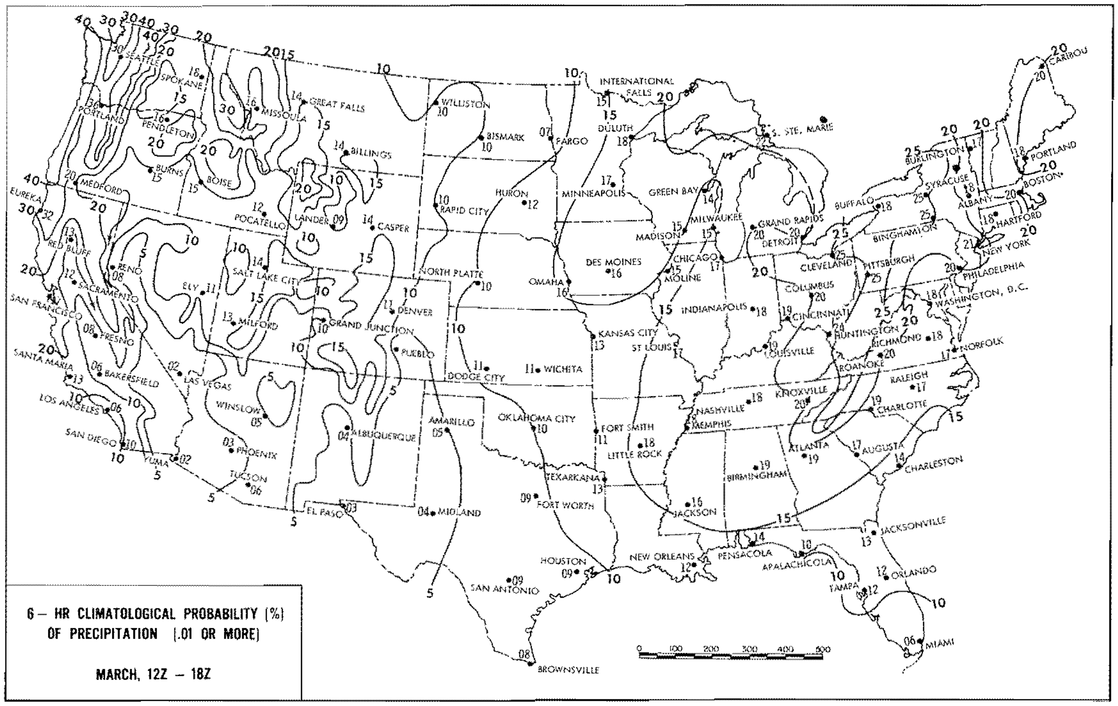


Chart 3 - 3

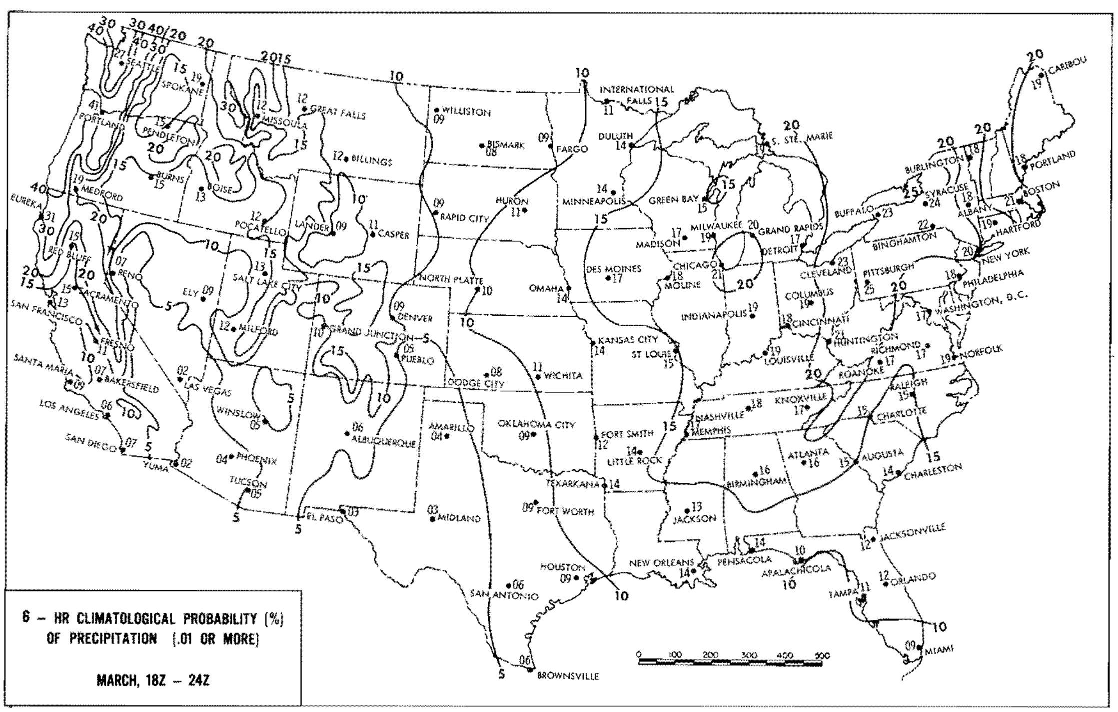


Chart 3 - 4

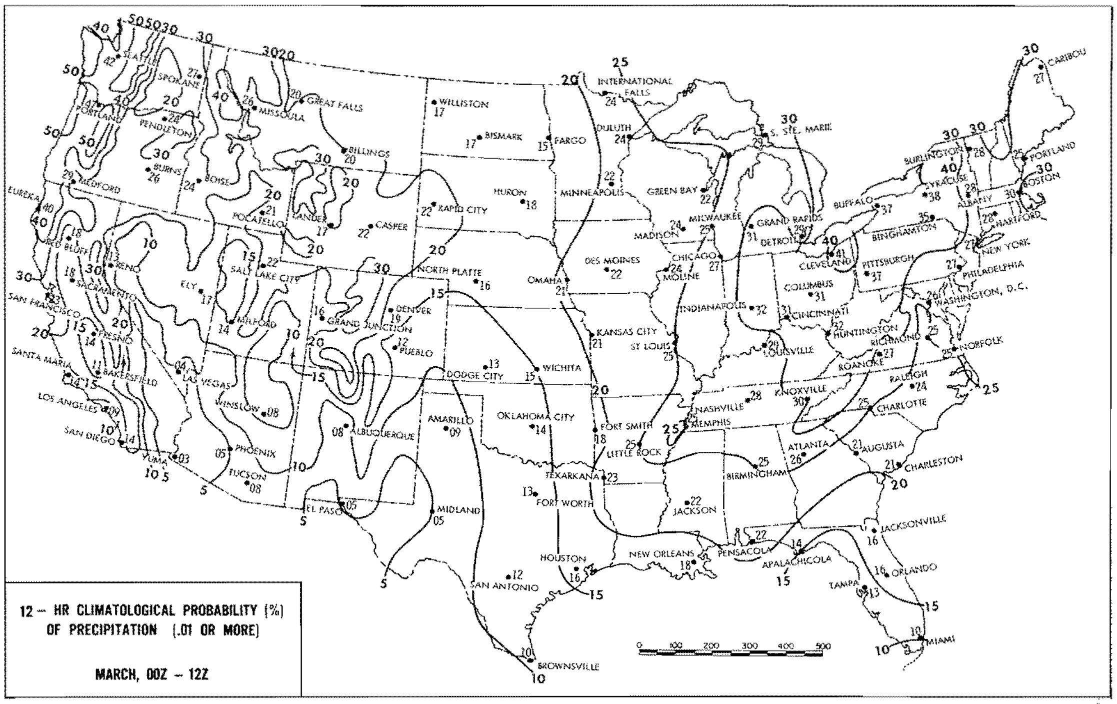


Chart 3 - 5

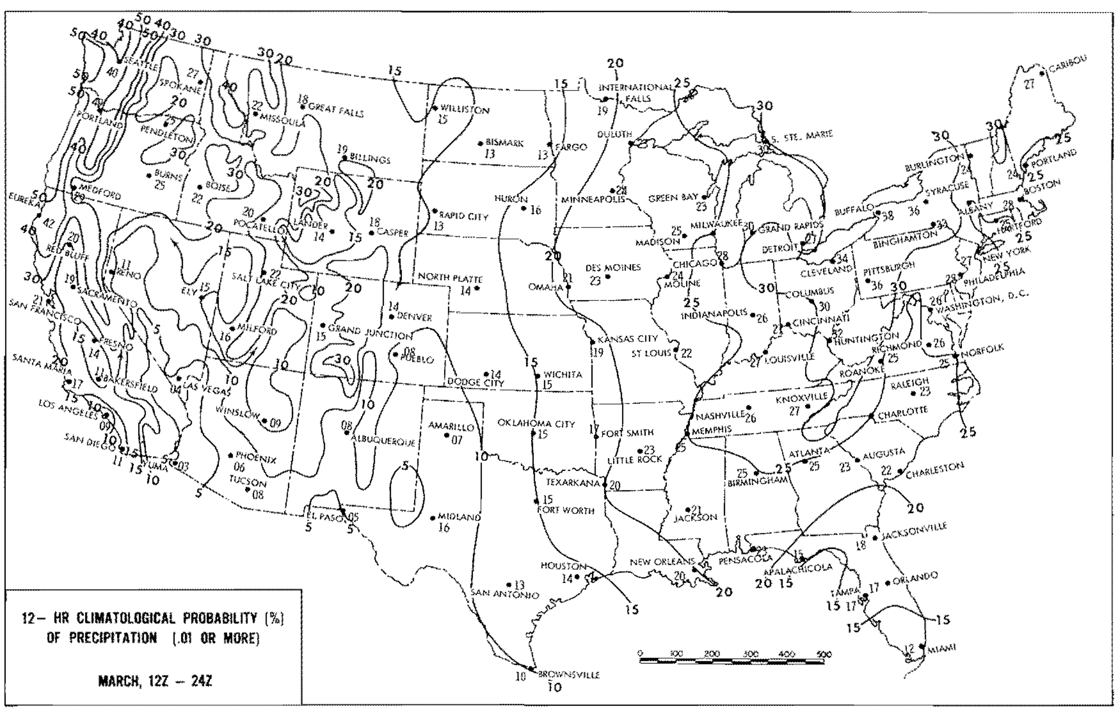


Chart 3 - 6

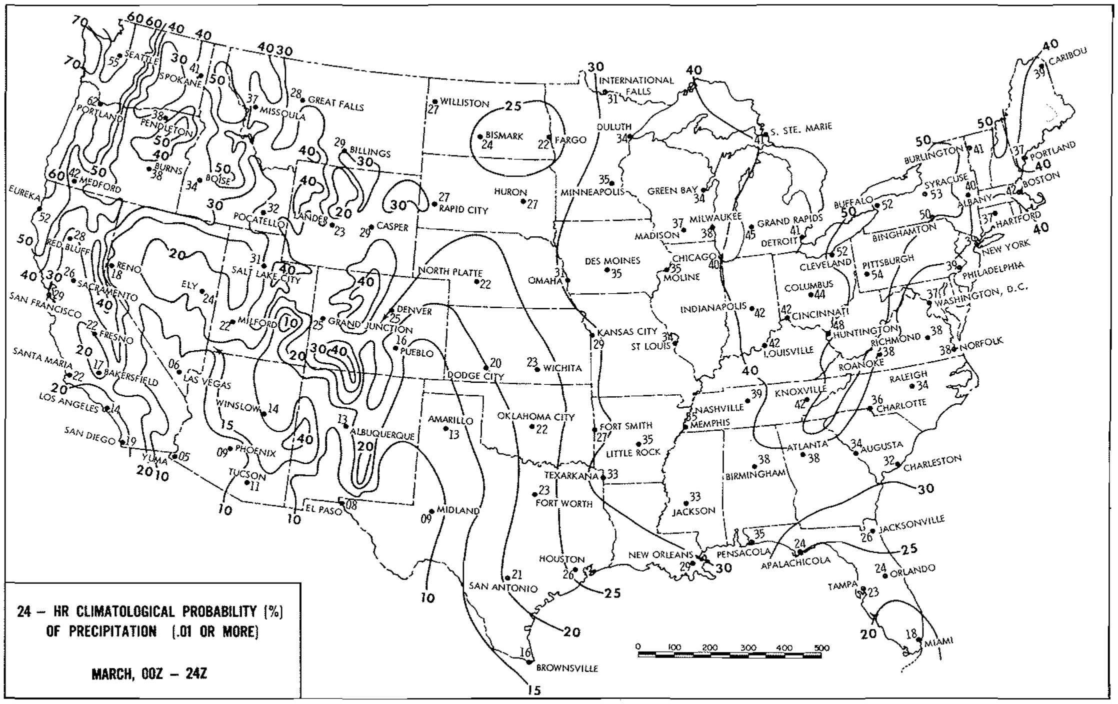

24 – HR CLIMATOLOGICAL PROBABILITY (%)
OF PRECIPITATION (.01 OR MORE)
MARCH, 00Z – 24Z

Chart 3 - 7

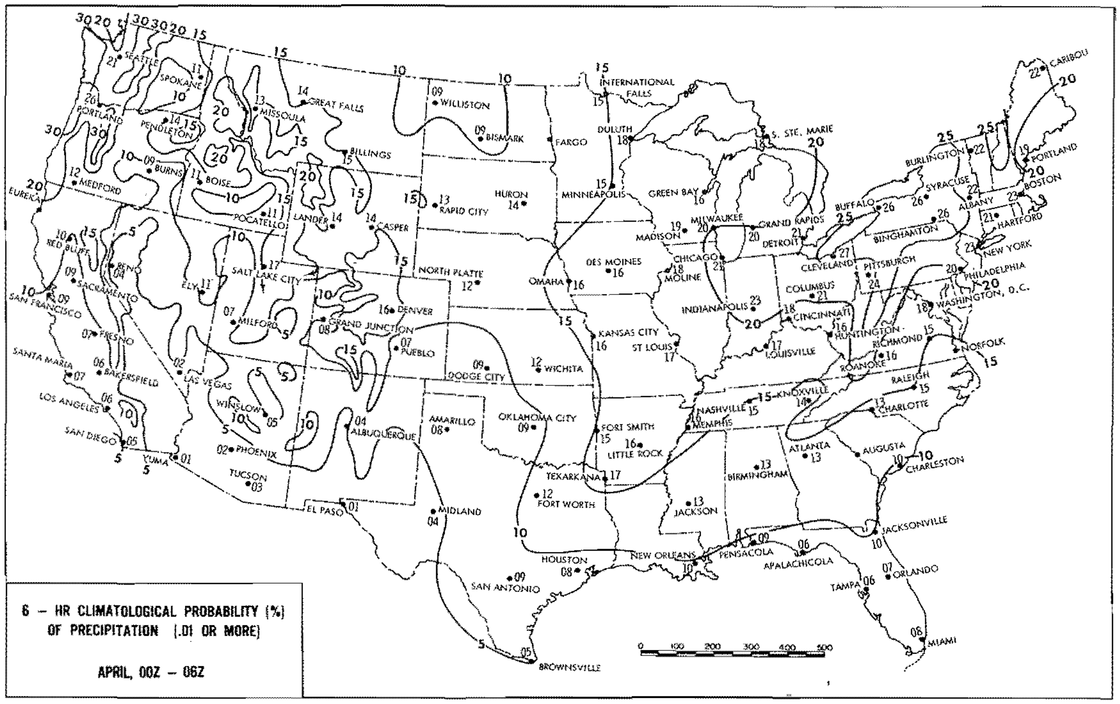
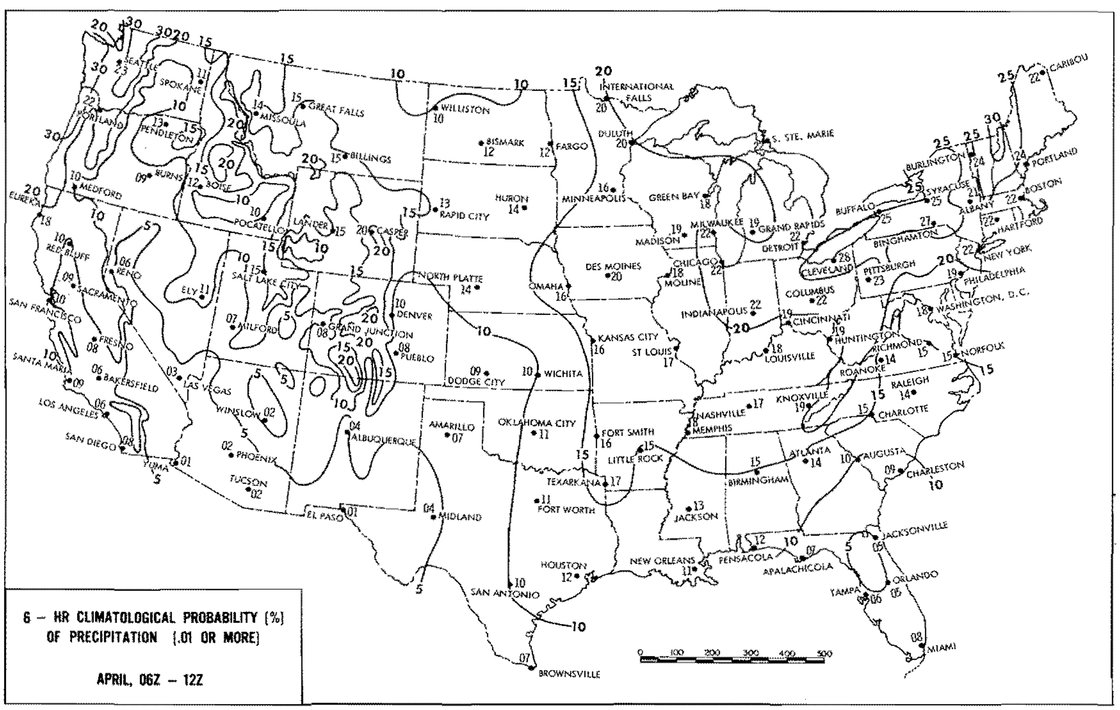


Chart 4 - 1



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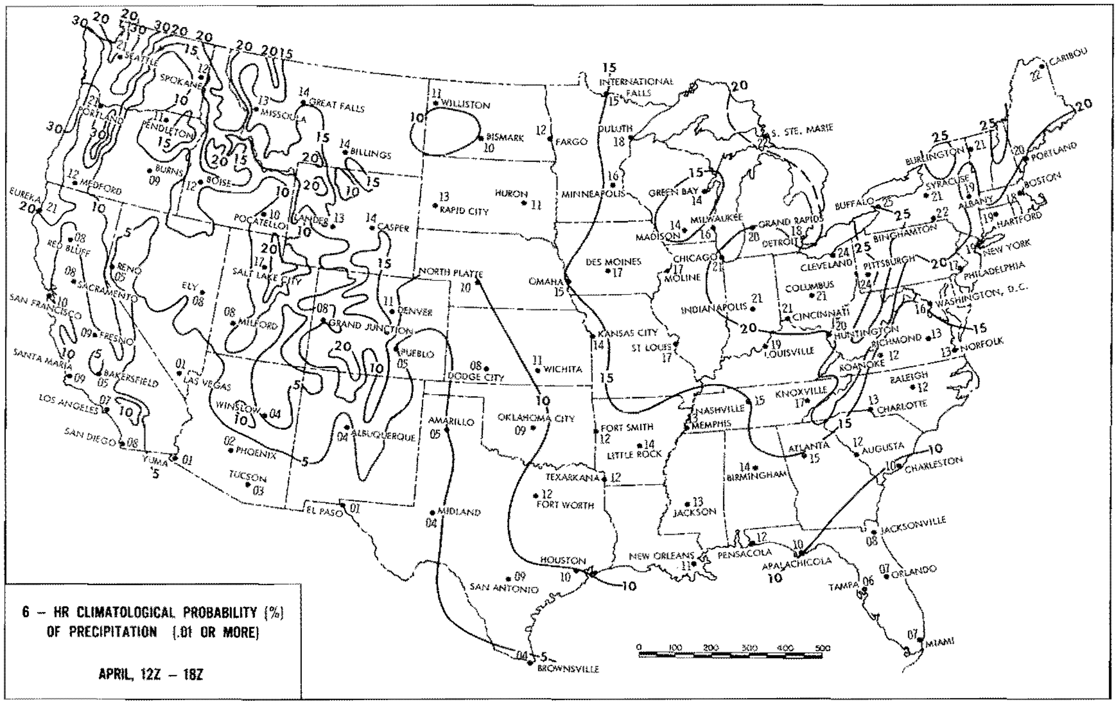

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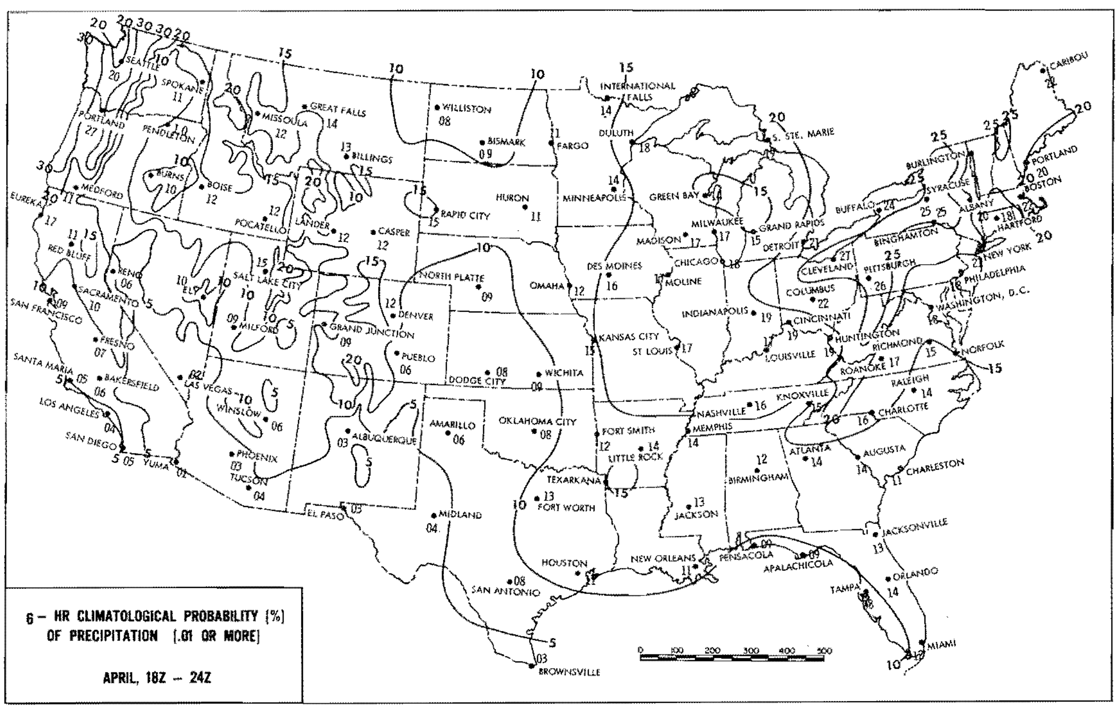
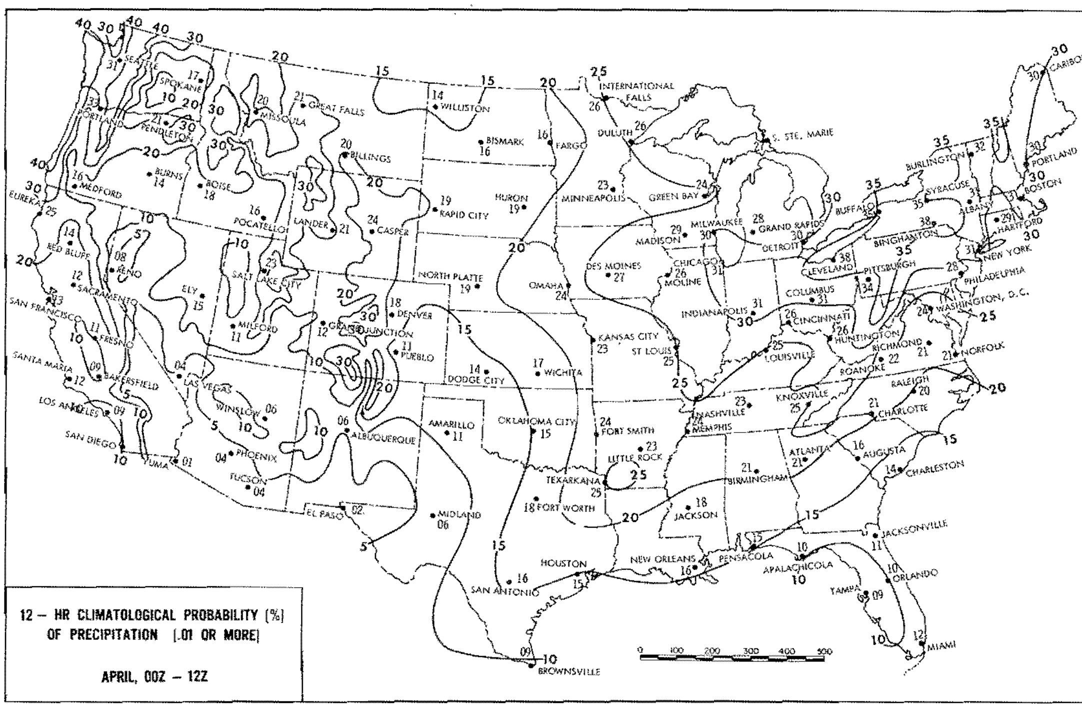


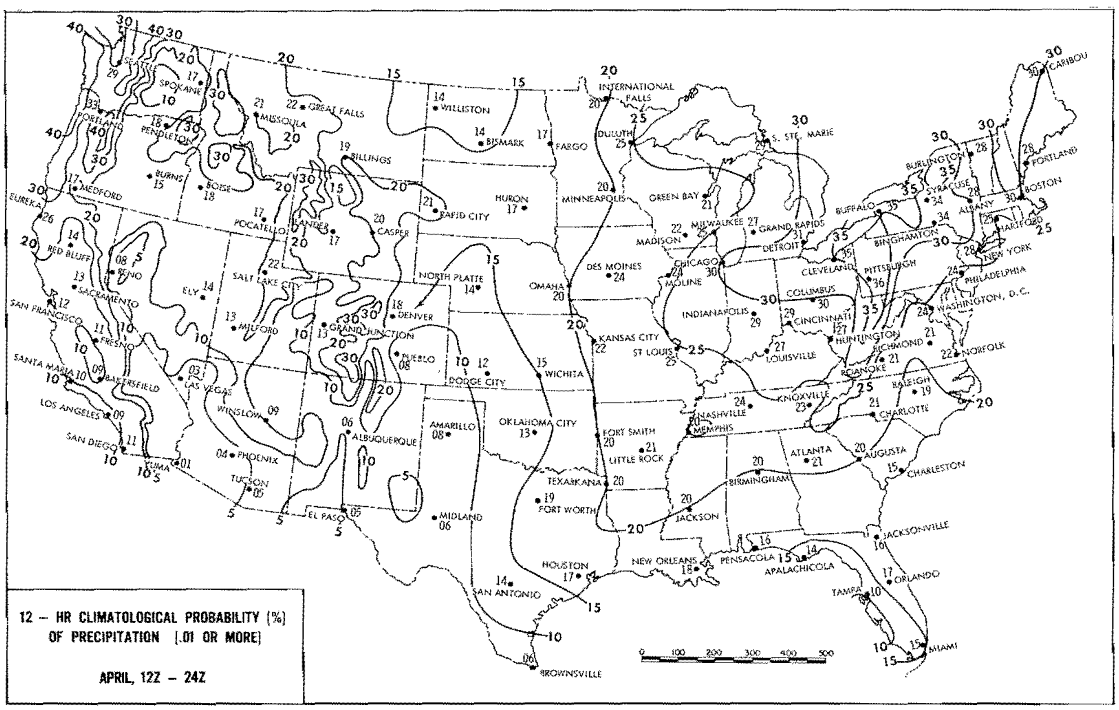
Chart 4 - 4



12 – HR CLIMATOLOGICAL PROBABILITY (%) OF PRECIPITATION (.01 OR MORE)

APRIL, 00Z – 12Z

Chart 4 - 5



12 – HR CLIMATOLOGICAL PROBABILITY (%) OF PRECIPITATION (.01 OR MORE)

APRIL, 12Z – 24Z

Chart 4 - 6

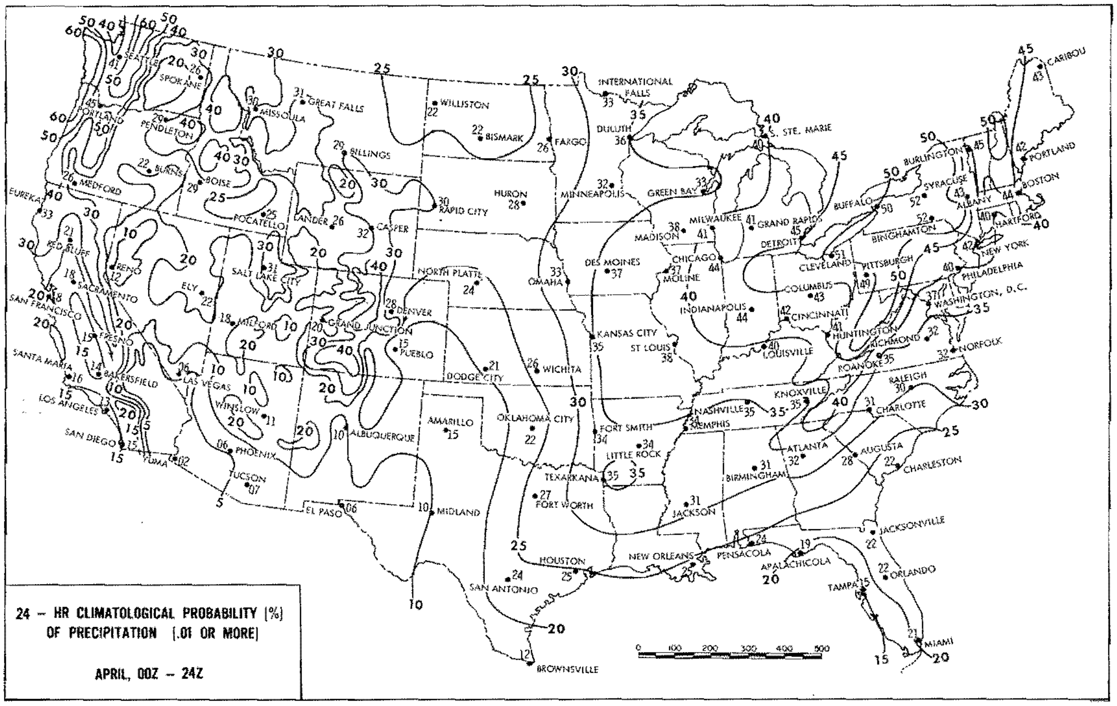

24 – HR CLIMATOLOGICAL PROBABILITY (%) OF PRECIPITATION (.01 OR MORE)
APRIL, 00Z – 24Z

Chart 4 - 7

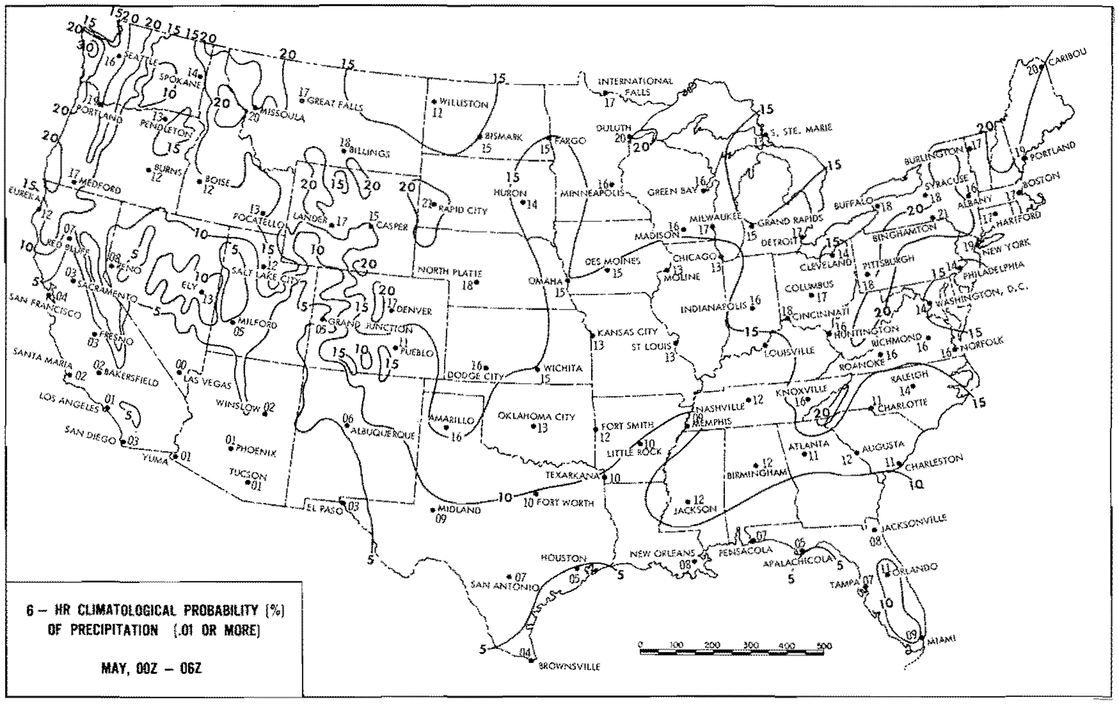


Chart 5 - 1

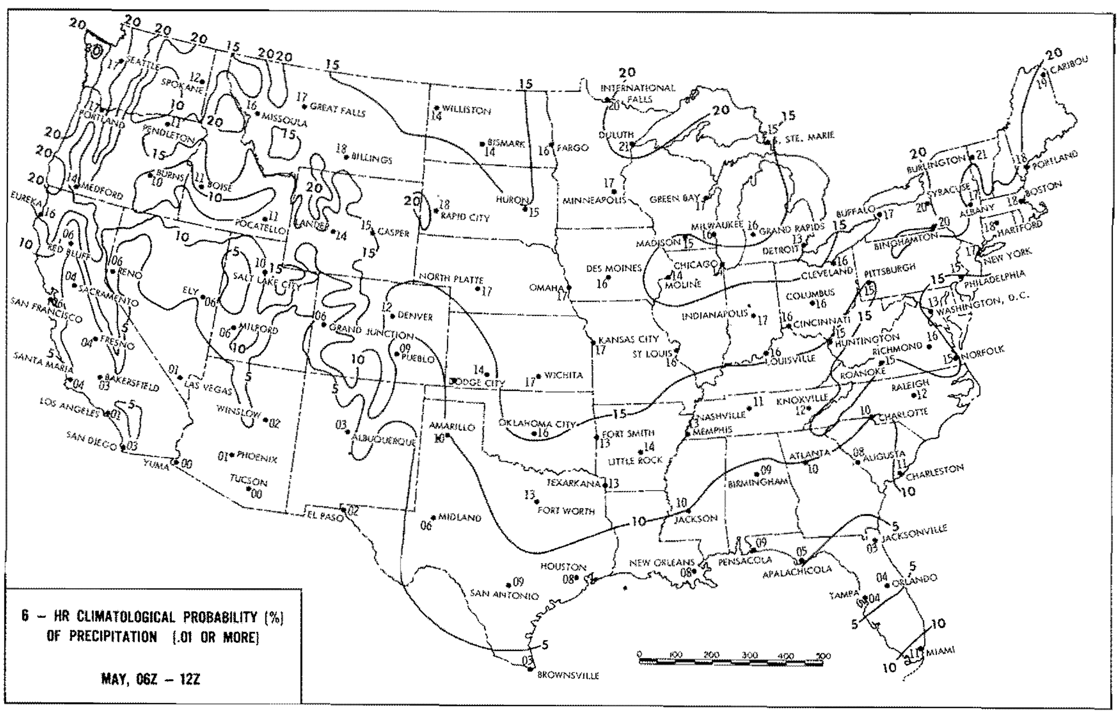


Chart 5 - 2

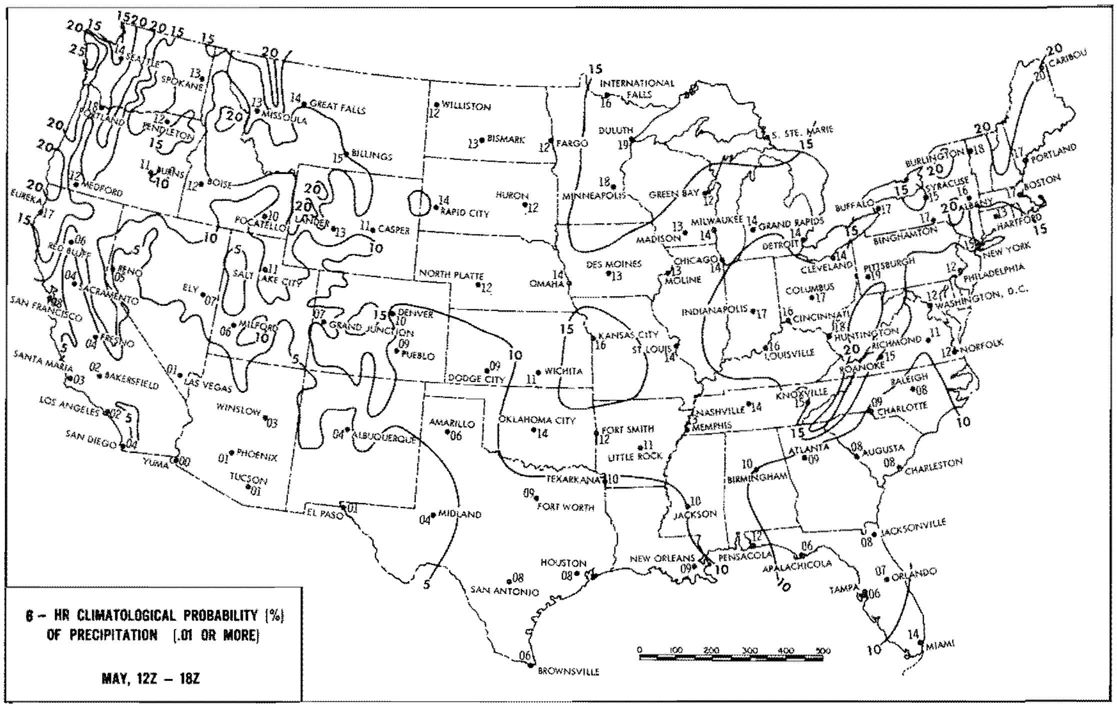
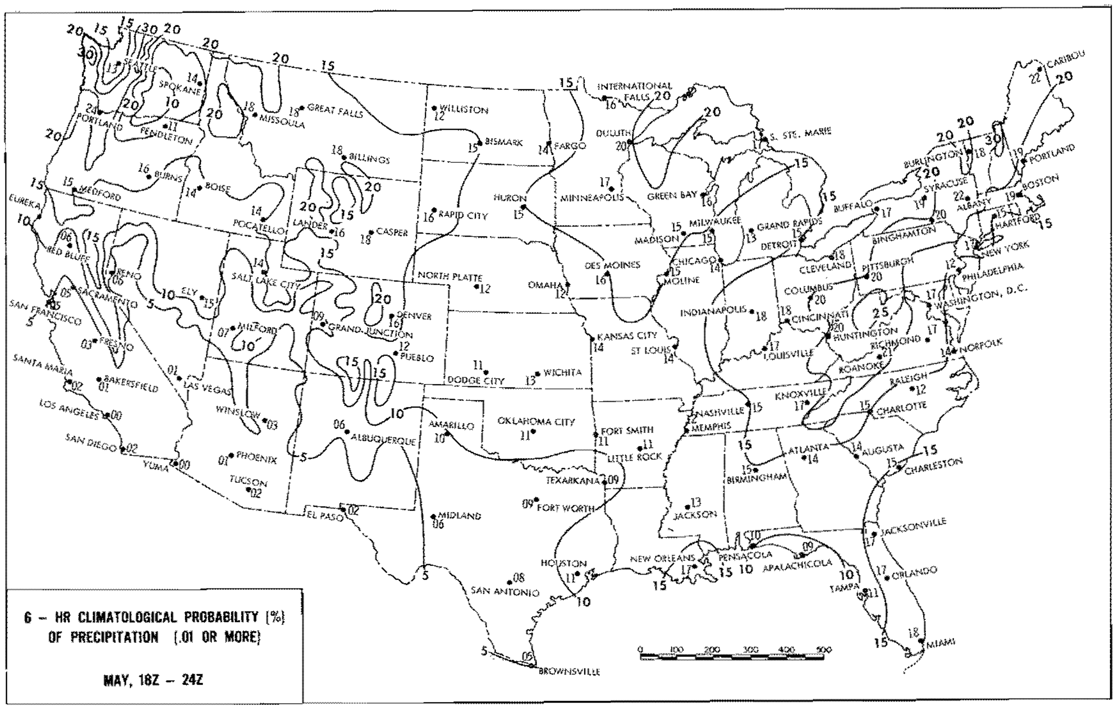


Chart 5 - 3



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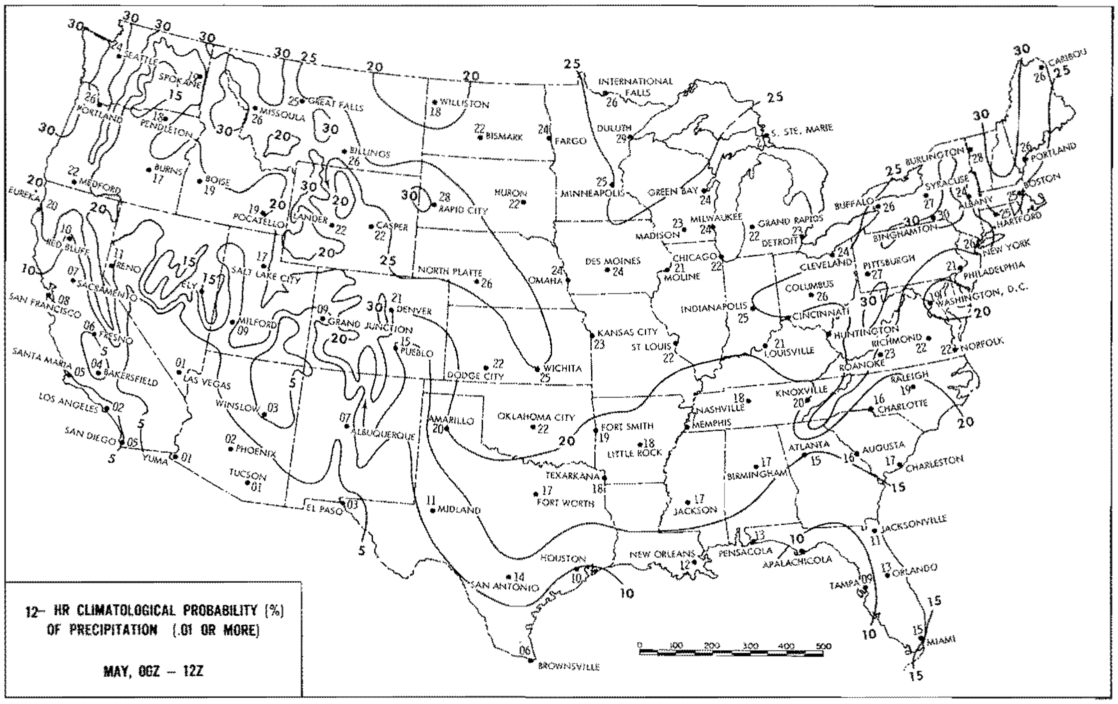


Chart 5 - 5

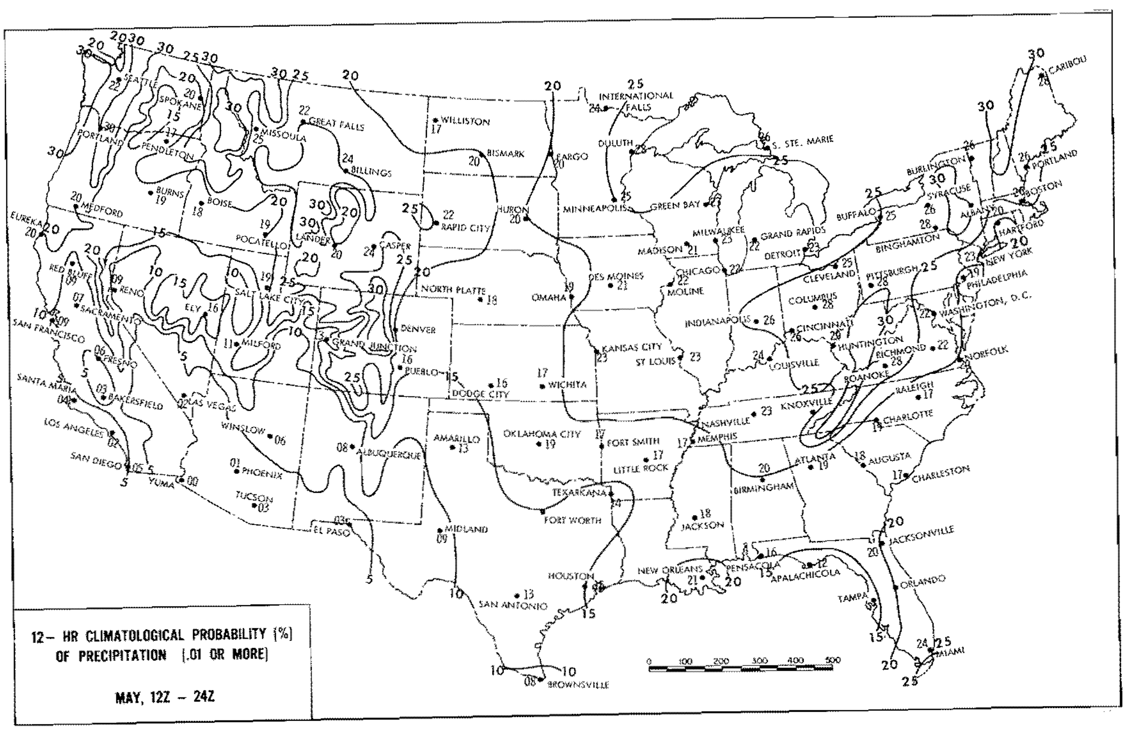
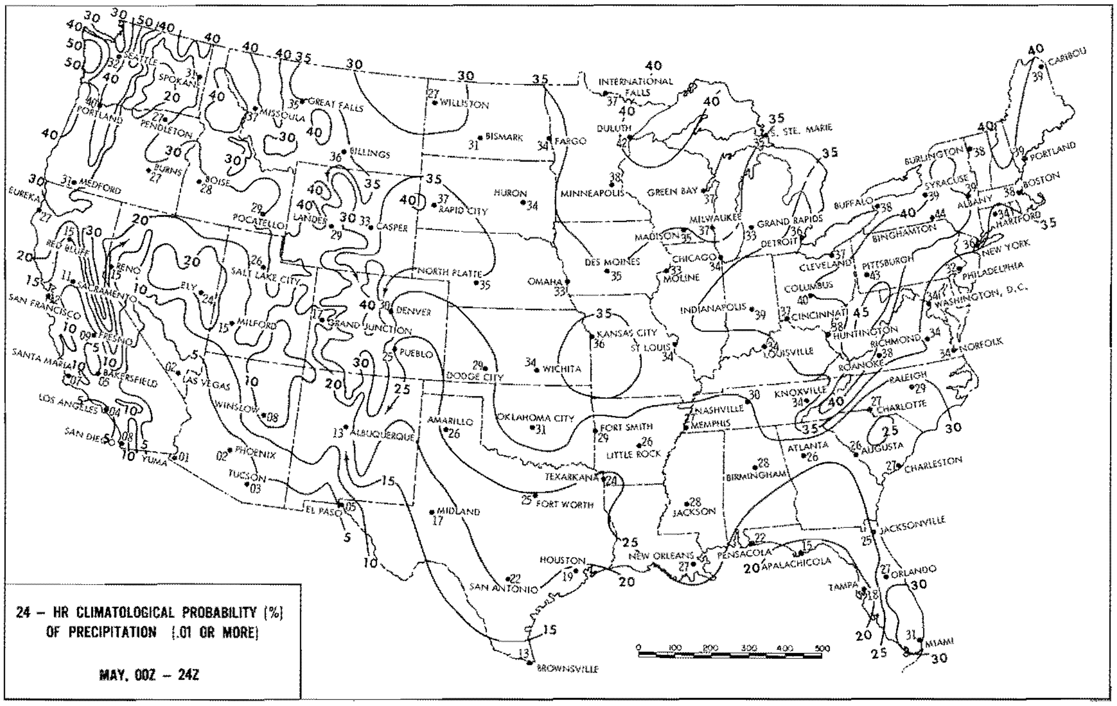


Chart 5 - 6


24 - HR CLIMATOLOGICAL PROBABILITY (%)
OF PRECIPITATION (.01 OR MORE)
MAY, 00Z - 24Z
SEATTLE
SPOKANE
PORTLAND
PENDLETON
MISSOULA
GREAT FALLS
WILLISTON
BISMARCK
FARGO
INTERNATIONAL FALLS
DULUTH
S. STE. MARIE
CARIBOU
BURNS
BOISE
MEDFORD
EUREKA
BILLINGS
POCATELLO
LANDER
CASPER
RAPID CITY
HURON
MINNEAPOLIS
GREEN BAY
MILWAUKEE
GRAND RAPIDS
DETROIT
MADISON
BUFFALO
BURLINGTON
SYRACUSE
ALBANY
BOSTON
HARTFORD
NEW YORK
BINGHAMTON
PHILADELPHIA
WASHINGTON, D.C.
RED BLUFF
RENO
SACRAMENTO
SAN FRANCISCO
FRESNO
ELY
SALT LAKE CITY
MILFORD
GRAND JUNCTION
DENVER
NORTH PLATTE
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FORT WORTH
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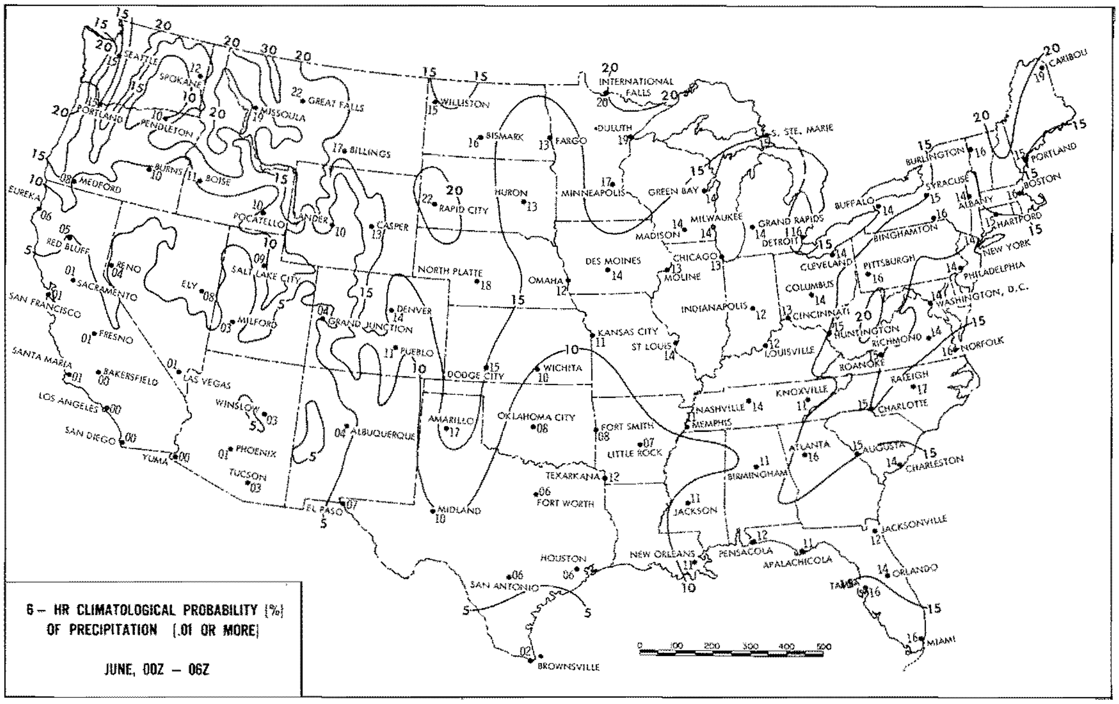
MIDLAND
HOUSTON
SAN ANTONIO
NEW ORLEANS
PENSACOLA
APALACHICOLA
JACKSONVILLE
ORLANDO
TAMPA
MIAMI
BROWNSVILLE

Chart 5 - 7



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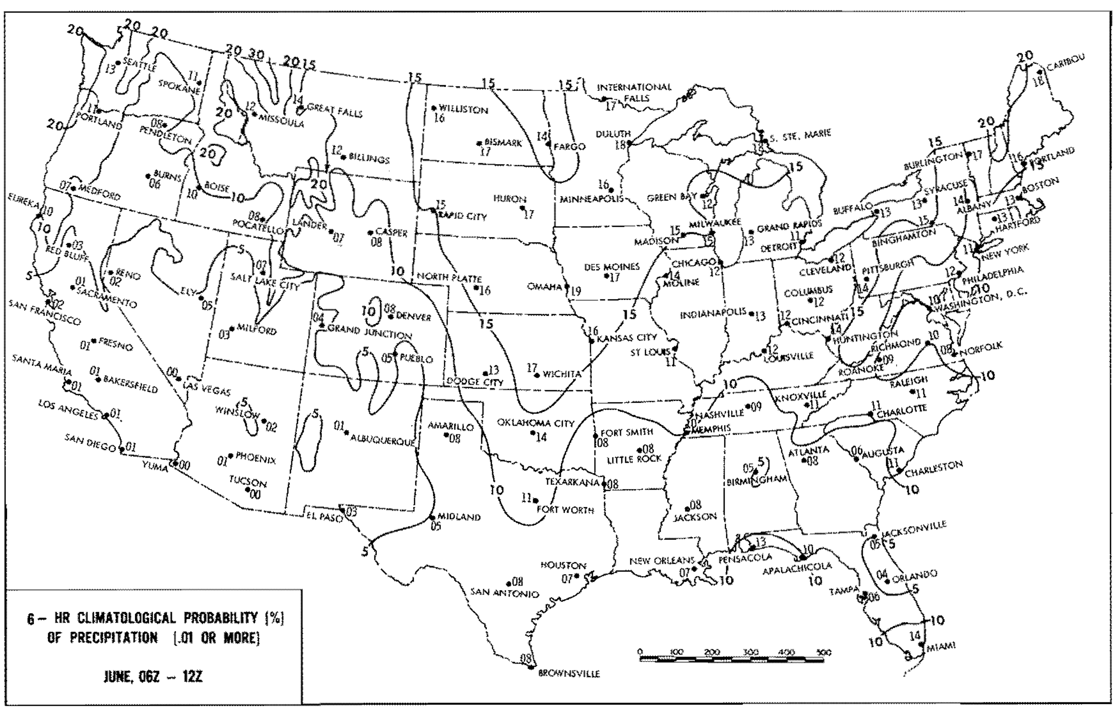

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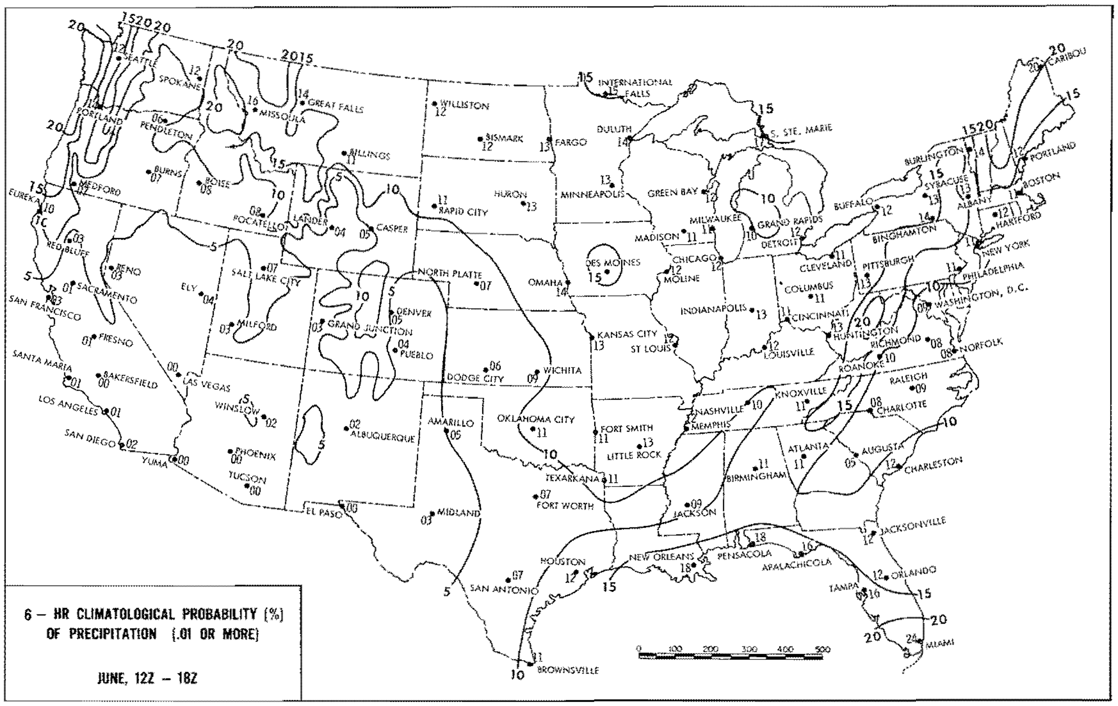

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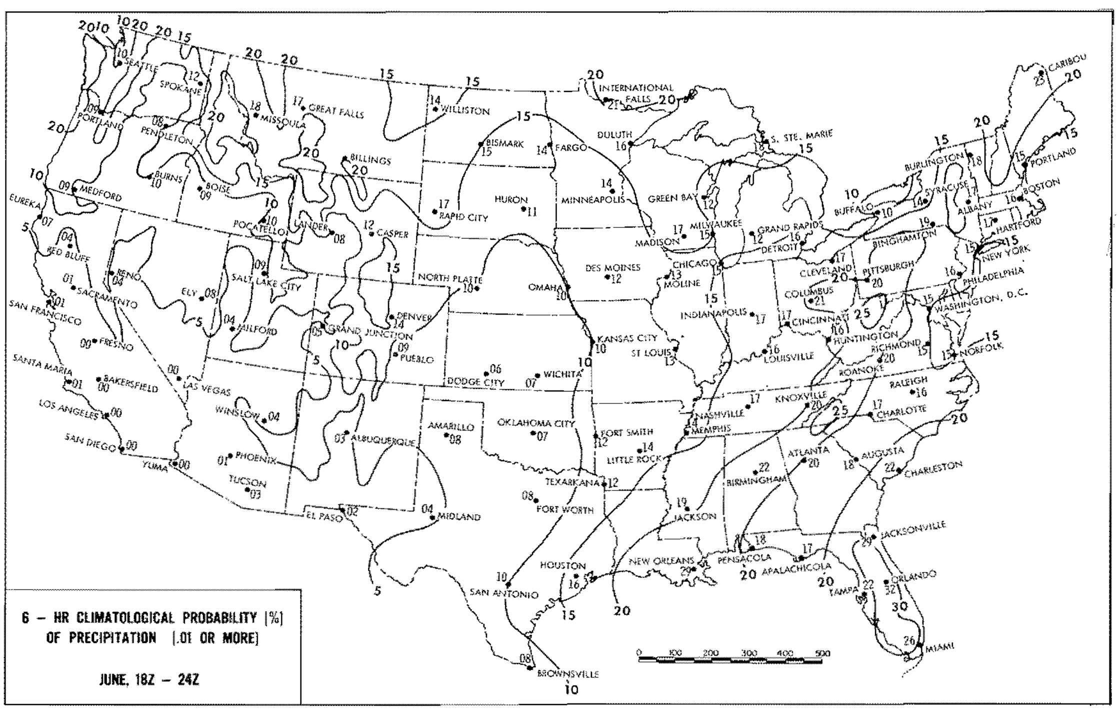

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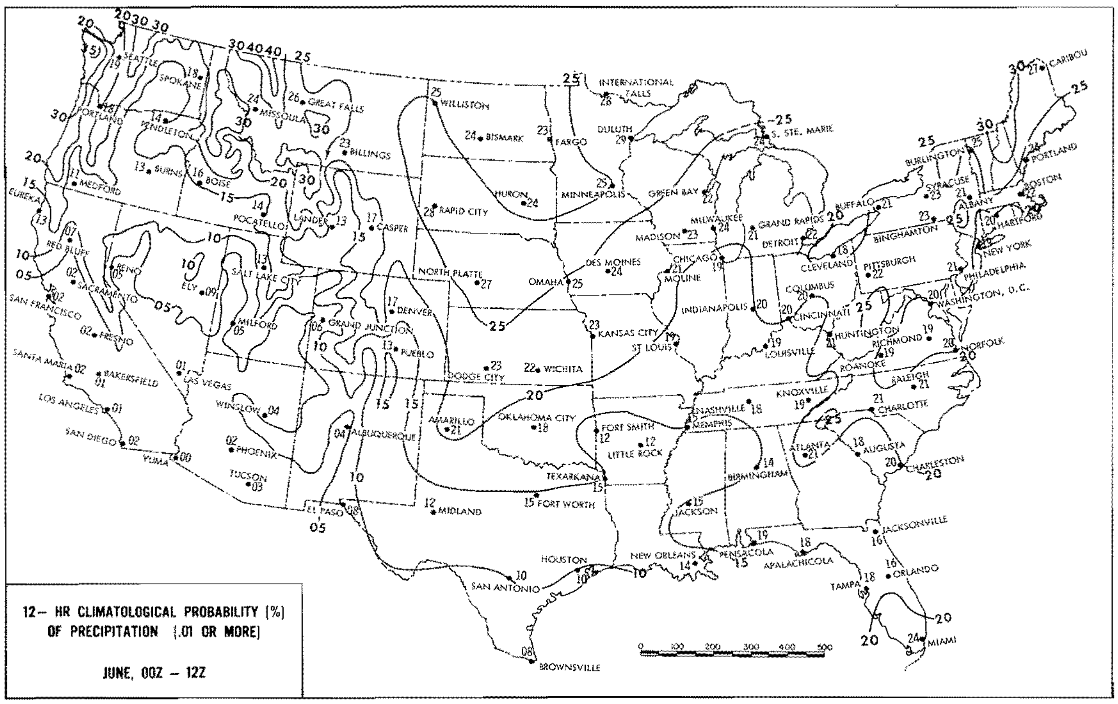

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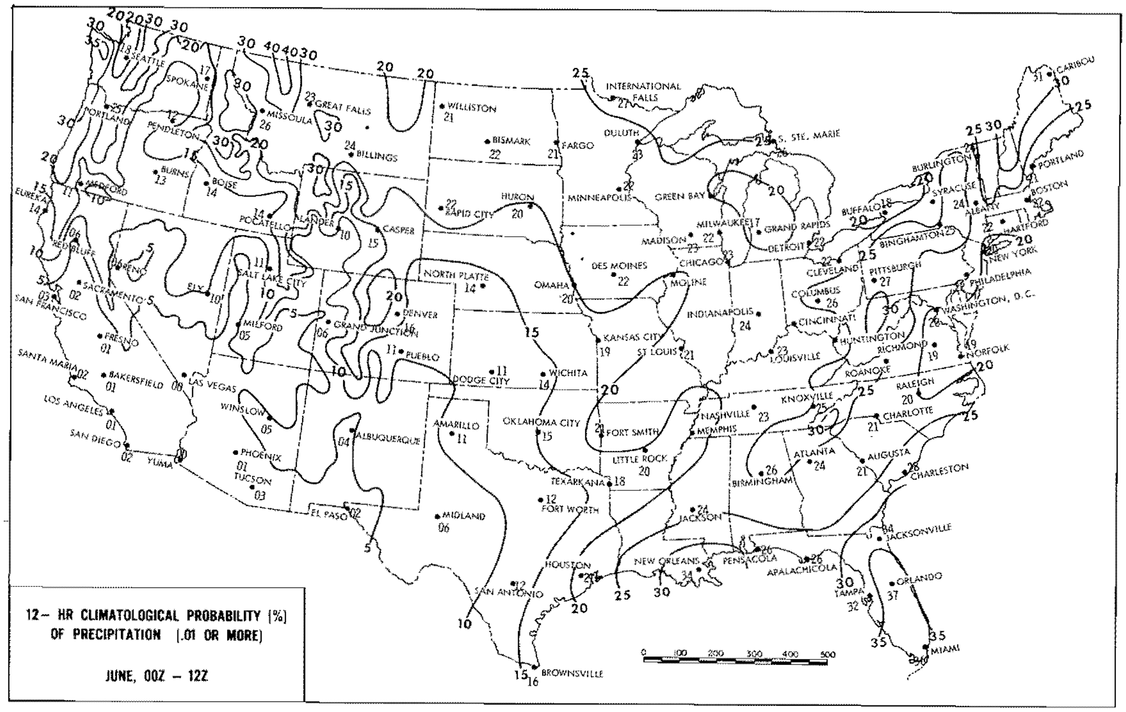

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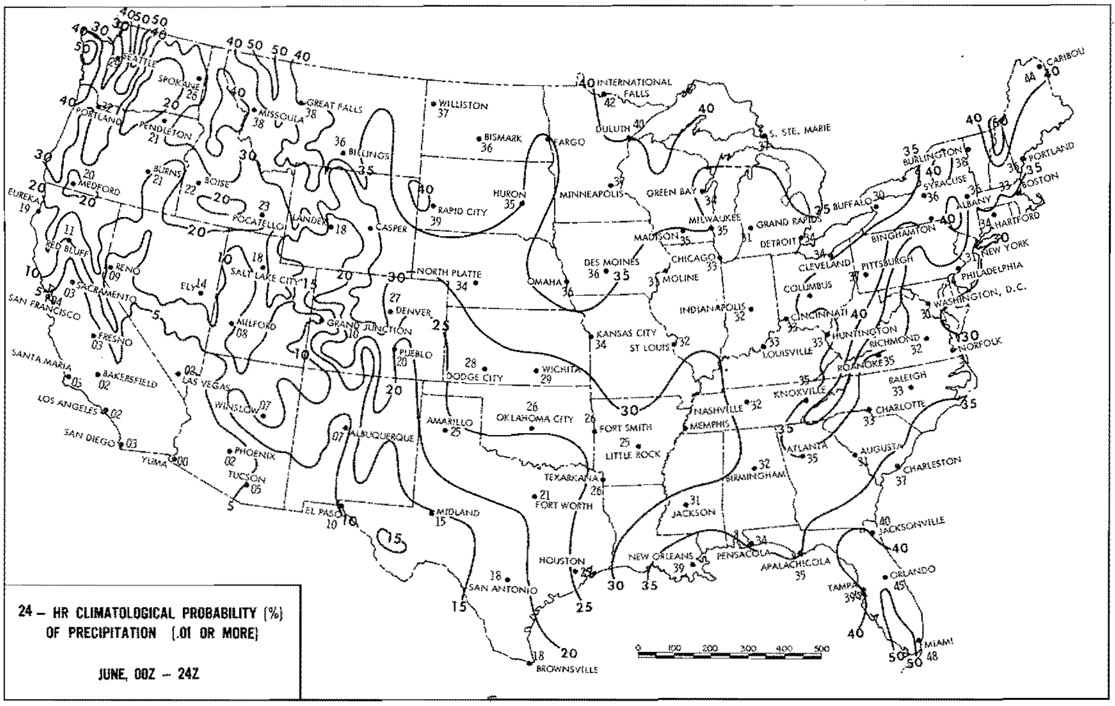
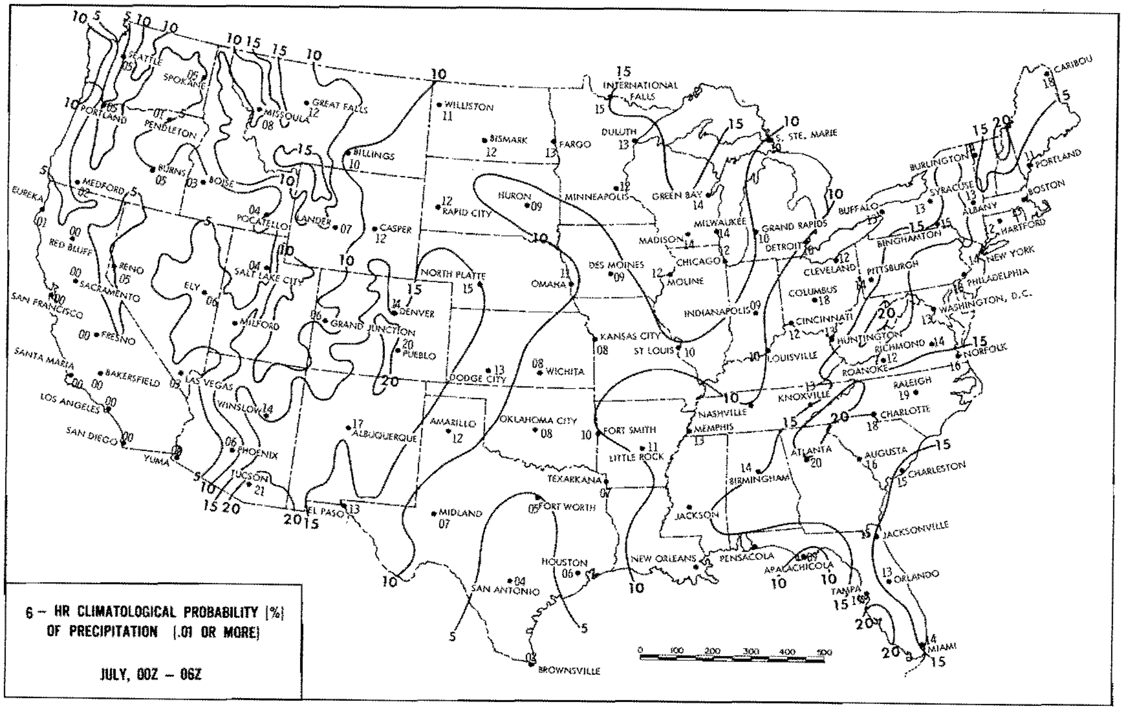

24 – HR CLIMATOLOGICAL PROBABILITY (%)
OF PRECIPITATION (.01 OR MORE)
JUNE, 00Z – 24Z

Chart 6 - 7



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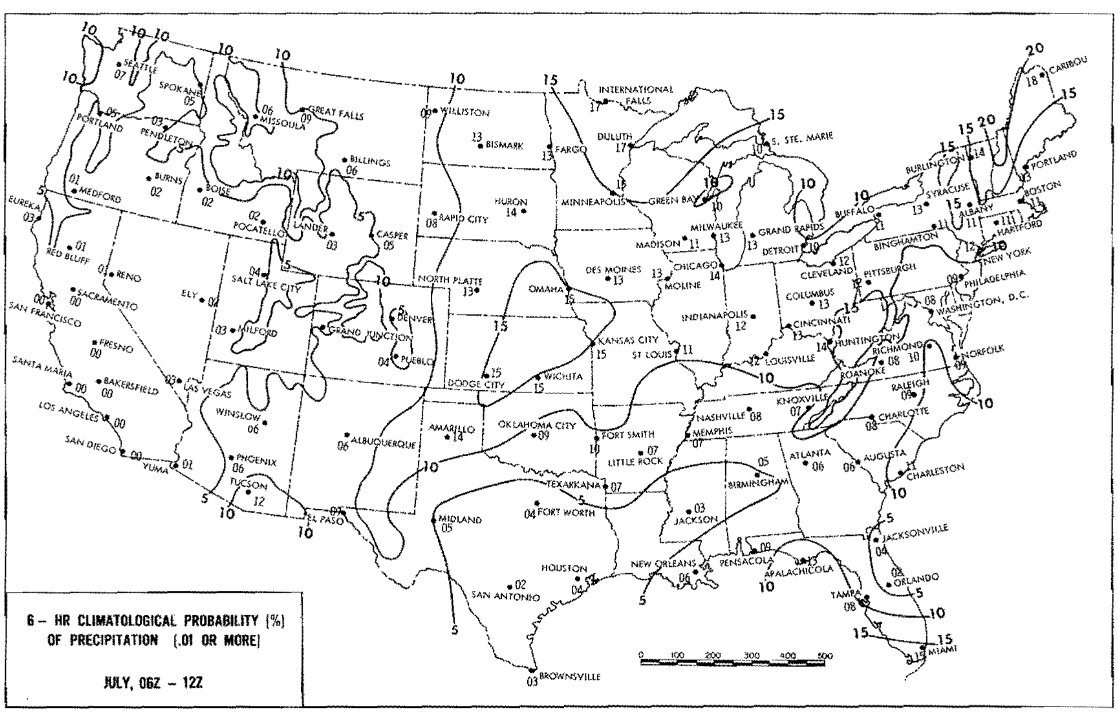

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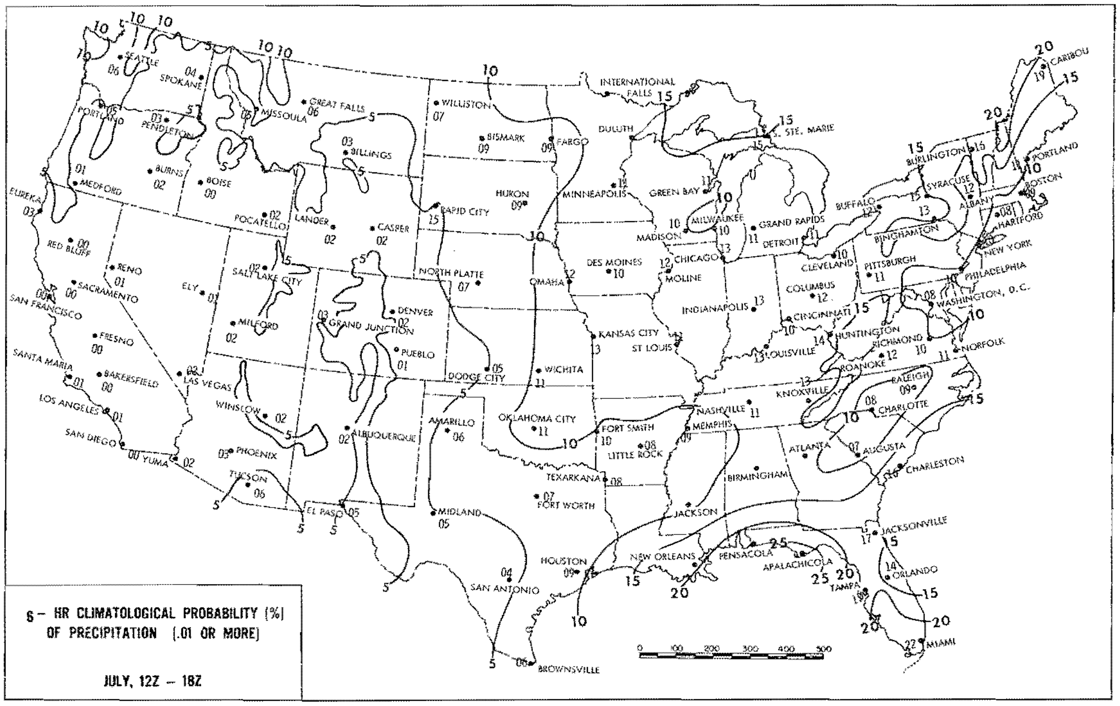

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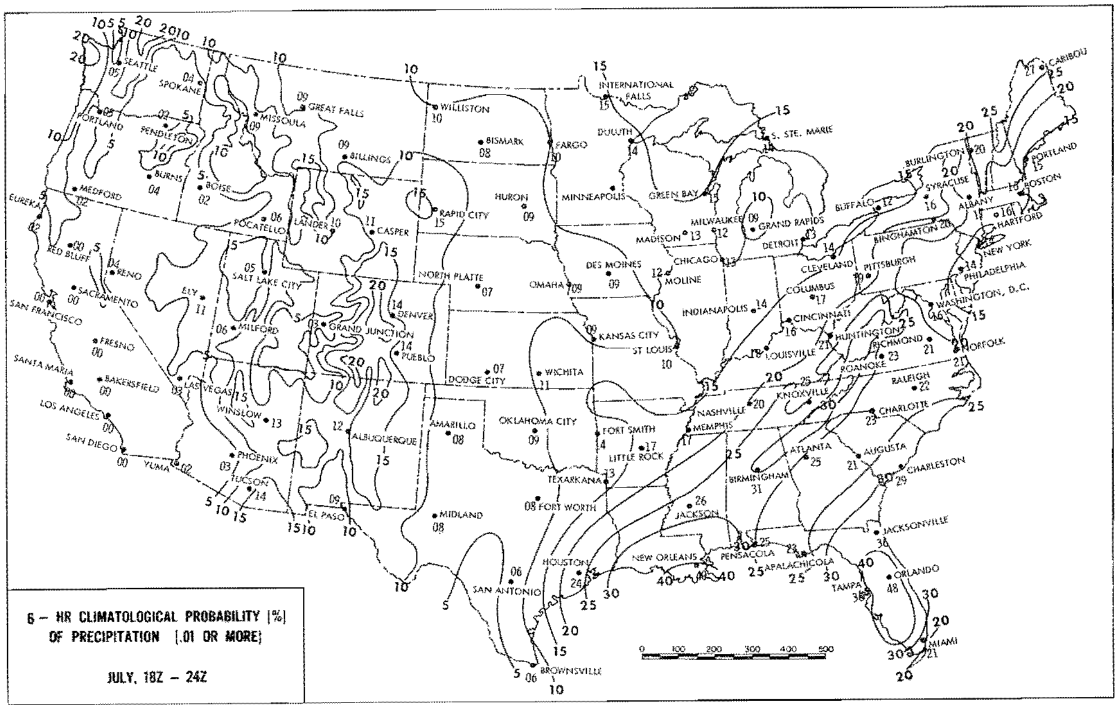

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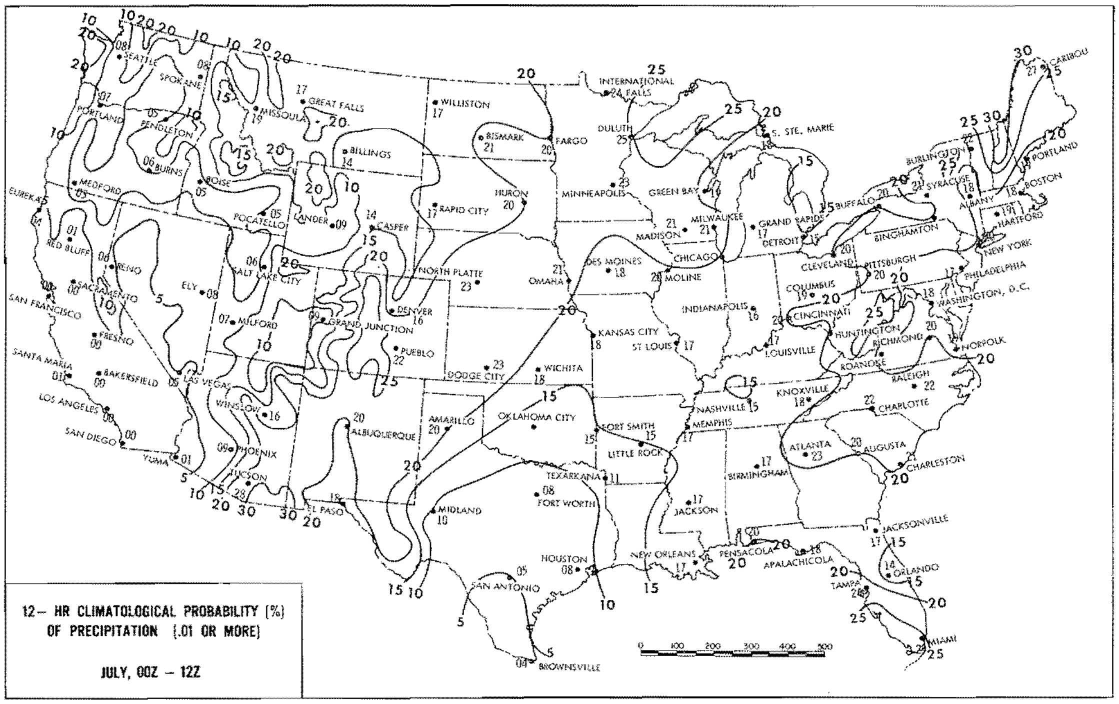

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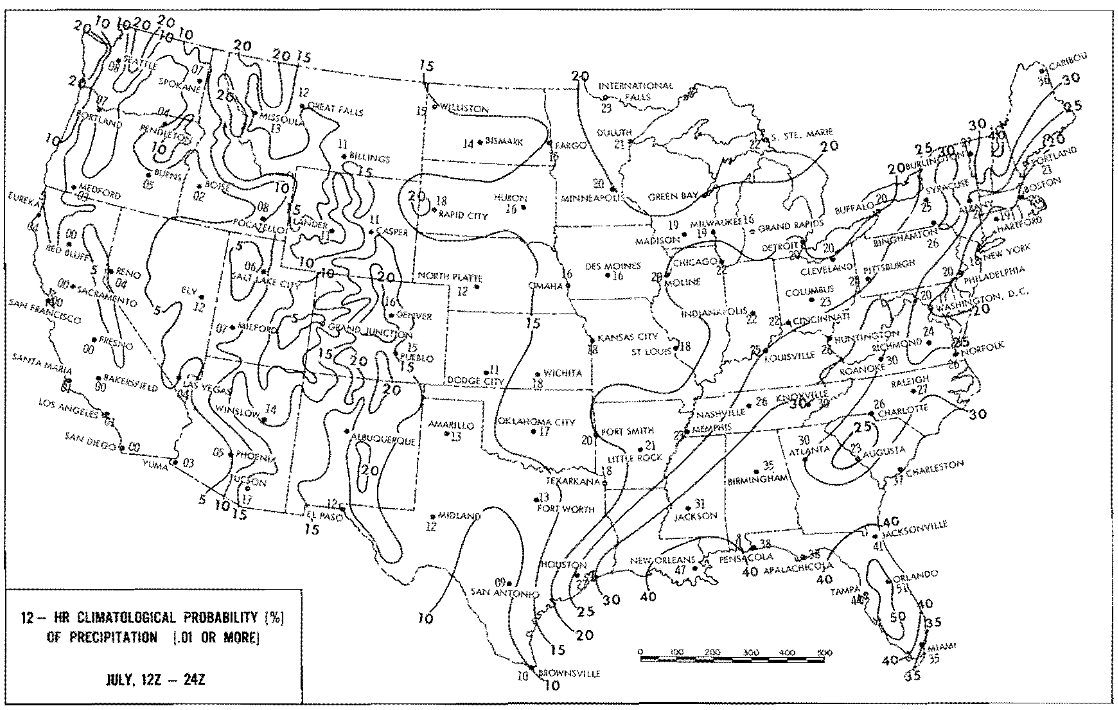

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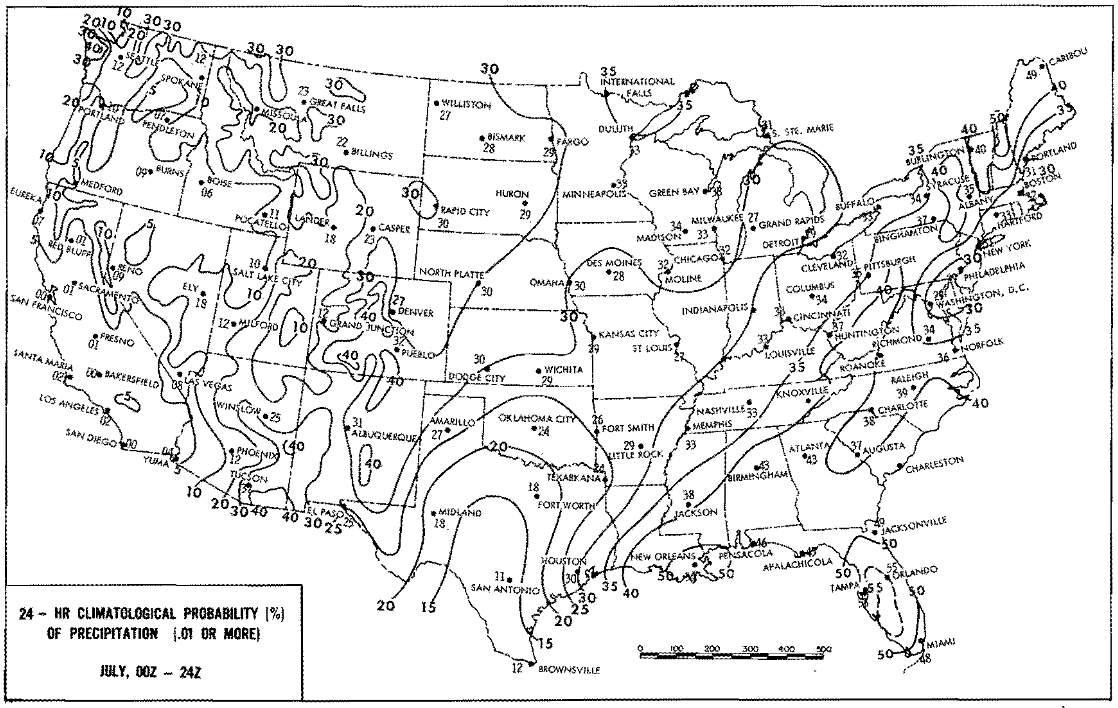
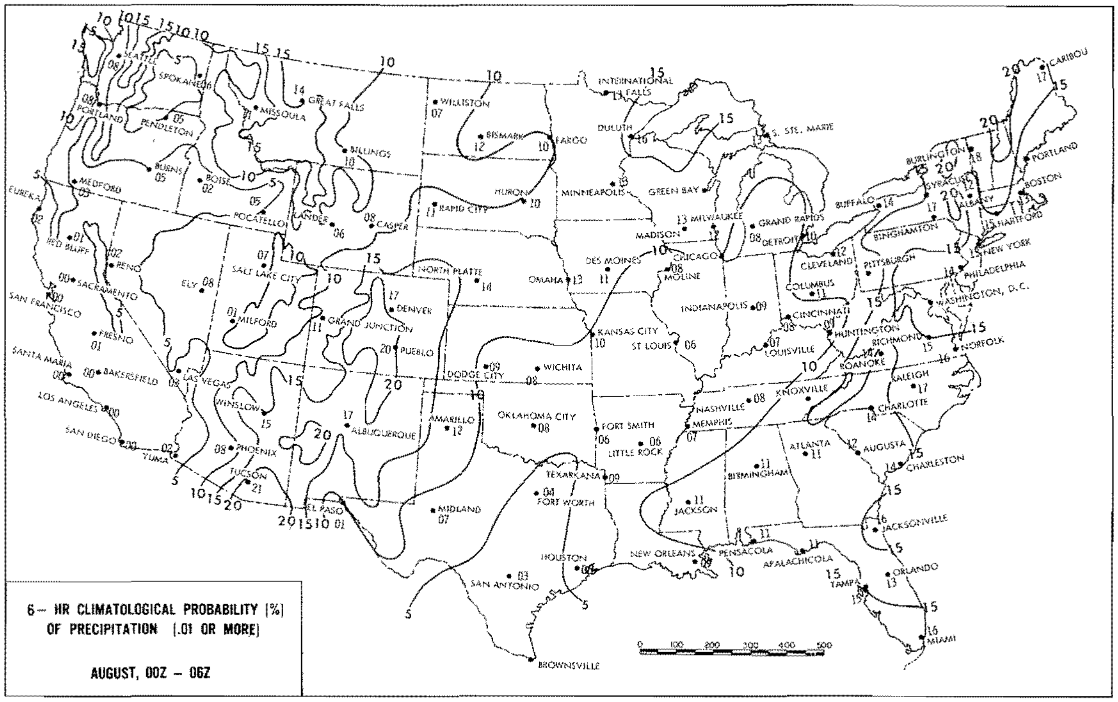

24 – HR CLIMATOLOGICAL PROBABILITY (%)
OF PRECIPITATION (.01 OR MORE)
JULY, 00Z – 24Z

Chart 7 - 7



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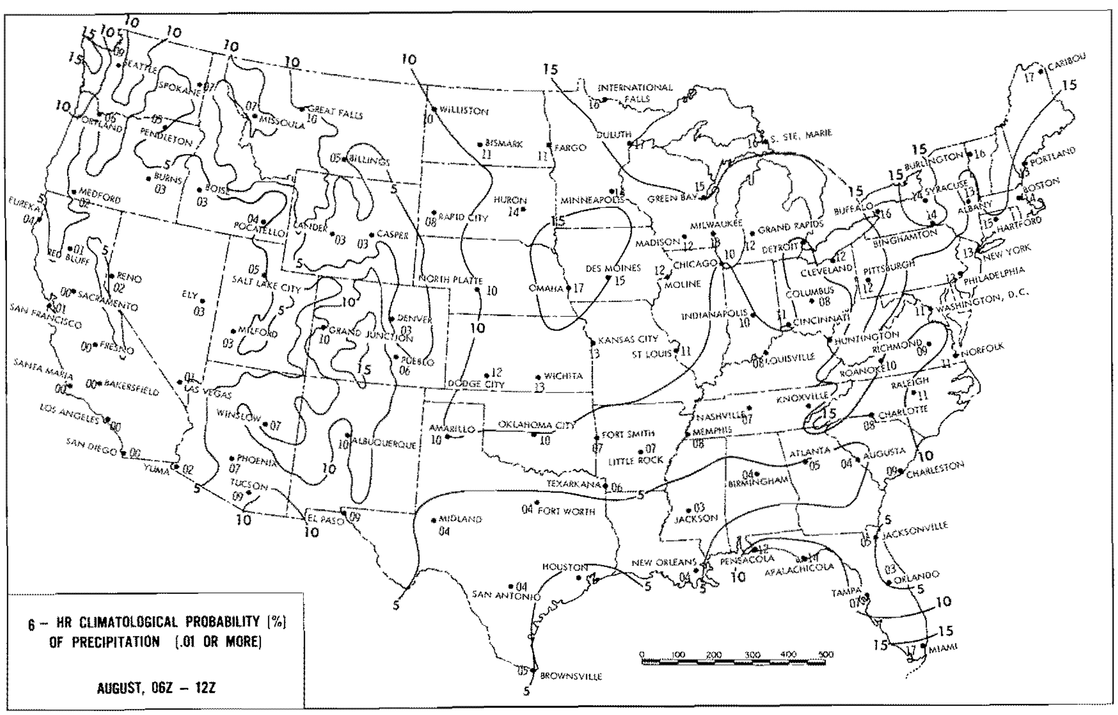

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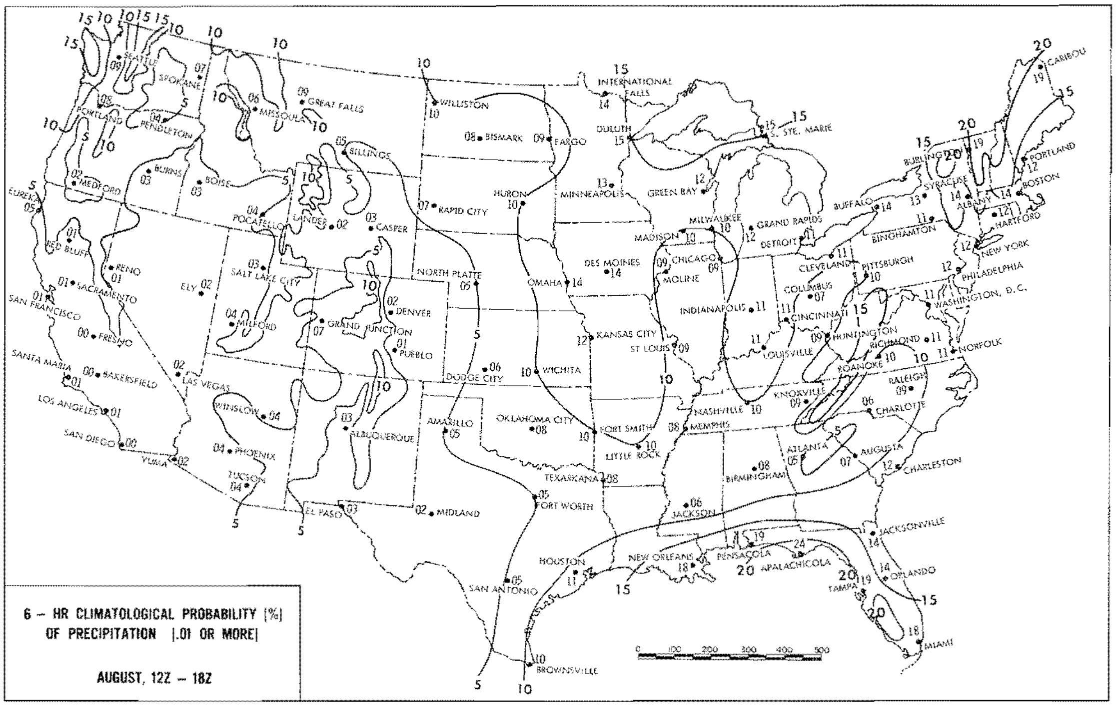

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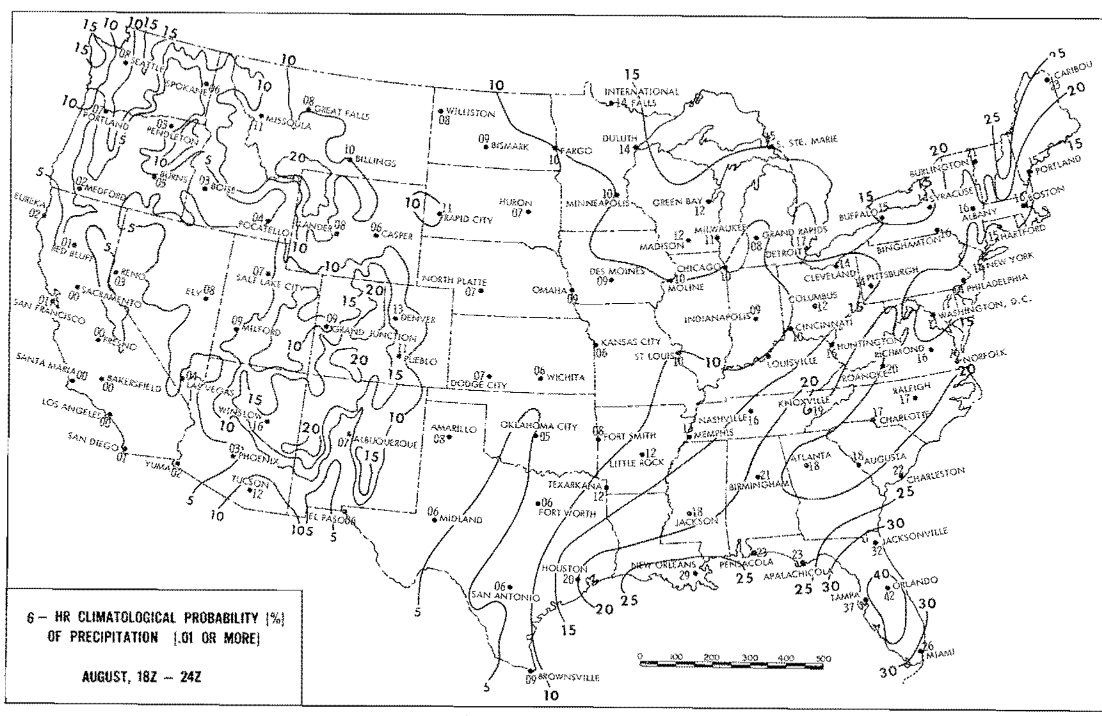

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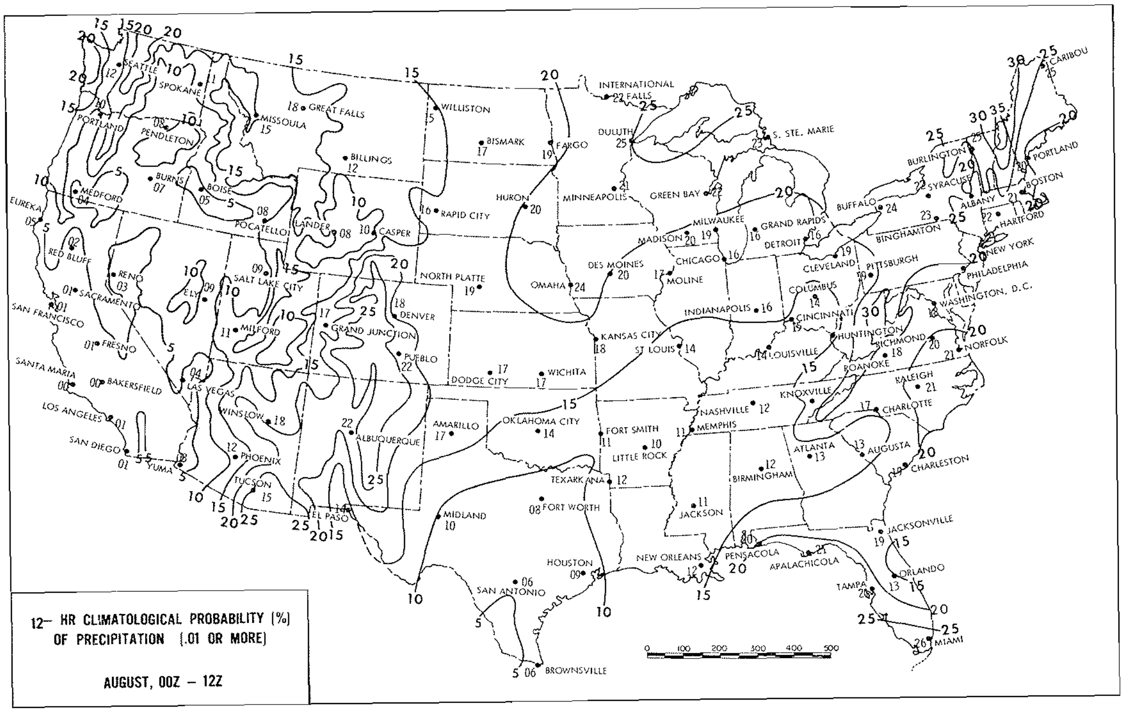

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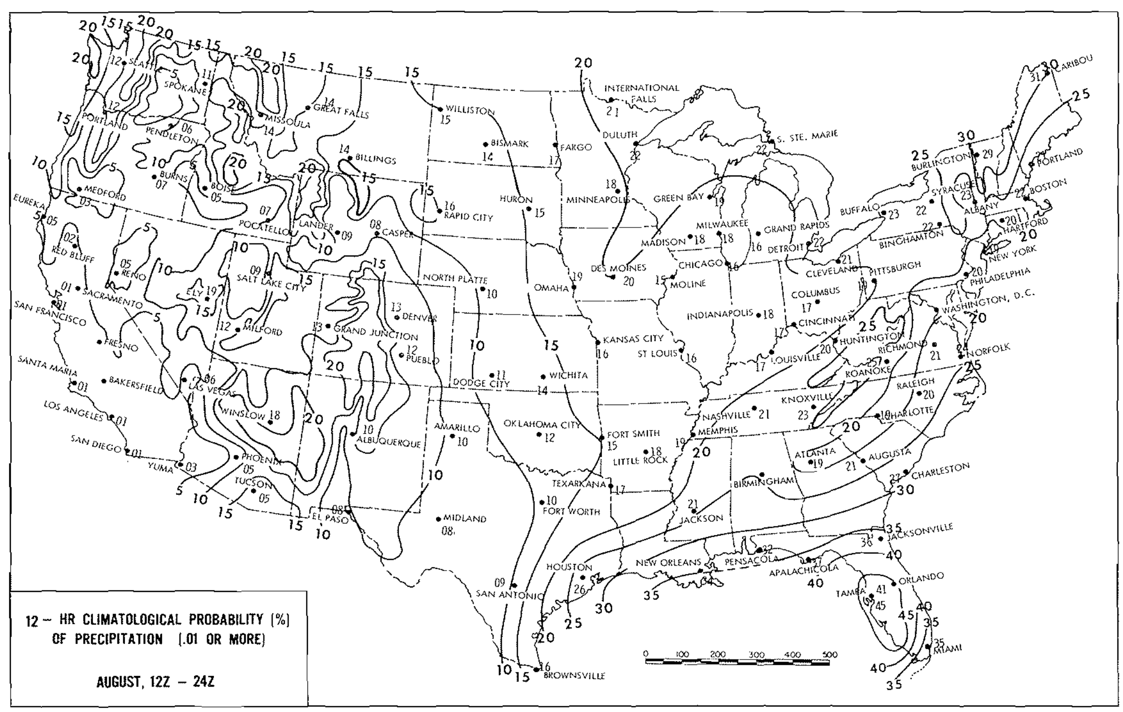

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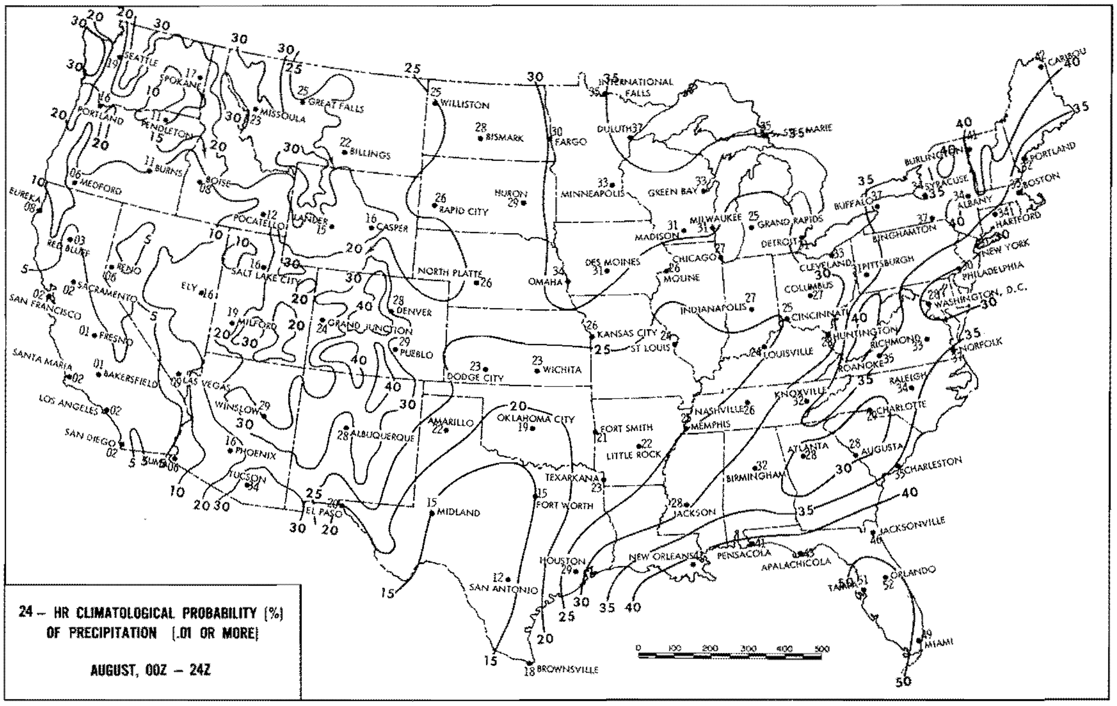
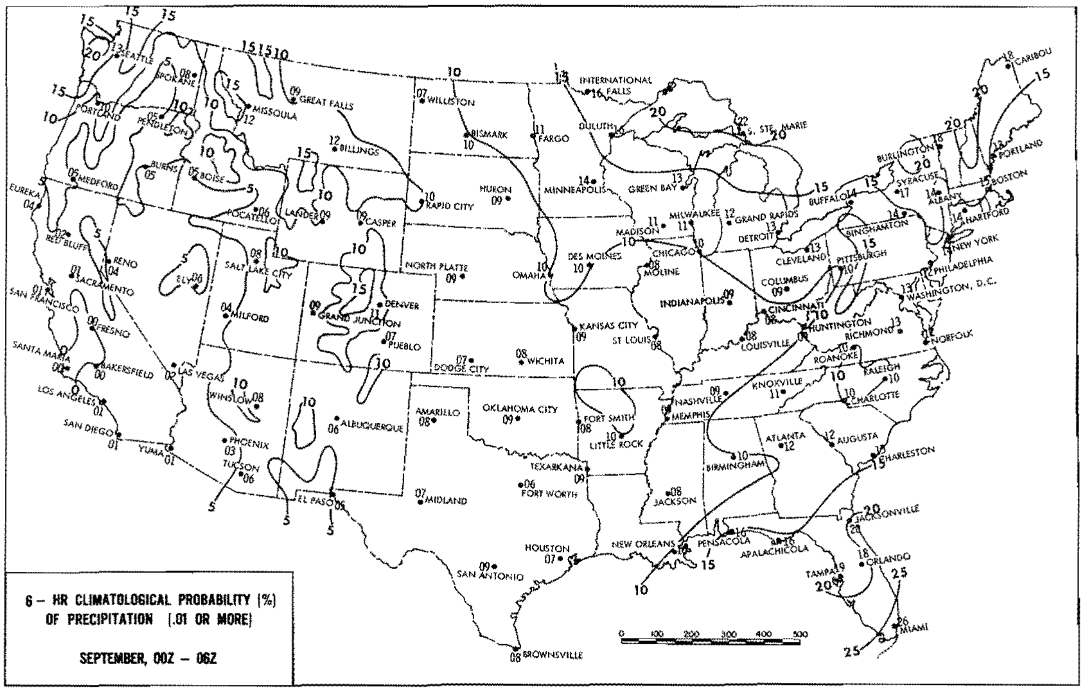


24 – HR CLIMATOLOGICAL PROBABILITY (%) OF PRECIPITATION (.01 OR MORE)

AUGUST, 00Z – 24Z

Chart 8 - 7



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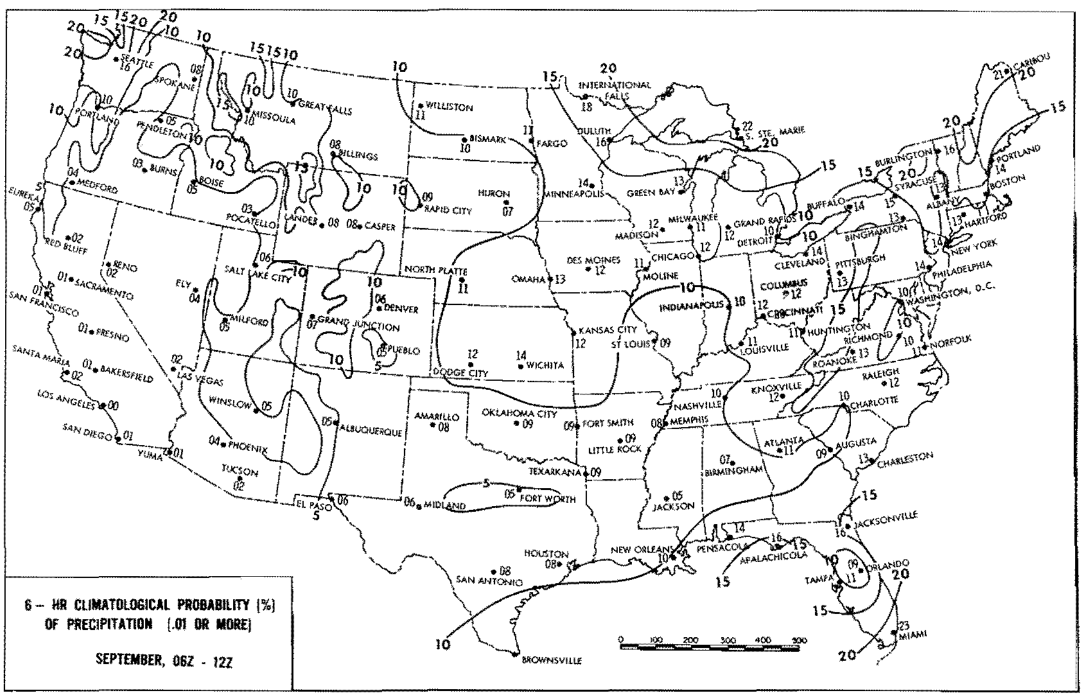

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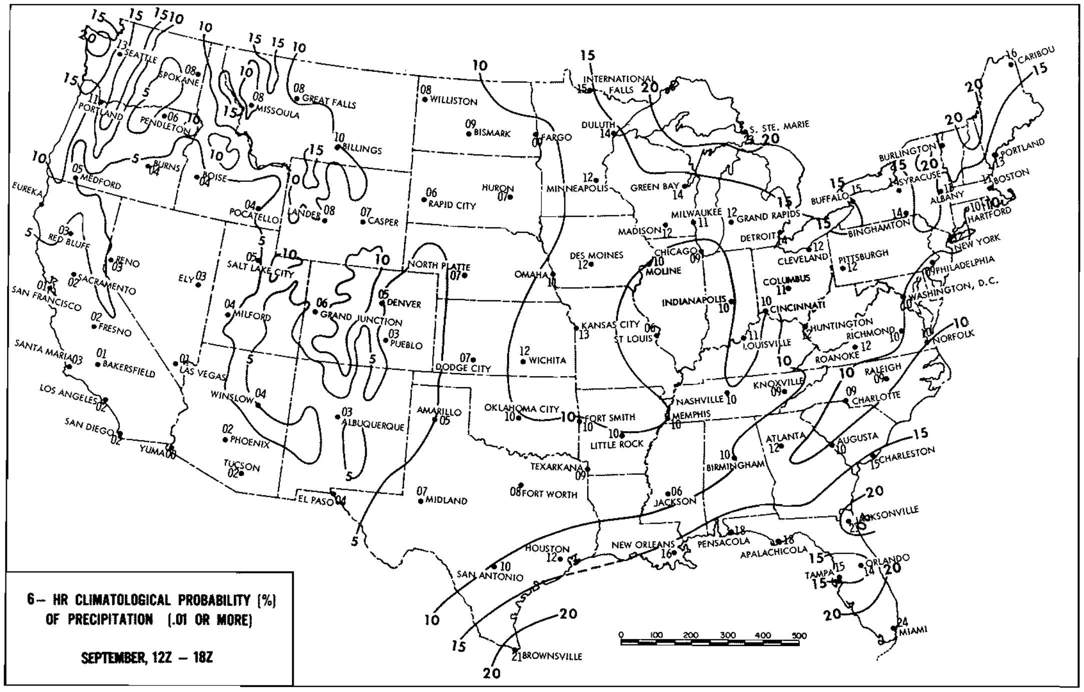

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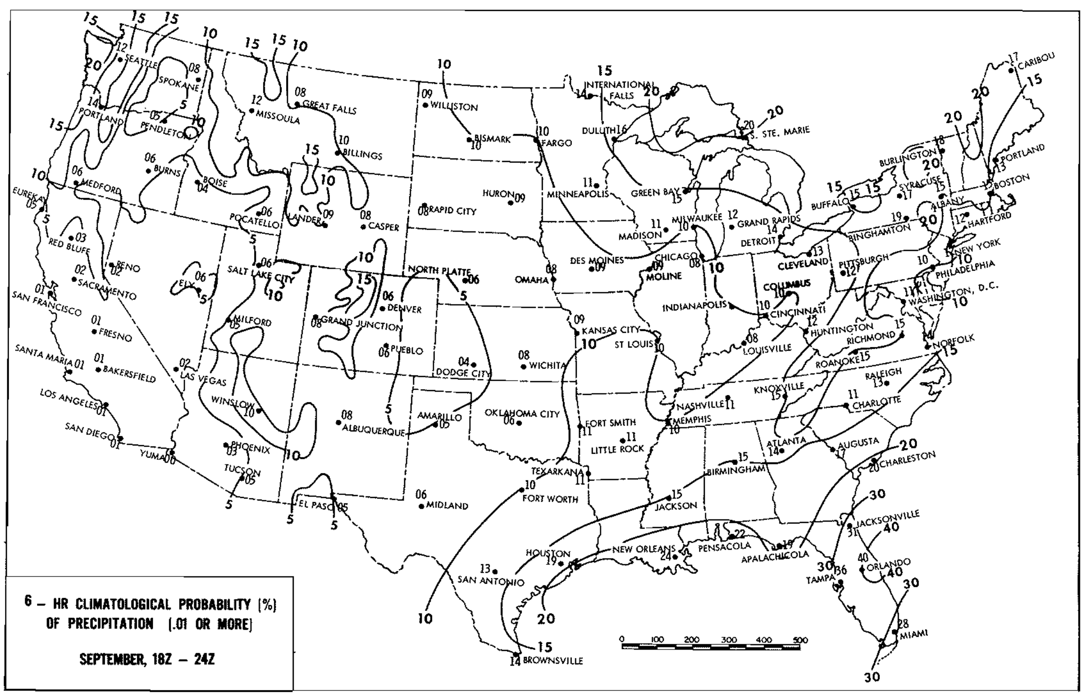

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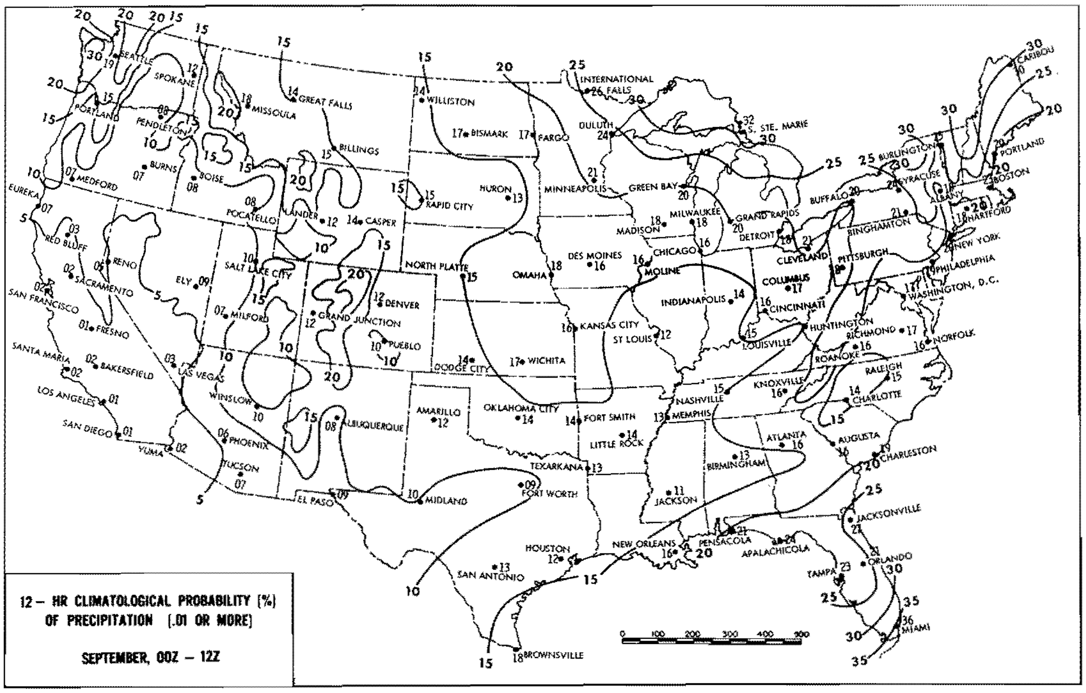

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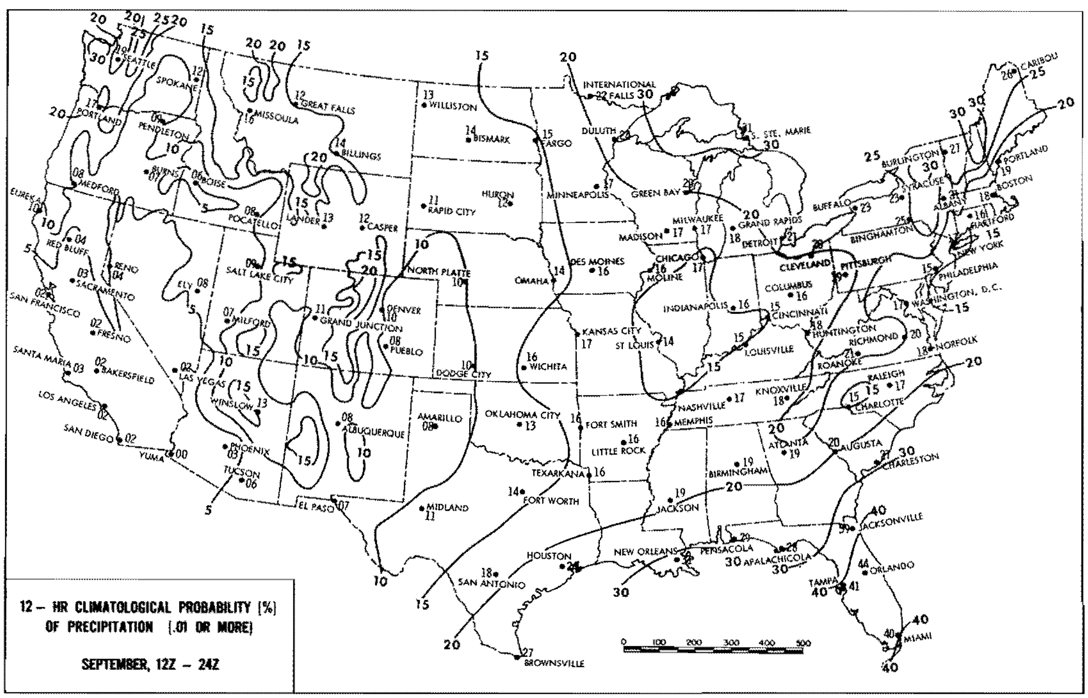

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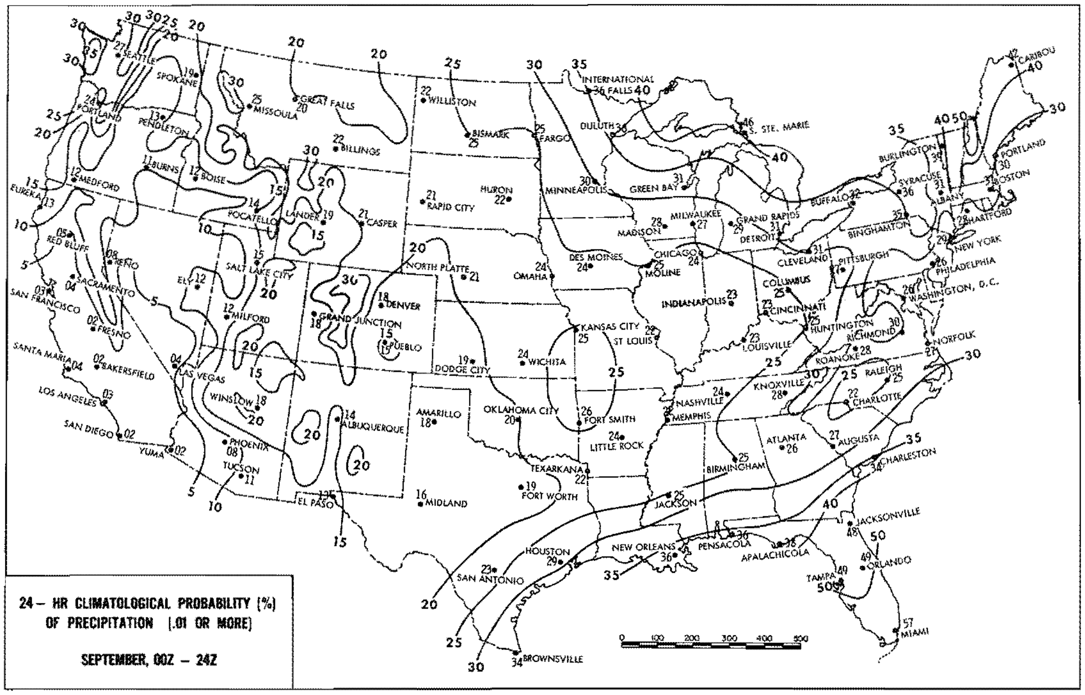
24 – HR CLIMATOLOGICAL PROBABILITY (%)
OF PRECIPITATION (.01 OR MORE)
SEPTEMBER, 00Z – 24Z

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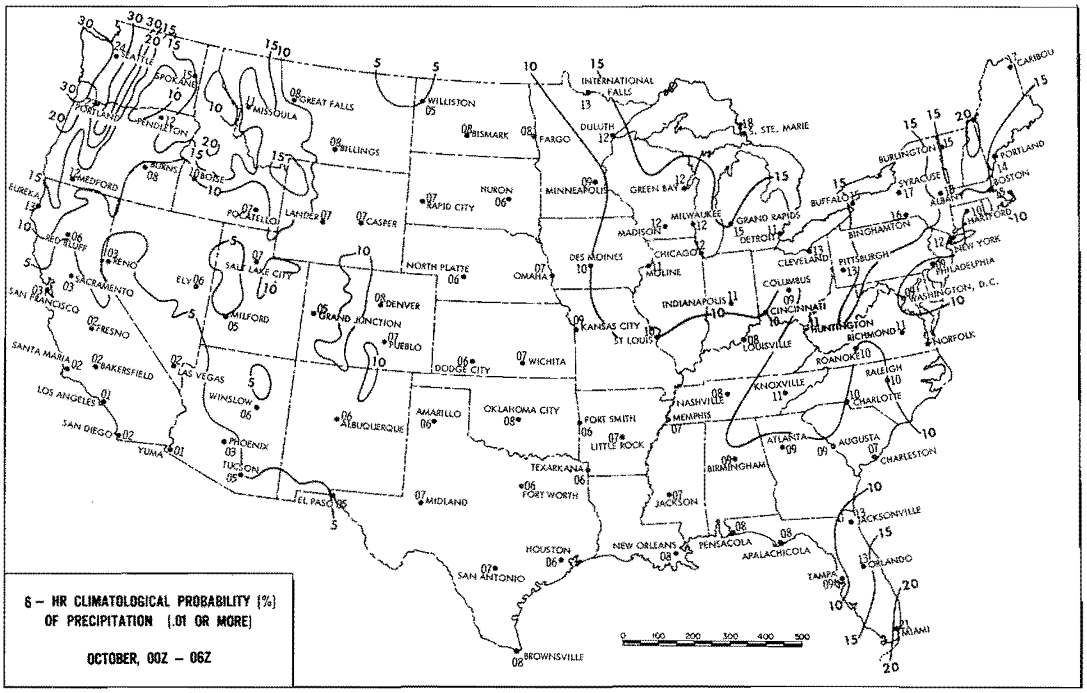

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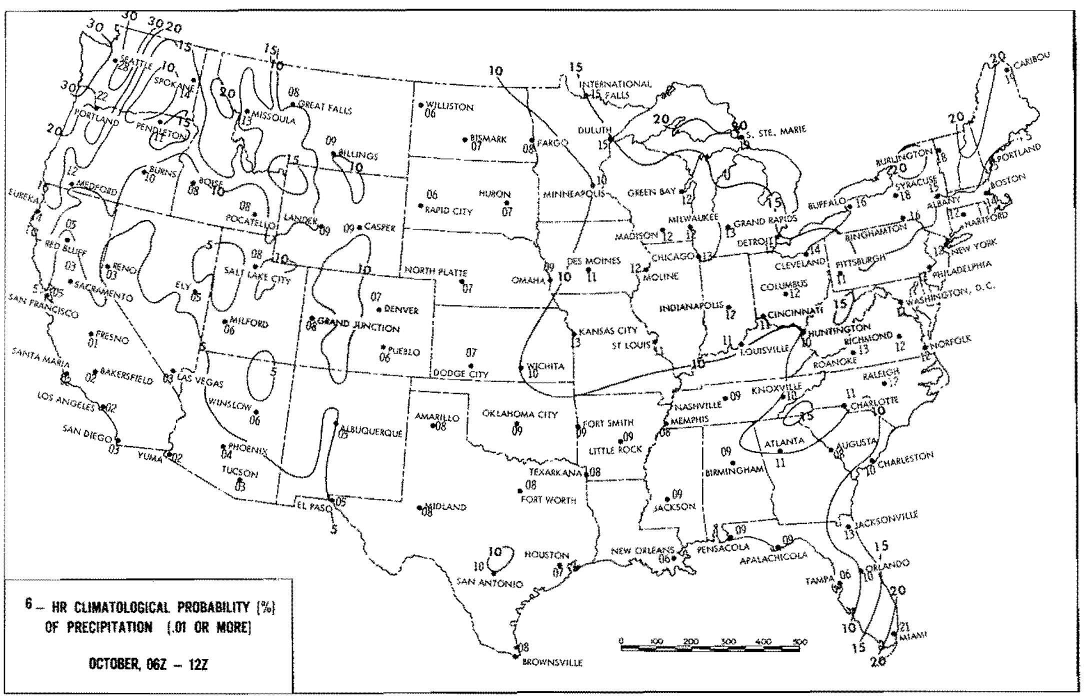

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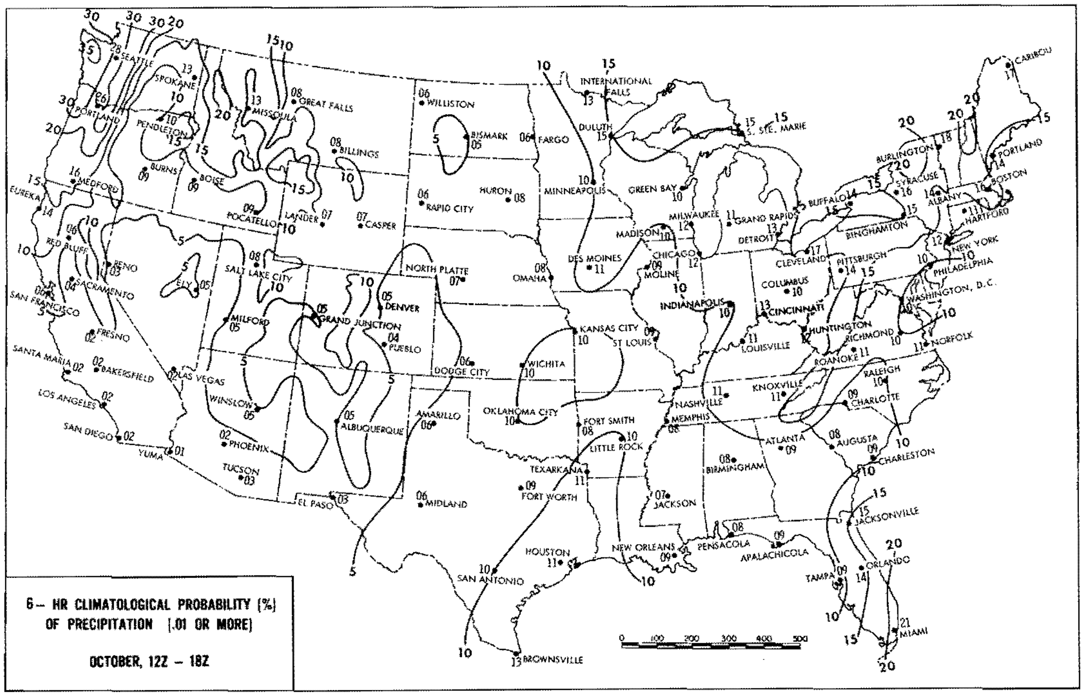

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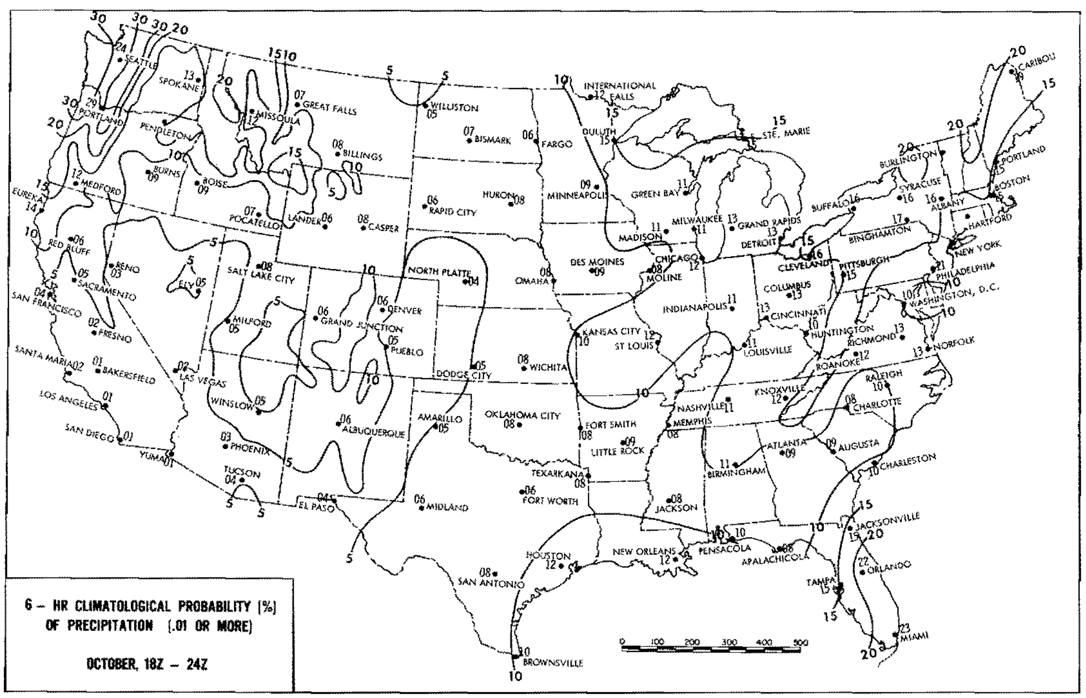

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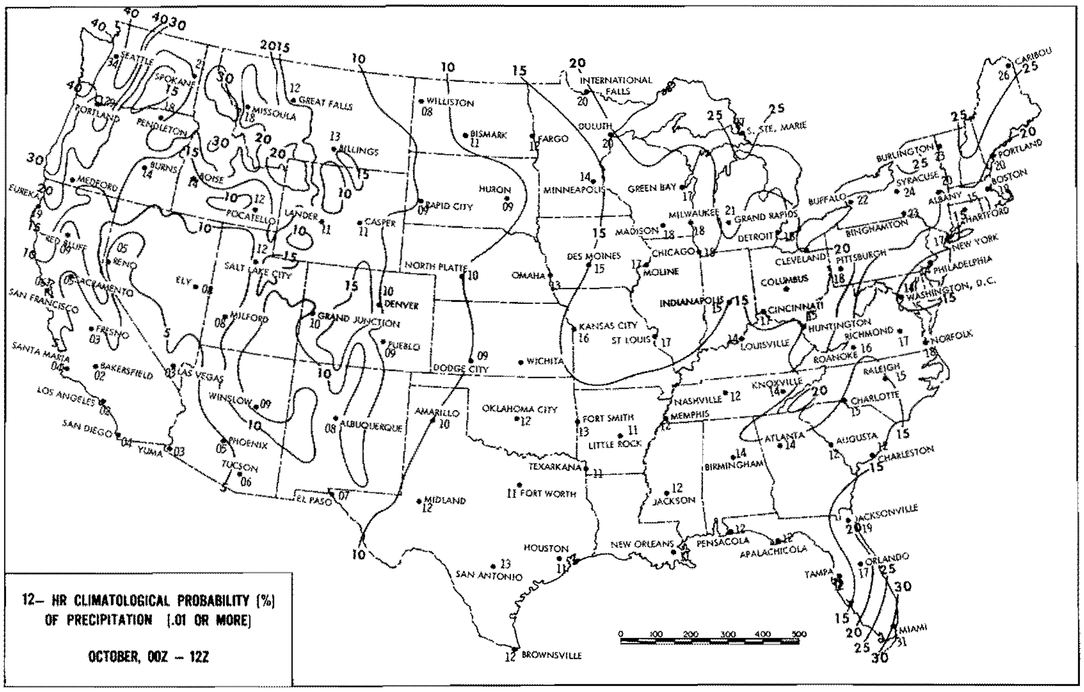

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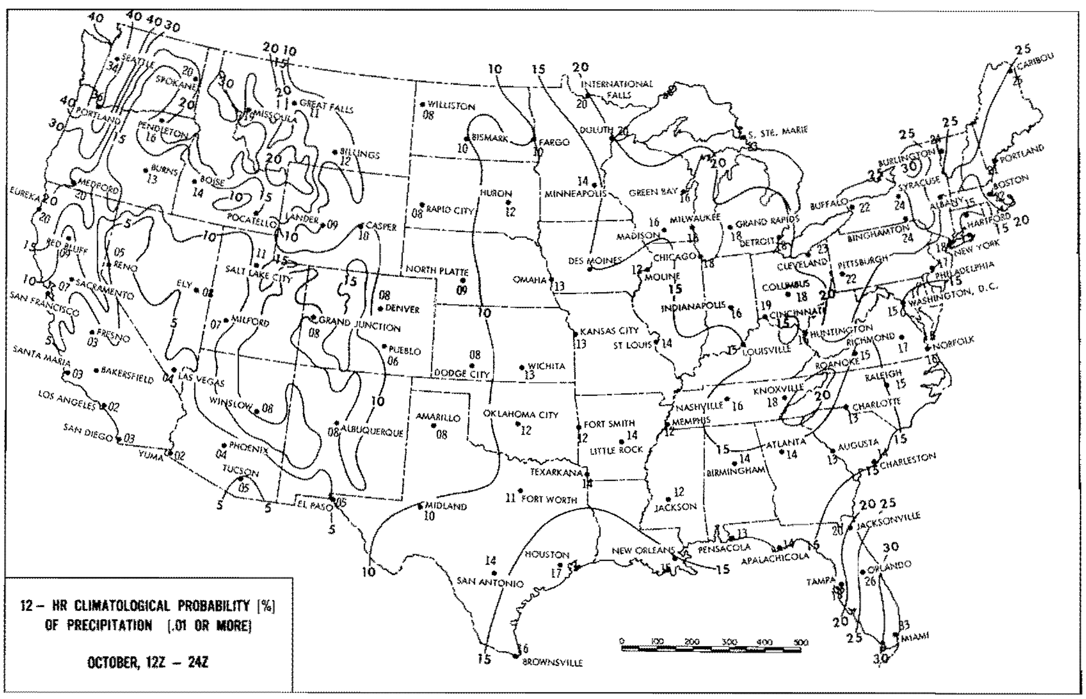

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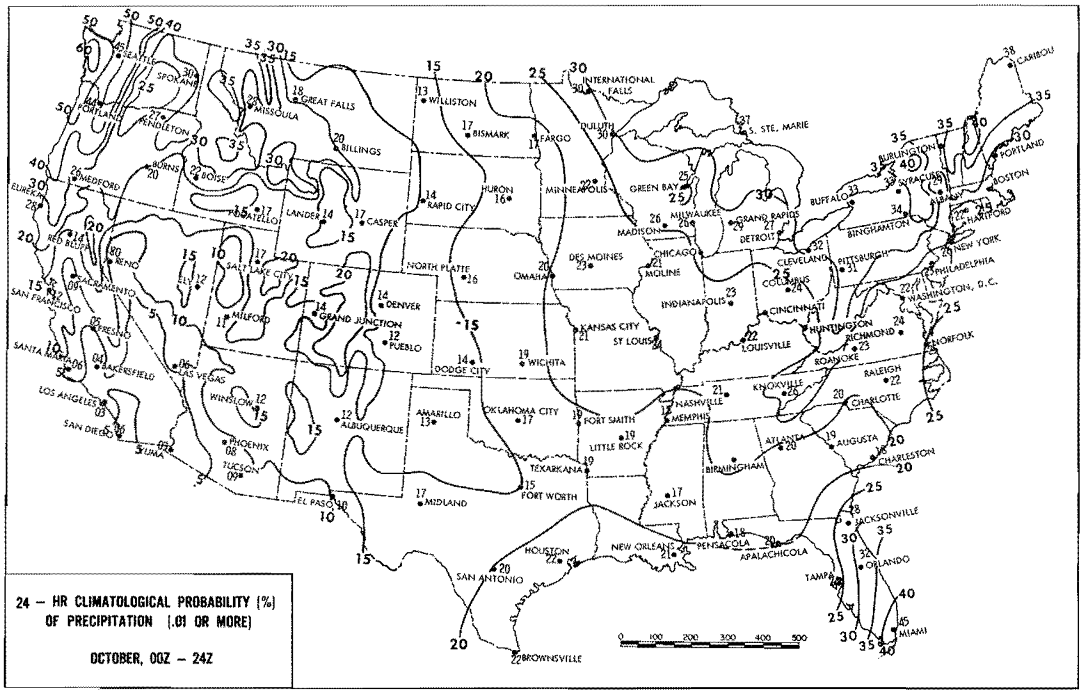

24 – HR CLIMATOLOGICAL PROBABILITY (%) OF PRECIPITATION (.01 OR MORE)
OCTOBER, 00Z – 24Z

Chart 10 - 7

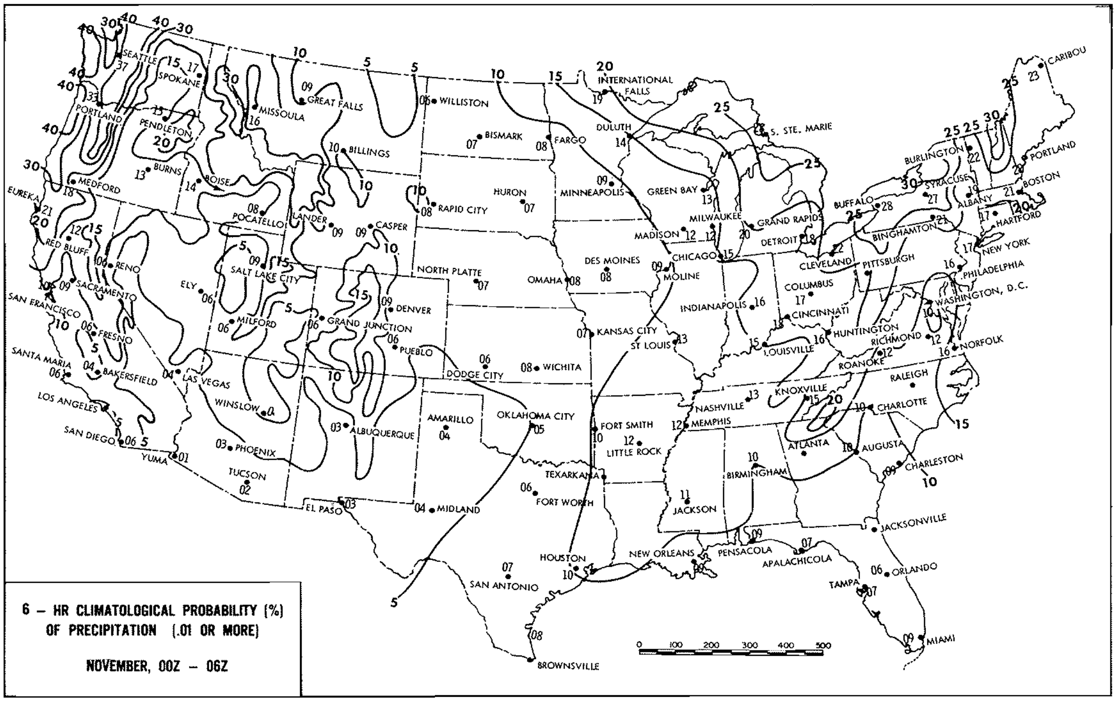
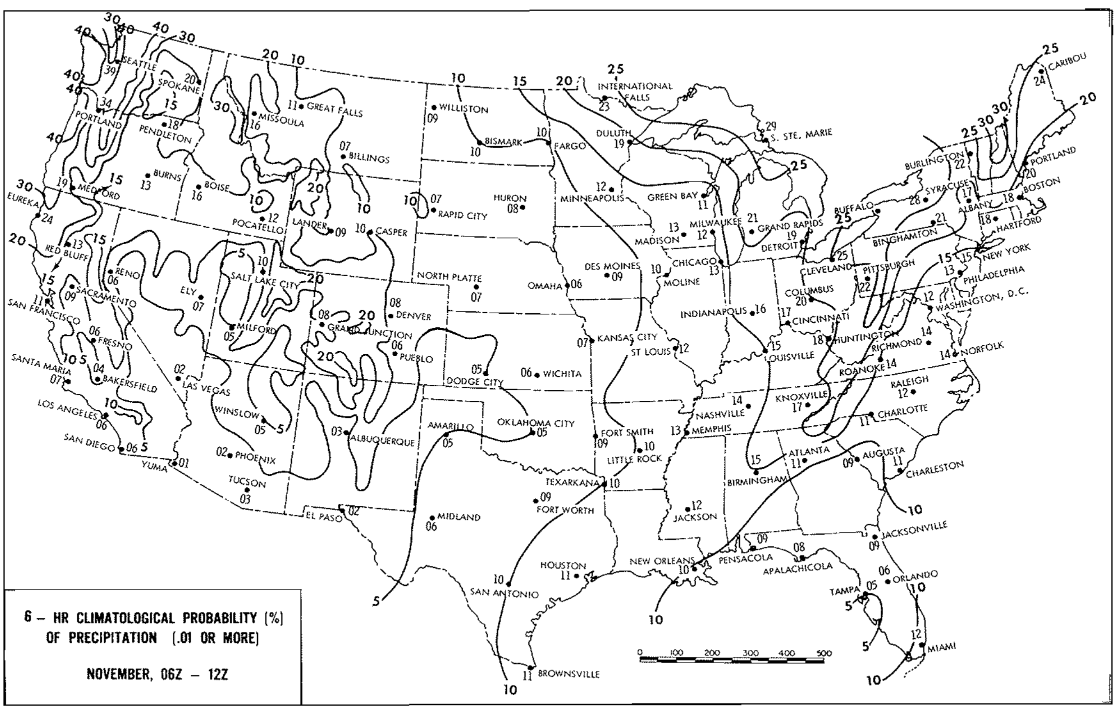


Chart 11 - 1



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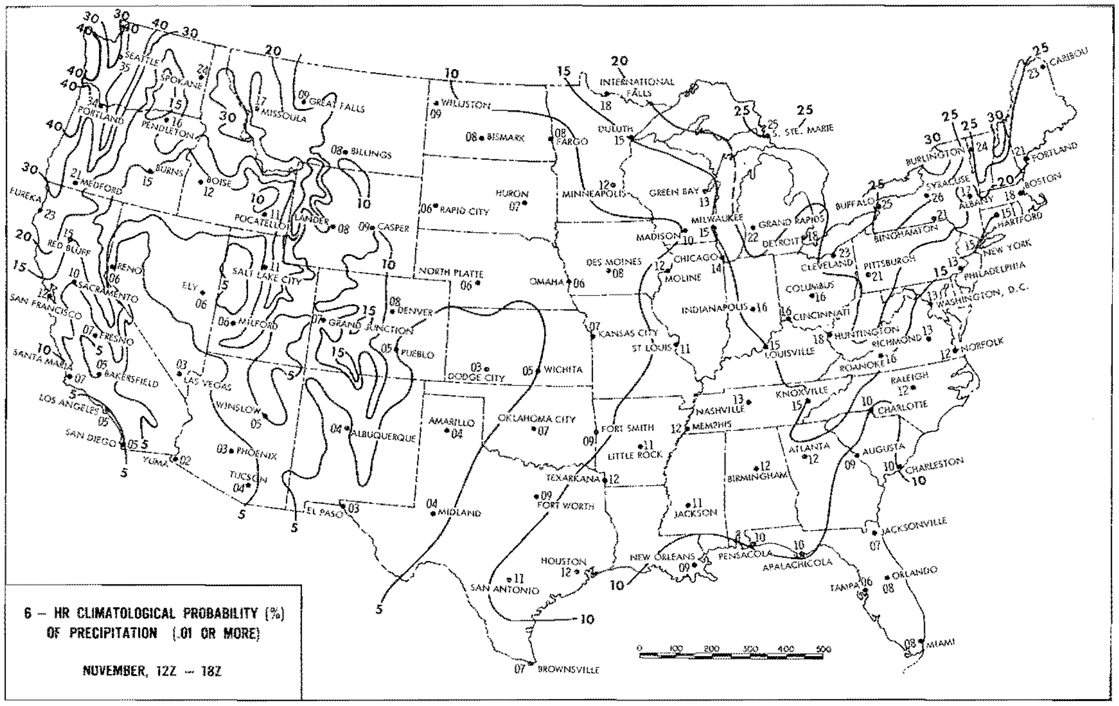

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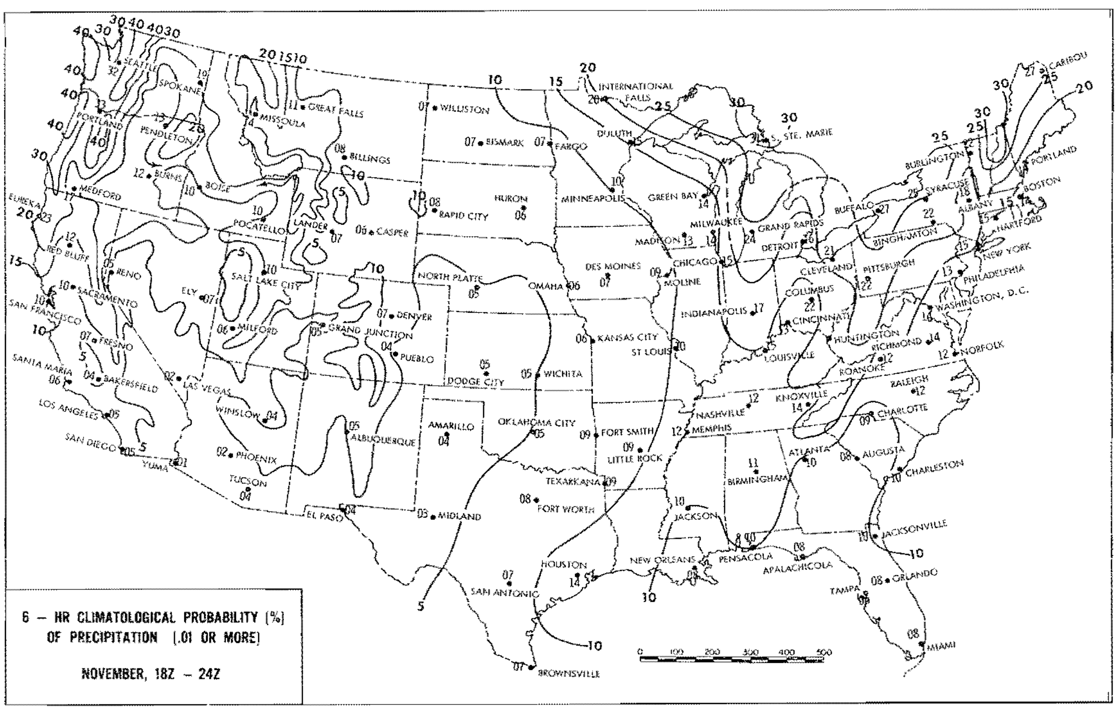

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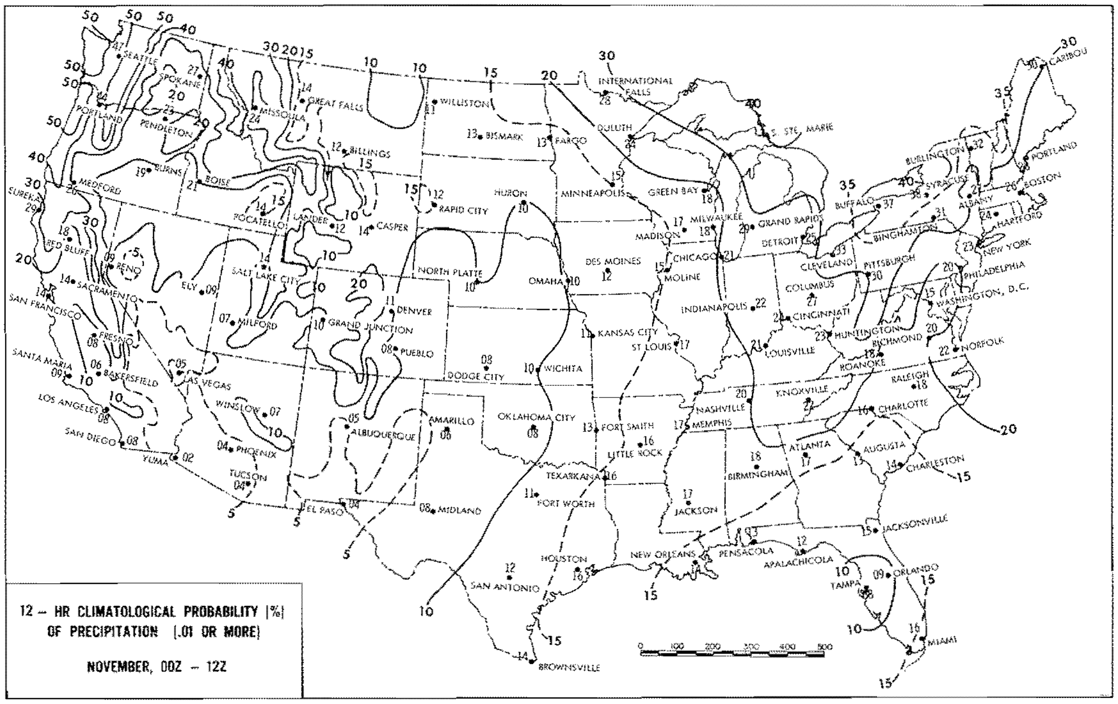

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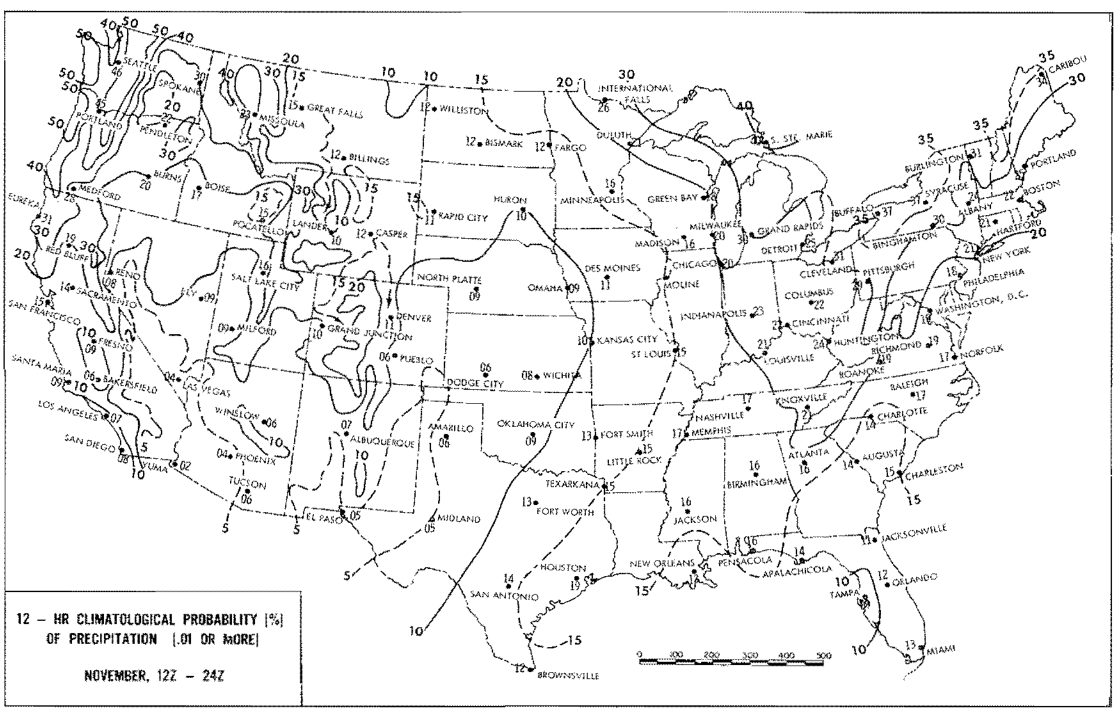

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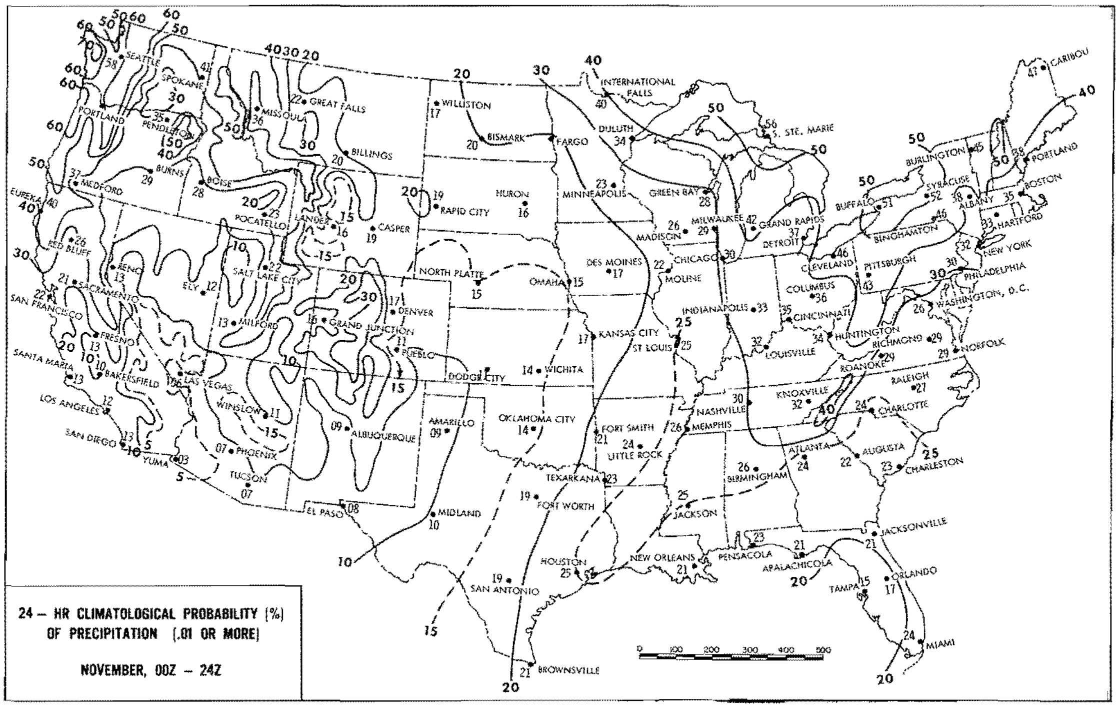

24 – HR CLIMATOLOGICAL PROBABILITY (%) OF PRECIPITATION (.01 OR MORE)
NOVEMBER, 00Z – 24Z

Chart 11 - 7

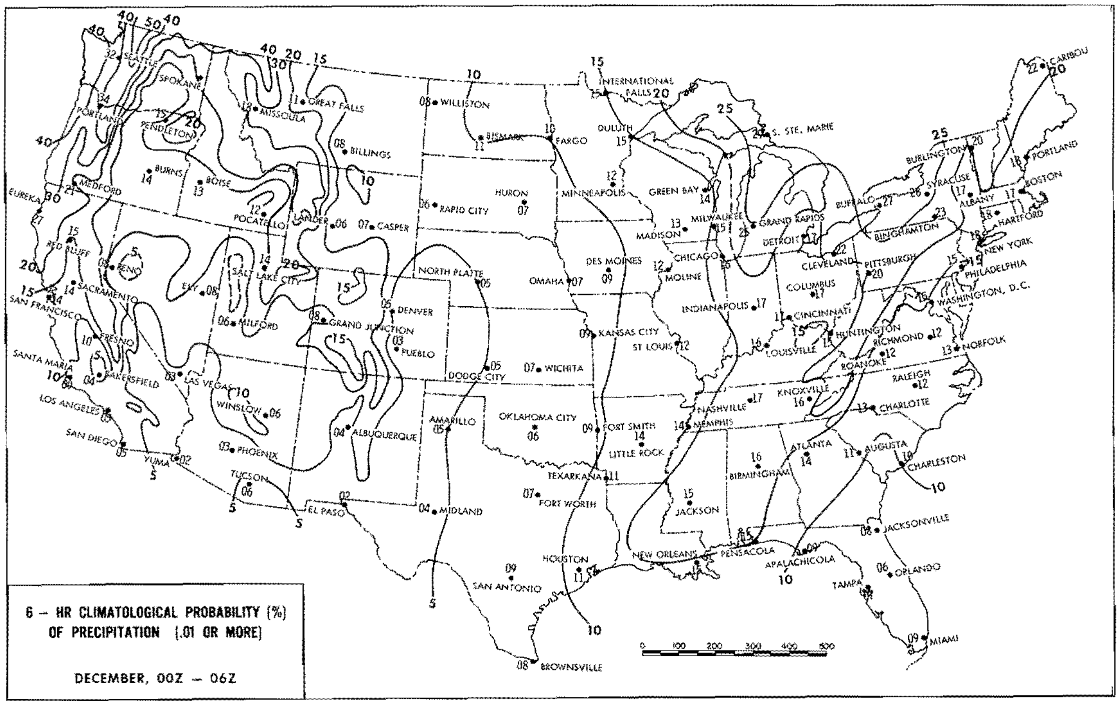
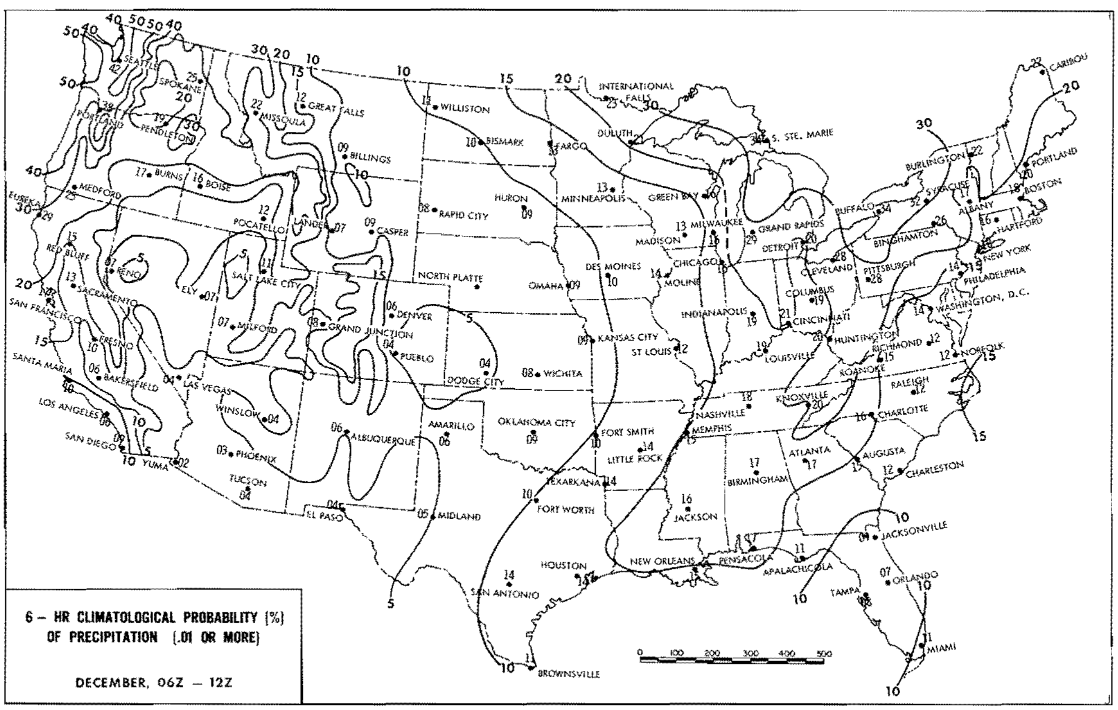


Chart 12 - 1



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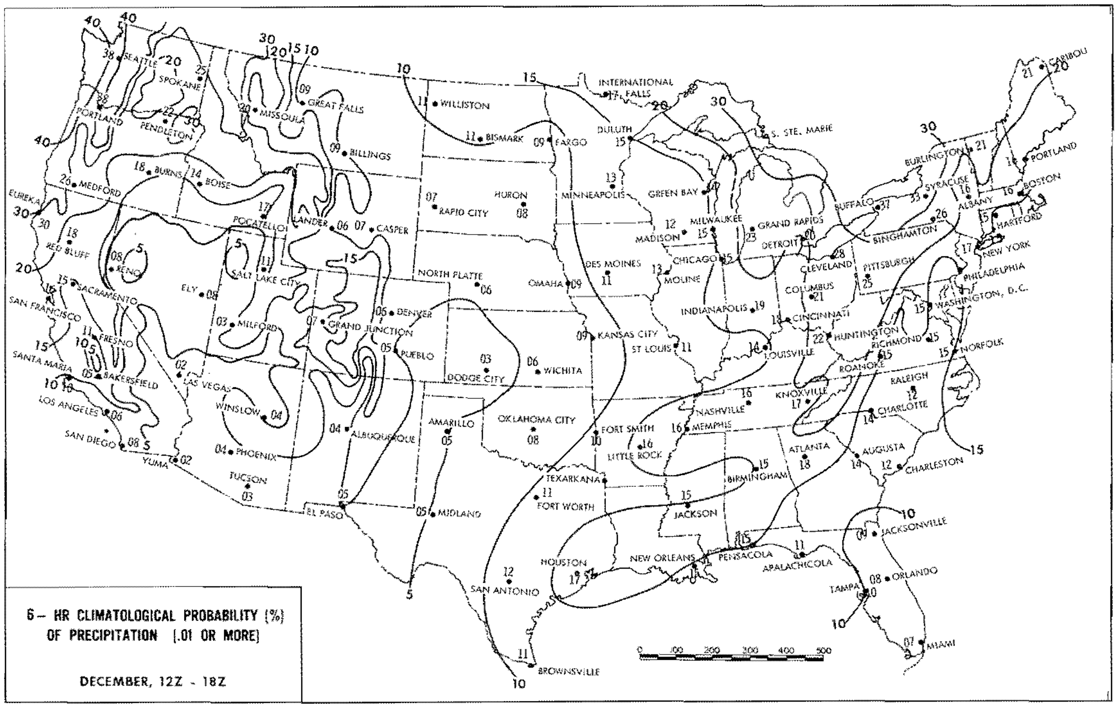

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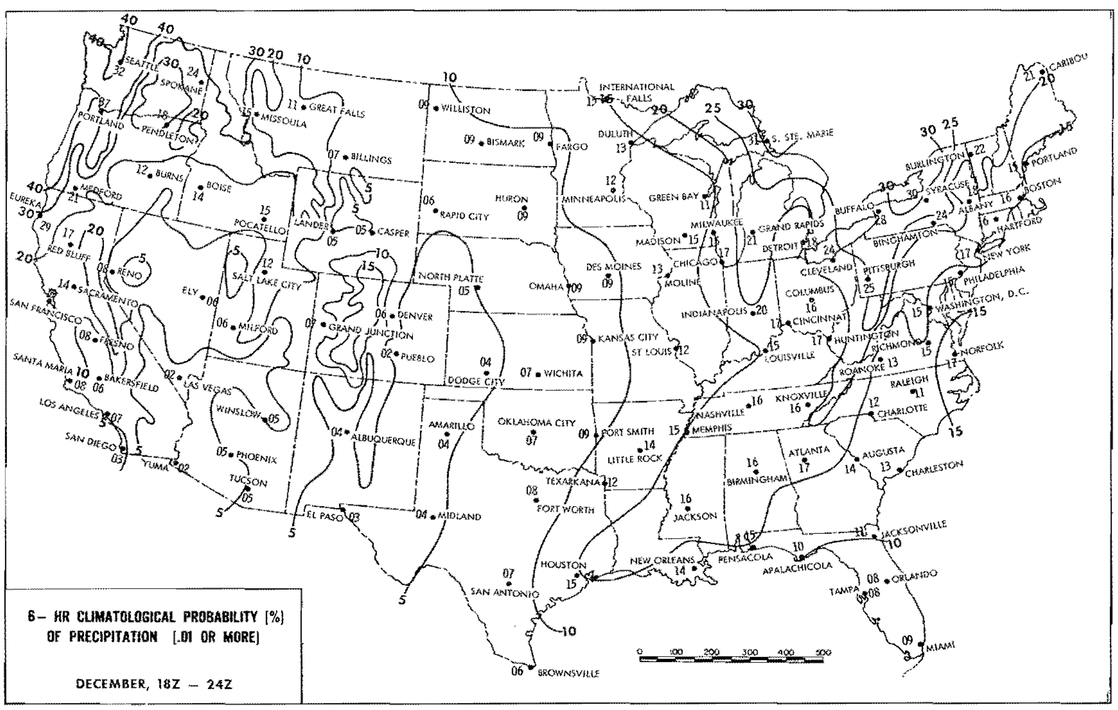

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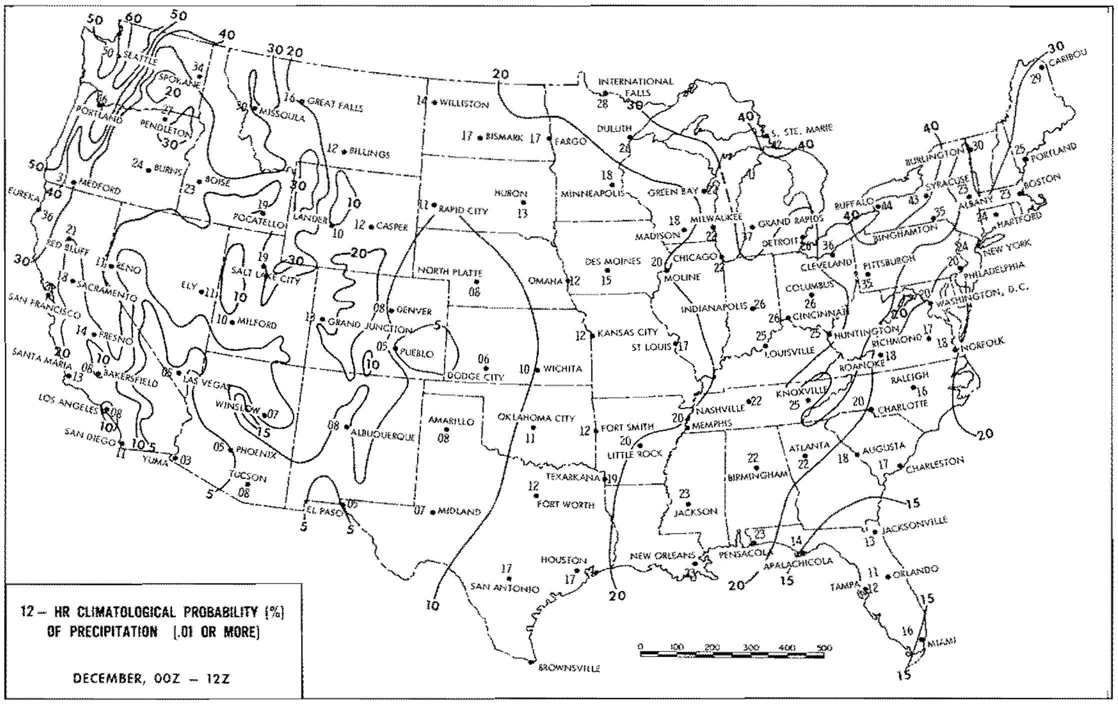

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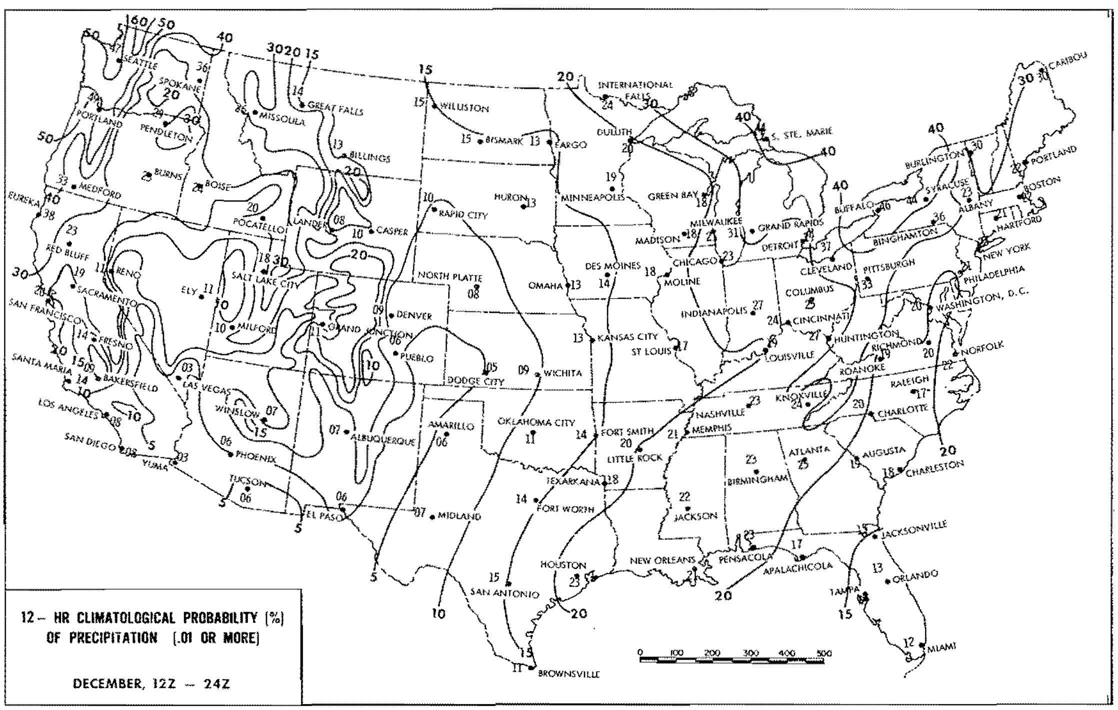

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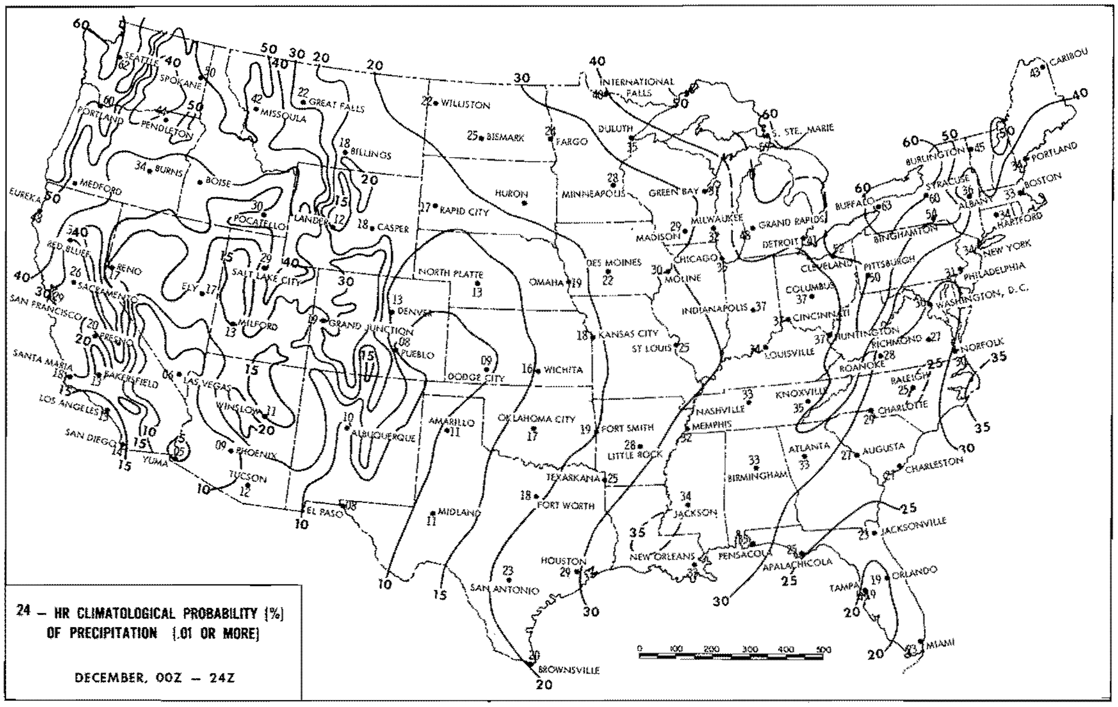

Chart 12 - 7

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