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Hydrometeorological Report No. 18

TENTATIVE ESTIMATES
OF
MAXIMUM POSSIBLE FLOOD-PRODUCING METEOROLOGICAL CONDITIONS
IN THE
COLUMBIA RIVER BASIN

Submitted by

The Hydrometeorological Section

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Chapter I

INTRODUCTION

1. The Assignment. The Hydrometeorological Section has been requested by the U. S. Engineer Department, Corps of Engineers, to evaluate meteorological conditions causing floods of recent record in the Columbia River Basin, to prepare an estimate of limiting meteorological factors in comparison with those associated with the 1894 flood, and to prepare a tentative estimate of maximum possible snow-melt rates in the basin.

2. In conferences following this request, a desire was expressed for a tentative estimate for the entire basin above The Dalles and for smaller areas above a number of prospective dam sites. The areas indicated by the District Offices of the Corps of Engineers as having greatest urgency are above the sites listed:

1. Columbia River at Foster Creek dam site
2. Flathead River, N. Fork at Glacier View dam site
3. Pond Oreille River at Albeni Falls
4. Flathead River at outlet of Flathead Lake (Big Rock dam site)
5. Columbia River just above mouth of Kootenai R. (Arrow Lakes dam-site)
6. Kootenai River at Loonia (Katka dam site)
7. Coour d' Alene River at Leland Glenn dam site
8. Blackfoot River at Nine-mile Prairie dam site
9. Columbia River at Umatilla dam site

Also, a study of such individual sub-basins is required because the integrated discharge from a large river system such as the Columbia may obscure the variations and extreme contributions of the smaller tributaries.

3. Corps of Engineers personnel, from the Office of the Chief of Engineers, the San Francisco Division Office, and the Seattle and Portland District Offices, were detailed to the Hydrometeorological Section for assistance on this project.

4. Aspects of the Problem. Heretofore, basin studies of the Hydrometeorological Section have covered critical periods of only a few days' duration. Extreme situations could be analyzed synoptically and dynamically, major meteorological factors determined, and their physical upper limits evaluated individually and in combination for inclusion in the synthesized maximum possible storm. The snow-melt floods of the Columbia Basin, however, result from sequences of meterological events extending over periods of several months. Such protracted sequences can also be analyzed synoptically and, within limits, even dynamically. The synthosis of extreme or optimum events, however, involves a determination of the dynamical limits on recurrence, as well as the physical upper limits of the factors involved. In the present stage of meteorological knowledge the former determination is as uncertain as the long-range forecast and must be approached, like the long-range forecast, chiefly along climatological and empirical lines.

It is unfortunate that even the climatological approach is beset by difficulties arising from the inadequacy of hydrometeorological data in the Columbia Basin.

5. Although the maximum flood on the Columbia is almost directly related to previous snow accumulation, available records fail to define that accumulation accurately. Many original records permit identification of precipitation as rain or snow, or as either falling on a snow pack, but the stations in general are not at representative elevations. Figure 24 shows the height (1000 to 1500 feet) by which the average basin elevation exceeds the average elevation of precipitation stations, which are mostly in sheltered valleys. Recent increases in snow-survey courses have not as yet corrected the fundamental inadequacy of records for the determination of snow quality, water equivalent, and distribution. Streamflow records serve as the best available index to the melting rates but the changing sizes and locations of the contributing areas during the melting season are not adequately known. Even the length of the snow-accumulation season varies widely from point to point within the basin. The seven-month duration used in this report is only a rough approximation.

6. Without such quantitative observations, it was necessary to use index relations depending on the available observations of precipitation and temperature. Separately and in combination, their values at selected stations in and near the Columbia Basin serve as indices to the extent of snow cover, to the amount of water stored, and to the melting rates. For the determination of the upper limits, the basis was an analysis of the variations and extreme values at these stations and combinations of stations. The precipitation analysis was made for durations of one day to several years, consideration being given to dynamic and synoptic limitations for the shorter periods and to the position of the region in world-wide climatological relationships for the longer periods.

7. The Canadian portion of the Columbia Basin is similar to the adjoining United States area. While available Canadian data have been thoroughly examined, it has been more convenient to use United States records for examples in this report.

Chapter II

CLIMATOLOGY AND METEOROLOGY

8. Role of Location and Topography. The climate of the Columbia River Basin is determined primarily by its location within the zone of the prevailing westerlies and its proximity to an oceanic moisture source. There are striking climatic variations within the basin, however, which can be explained by the topography of the region.

9. The obvious effects of location within the zone of prevailing westerly winds and proximity to the Pacific Ocean are high frequency of precipitation, especially in winter, and modification of temperatures to values higher than the average for the latitude in winter and generally lower in summer.

10. The effects of topography are variation in normal annual precipitation from about 6 inches to more than 50 inches and variations in temperature due to differences in elevation, which far outweigh the effect of differences in latitude.

11. The most important topographic effect is provided by the Cascade Range, which forms the western boundary of the basin. This range, which has an average height of 5000 to 6000 feet, reduces the effective precipitable water within a mass of air moving inland to the Columbia Basin to less than half of that which such air normally contains when it arrives at the sea coast*. An examination of precipitation records indicates that the ratio of the greatest mean annual values west of the Cascades to the greatest mean annual values within the Columbia Basin is nearly the same as the ratio between the effective precipitable water values for the two areas. However, it is not to be expected that the rainfall ratio should be maintained throughout. Because the frequency of storms is higher on the coast, the ratio of coastal to basin rainfall is generally higher. The ratio also increases as the representative dew point in the inflowing air mass decreases.

12. Semipermanent Centers of Action. Associated with the band of prevailing westerlies in the region are the semipermanent centers, the Aleutian Low to the north and the Pacific High to the south. Variations in their position and intensity, seasonal and otherwise, are reflected in the intensity and orientation of the westerly current and hence in variations of the weather and climate of the Columbia Basin. Occasionally lying athwart the westerly current, and displacing it or sharply influencing its orientation over the Columbia Basin, are two other pressure centers, more seasonal and also more transient in their occurrence, the Great Basin High and the North American or Canadian Polar Anticyclone. Almost wholly cold-season phenomena, they cannot coexist at the same latitude in an intensive or extensive form.

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* See Sacramento Report, figure 18.

13. In combination, two or three of these semipermanent centers may dominate the weather of the region for weeks, months, or seasons, and it is possible, as will be shown, to use the mean pressure over the region (or its departure from normal) as an index to the mean weather pattern.

14. Because of the dominance of the Aleutian Low in winter, the greatest precipitation over the area occurs during that season, although over portions of western Montana the summer precipitation is heavier. Typically, the winter season is made up of a succession of migratory cyclonic centers imbedded in the westerly stream and therefore passing over the region in a generally west-to-east path. In December 1933, for example, ten centers passed and precipitation occurred at many stations on 25 out of 31 days.

15. Between the low-pressure centers the anticyclonic development ordinarily is not pronounced. One exception is the occasional intrusion westward beyond the Continental Divide of the continental polar air mass and its attendant pressure system, the North American Anticyclone. This is perhaps the most common cause of protracted periods of low temperatures in the Columbia Basin, particularly at valley stations, and it also provides the wedge of cold air over which moist Pacific air is lifted to produce many of the heavier snowstorms of the region. Another exception to the limited anticyclonic development over the area is the occasional appearance of a pronounced Great Basin High whose influence extends farther north than usual. Under these circumstances most of the basin usually experiences a protracted period of fair weather, the paths of low-pressure centers being displaced northward.

16. For examples of the various weather types discussed reference is suggested to the daily weather maps of the Northern Hemisphere for a 40-year period, on file at Weather Bureau Forecast Centers. High frequency of cyclonic activity in the region can be found in the series of charts for November 1909, December 1917, February 1904, or March 1916. The westward extension of the North American Polar Anticyclone which accompanies heavy-snow sequences is shown on the maps for November 12, 1911, and March 27, 1936, when the maximum 24-hour snowfalls occurred at Spokane and Kalispell, respectively. For the weather associated with Great Basin High development, the series of December 1930 is recommended.

17. Mean Pressures. The relationship between monthly mean isobaric patterns and tracks of Low centers is indicated in figures 2 to 10, in which both are charted for the 1893-94 season. It may be observed, incidentally, that the storm tracks cover the entire basin, indicating no concentration of activity in any one part of the exclusion of storm occurrence elsewhere. Figure 5 shows that in January 1894 eight or nine Low centers passed over or near the Columbia Basin, resulting in a pronounced low-pressure trough extending eastward across the area on the monthly mean-pressure pattern. In February 1894, however, the mean pressures (figure 6) indicate extensive anticyclonic development over the Rocky Mountain region with pressures above normal over the Columbia Basin and adjacent areas, and

only one storm track crossing the basin. It is especially noteworthy that available records indicate 150 to 200% of normal monthly precipitation for January 1894 and only normal or slightly below in February. The relationships indicated are supported in figures 11 to 19, which show the departures of monthly mean pressure from normal for the 1893-94 season. January 1894, for instance, shows a negative departure while February shows a positive departure.

18. Because observations of atmospheric pressure are fundamental, and pressure distribution a feature of, and an index to, the general circulation controlling storm movements, a further analysis of monthly mean pressures in the Columbia Basin is shown in figure 20. Here the monthly mean pressure anomalies are graphically correlated with monthly precipitation for the winter season in the water years 1923 to 1943. Two relations are shown. One is the association of high precipitation with low pressure; the other is the association of high precipitation with decrease in mean pressure from the previous month. December 1933 (in the 1934 water year) is an example of both relations. The first relationship is meteorologically plausible because both high precipitation and low pressure depend on the frequency of cyclone occurrence. The second relationship lacks meteorological explanation[7] and has therefore been omitted in the consideration of maximum possible precipitation sequences. However, the pressure sequences shown, and also others that have been studied, suggest no possibility of a season with each month having mean pressure much below normal. The composition of a synthetic season of months of maximum precipitation is thus limited.

Chapter III

PRECIPITATION

19. Outstanding Records. The maximum flood of record at The Dalles occurred in June 1894. The hydrograph and accompanying meteorological record are shown in figure 1. Inadequate station density makes it difficult to estimate the mean depth of precipitation contributing to the flood but, from careful analysis of the record, it is believed to be about 150% of normal.

20. The individual occurrences of precipitation shown in figure 1 apparently had very little immediate response in streamflow. The record of decreasing depth of snow on the ground at these stations also shows no direct relation to discharge, the relation being obscured by the topographic features of the basin and the temperature regime, which, together influence the size of the contributing area.

21. The degree of uniformity in the temperature anomalies of the three stations shown suggests that the temperatures are representative of areas of considerable extent. The temperatures in 1893-94 were not far from normal. It is to be noted that temperatures above normal and above freezing, at elevations less than 5000 feet, preceded individual peaks of streamflow by five to ten days. The broken lines in figure 26, to be described later, show estimates of monthly mean temperatures in Idaho and precipitation in Southwest Idaho in the 1893-94 season.

22. December 1917 and December 1933 were two of the heaviest monthly periods of precipitation of record in the Columbia Basin. In each of these months, in a large portion of the basin, about 30% of the mean annual precipitation occurred. It is significant that in each instance the January discharge at The Dalles was about half that of the following June, and that these were the highest January discharges of record.

23. One of the heaviest storms of record for this area occurred during the period December 10-20, 1933. For the 60-hour period ending at 6 p.m. December 19, over a 10,000-square-mile area in northern Idaho and vicinity, the average depth of precipitation was 2.7 inches. This value appears low, but on the basis available moisture (diminished by passage over the Cascade Range and from a source region with relatively low temperatures) it compares favorably with record storms for other areas in the United States.

24. Figure 23 shows the maximum monthly precipitation of record for climatological subsections in the Columbia Basin for the months of October through June, and also maximum precipitation occurring in months with mean temperature less than 36 F and less than 32 F. In Eastern Washington and Northern Idaho, it can be seen that the maximum observed monthly precipitation has been about 40% of the mean annual - but the maximum value falls to about 30% when only months of mean temperature of 32 F or less are considered.

25. In order to gain perspective, records from other areas have also been examined. Although the lack of meteorological and climatological

homogeneity is recognized, certain broad relationships between maximum possible and mean annual precipitation become apparent.

26. Figure 21, from Jarvis' tabulation, shows a well-defined envelopment of upper limits of annual point rainfall as a function of the mean annual. The tremendous volume of data represented lends great weight to this particular parameter. A similar relationship for state areas is indicated in figure 22, where the data are from U. S. Weather Bureau records. Both charts suggest the use of local mean annual precipitation as an effective basis for the estimate of the maximum possible.

27. For short durations, upper limits of precipitation can be more accurately defined. In April 1921 a snowstorm in northern Colorado deposited 45% of the mean annual precipitation at Fry's Ranch in one day. The same storm deposited an average of 3.1 inches (water equivalent) over 10,000 square miles in 24 hours. On the basis of theoretical computations, even with the assumption of extreme conditions of lapse rate and moisture content in air flowing over the Columbia area, such an amount cannot be exceeded in that region. The theoretical computation was based on the Elba, Alabama, storm of March 15, 1929, which produced 12.1 inches of rainfall over 10,000 miles in 24 hours. Extending the computation to 50,000 square miles (average depth: 6.3 inches in the Elba, Alabama, storm) gave 1.7 inches over the Columbia area. Another extreme value is given by the record of 125% of mean annual rainfall which occurred in 24 hours at a point near Kerrville, Texas, early in July 1932. Some of the storms mentioned occurred without the diminishing effect of a barrier such as the Cascade Range and in a region of much higher possible moisture content. Though not analogous to storms occurring in the Columbia Basin, they suggest values below which the maximum possible values for the Columbia must fall.

28. Basis of Estimate. A guide to the magnitude of the optimum seasonal precipitation over the Columbia Basin was obtained by combining maximum monthly precipitation totals of record for the months October through April. To make such a combination, the published Climatological Data were examined for the years of occurrence of the three wettest of each of the months for the four climatological subdivisions involved: Eastern Washington, Northern Idaho, Southwestern Idaho, and Montana West of the Divide. From a tabulation of the monthly averages, a synthetic season, October through April, was selected on the basis of the largest positive departures from normal monthly precipitation in two or more of the climatological subdivisions. The following sequence resulted: October 1933, November 1909, December 1917, January 1909, February 1940, March 1916, and April 1937. The seven-month precipitation totals thus determined, expressed in terms of mean annual, were: Eastern Washington - 162%, Northern Idaho - 153%, Southwestern Idaho - 148%, and Montana West of the Divide - 136%.

29. A study of the mean-pressure distribution for the months of the synthetic season indicated that the selected months could

reasonably follow in the order named. Both the monthly pressure-departure values and the synoptic charts for the end and beginning of consecutive months were considered in the appraisal.

30. Next, the departures from monthly normal temperatures for the seasons of 1893-94 and 1915-16 were compared with the temperature departures of the synthetic season. This revealed temperatures near normal during the synthetic season as well as during the 1893-94 and 1915-16 seasons.

31. The synthetic season thus does not violate any of the known limitations imposed by the sequence of pressure patterns. Neither are the average temperatures of the synthetic season so high that they would necessarily prevent the optimum snow accumulation for the late-spring flood. Only exhaustive dynamic and statistical analysis, not now feasible, could determine whether the total precipitation of the synthetic season could be exceeded, but higher values would probably involve higher temperatures and therefore less snow accumulations. The heavy precipitation of December 1917 and December 1933, for example, was followed by record January discharges and may have contributed little to the crest when the snow melted in June.

32. While it is true that the monthly unit used in the synthetic season is an accident of calendar and custom, it is also a reasonable unit for the purpose. A consecutive sequence of calendar-day units with maximum precipitation of record would probably yield too high a seasonal total because the necessary intervening episodes of fair weather would be eliminated. On the other hand, use of the maximum 12-month or 7-month period as a unit would obviously yield too low a total. The unit of one month falls between these two extremes. A weekly unit was also tested for one climatological subdivision and yielded an answer of like magnitude. The results, however, require checking or corroboration from other sources.

33. A check was provided by approximating maximum precipitation values for the Columbia area by interpolating among the world-wide records showing climatological relationships of season, depth, area, duration, and location. Comparatively secure anchor points of area-depth were established at 30-year durations by the convergence of apparent trends in the data, and at short durations by the adjustment of observed storms on the basis of dew point, other synoptic data, and orography. In the area between these two types of anchor points were numerous pairs of points (at durations of a week, a month, etc.) between which the final curves were located. Lower limits on the final values were established by the consideration that the latter must exceed certain recorded values in the Columbia area. Upper limits were established by the records of phenomenal precipitation which, it is known, must exceed any possible values in the Columbia area. For comparable durations, areas, and values of mean annual precipitation, the depths in the synthetic season exceeded by 20% the depths obtained by interpolation among the world-wide records. Because the latitude involved in the process of interpolation was of the same magnitude, the curves derived by the interpolation method were adjusted by the 20% increase.

34. The Optimum Precipitation. While it is believed that the precipitation values derived as indicated above are maximum for a season in which depth of snow accumulation is most important, it is not certain that they are necessarily the maximum for a season on which no such restriction is placed. For that reason, it is preferred to designate these values as optimum precipitation in this report.

35. The curves giving the tentative estimate of optimum precipitation for the Columbia area are shown in figure 25. The estimates are for durations of one month to one year, all in terms of the mean annual precipitation. The magnitude of increments of precipitation for periods of less than one month is not believed important for accumulation of snow. While seven months has been indicated as the optimum snow season, and it probably is for average elevations, a shorter season would apply to the lowest elevations, and a longer season to the highest elevations.

36. Table I gives the same information as figure 25 with the addition of areas of other sizes and other values of mean annual precipitation, for greater ease in interpolation. The upper part of figure 26 illustrates the use of figure 25 or table I in designing a hypothetical season for a basin of 50,000 square miles having a mean annual precipitation of 15 inches. It is believed that as much precipitation as possible should be scheduled for the four-month period, December through March. Therefore, 125% of mean annual, or 18.7 inches, is distributed during this period. While the table and figures show that one of these months could have as much as 61% of mean annual, or 9.1 inches, this would leave a total of only 9.6 inches for the other three months. There is no apparent reason for believing that such an extreme distribution would cause a greater flood than a more uniform and more likely distribution having the same total accumulation of snow during the four-month period. The distribution of the precipitation for the maximum four-month period shown in figure 26 is arbitrary. The period of maximum seven months' precipitation, it is believed, should include the additional months of October, November, and April. The table shows 170% or 25.5 inches for the seven months. Having used 18.7 inches for the maximum four months, 6.8 inches remain for distribution among the months of October, November, and April. The distribution may be made to meet any hydrologic requirements, with the single restriction that the total precipitation for any duration should not exceed the value given in figure 25 or table I for that duration. For example, if all the 6.8 inches were scheduled for April, the total for the five months (December through April) would be 18.7 plus 6.8 inches. This would exceed the permissible 5-month precipitation, which is about 21.2 inches according to the curve in figure 25.

37. If, in this 50,000-square-mile area, sub-areas are to be dealt with individually, the total average depth may be distributed in any manner, provided that the average depth for any portion of the area does not exceed the values of figure 25 or table I for the proper-sized area, mean annual precipitation in that area, and proper duration.

Table I

TENTATIVE ESTIMATES OF MAXIMUM PRECIPITATION, COLUMBIA BASIN

For Mean Annual Precipitation of:

	Areas Thsds. Sq. Mi.	15 In. %	In.	20 In. %	In.	25 In. %	In.	30 In. %	In	40 In. %	In.	50 In. 5%	In.
12 Mo.	2	256	38.4	234	46.8	222	55.5	212	63.6	202	80.8	193	96.5
	5	247	37.0	223	44.6	210	52.5	202	60.6	192	76.8	186	93.0
	10	242	36.3	217	43.4	204	51.0	197	59.1	187	74.8	181	90.5
	20	239	35.8	214	42.8	202	50.5	193	57.9	184	73.6	179	89.5
	50	234	35.1	209	41.8	196	49.0	187	56.1	179	71.6	174	87.0
7 Mo.	2	198	29.7	178	35.6	166	41.5	160	48.0	150	60.0	144	72.0
	5	188	28.2	169	33.8	158	39.5	150	45.0	138	55.2	131	65.5
	10	180	27.0	163	32.6	152	38.0	144	43.2	133	53.2	125	62.5
	20	174	26.1	157	31.4	146	36.5	139	41.7	128	51.2	120	60.0
	50	170	25.5	150	30.0	140	35.0	134	40.2	124	49.6	119	59.5
4 Mo.	2	158	23.7	144	28.8	134	33.5	127	38.1	116	46.4	109	54.5
	5	144	21.6	130	26.0	120	30.0	113	33.9	103	41.2	96	48.0
	10	134	20.1	121	24.2	112	28.0	106	31.8	96	38.4	90	45.0
	20	128	19.2	116	23.2	108	27.0	102	30.6	92	36.8	86	43.0
	50	125	18.8	113	22.6	104	26.0	98	29.4	90	36.0	84	42.0
2 Mo.	2	124	18.6	112	22.4	103	25.8	97	29.1	89	35.6	82	41.0
	5	106	15.9	95	19.0	88	22.0	82	24.6	74	29.6	68	34.0
	10	95	14.2	85	17.0	79	19.8	74	22.2	67	26.8	62	31.0
	20	90	13.5	82	16.4	76	19.0	71	21.3	64	25.6	59	29.5
	50	86	12.9	78	15.6	72	18.0	68	20.4	61	24.4	58	29.0
1 Mo.	2	98	14.7	88	17.6	80	20.0	76	22.8	67	26.8	62	31.0
	5	78	11.7	70	14.0	64	16.0	60	18.0	53	21.2	49	24.5
	10	70	10.5	62	12.4	58	14.5	53	15.9	48	19.2	43	21.5
	20	65	9.8	58	11.6	53	13.2	49	14.7	44	17.6	41	20.5
	50	61	9.2	55	11.0	50	12.5	47	14.1	42	16.8	38	19.0

38. This report deals primarily with the snow-melt type of flood. It has been suggested, however, that small basins may experience their maximum possible floods as a result of heavy rain rather than melting snow. With the emphasis on snow, very little attention has been given to short-duration rainfall. In distributing the optimum precipitation to provide the maximum possible during the period October through April, only about 60% of the mean annual remains for possible occurrence during the remaining 5 months. It is estimated that as much as 10% of the mean annual could occur on any one day to synchronize with the snow-melt flood. The possibility of an optimum flood resulting from more rain and less snow has not been explored.

39. Limitations of Estimate. Further study may indicate that the optimum precipitation will include some rain at low elevations, the loss to pre-flood streamflow being more than compensated by the snow-fall at high elevations exceeding that which could occur with the lower dew points. The lower dew points, and therefore lower total volumes of precipitation, are required for snowfall at low elevations. This question will require considerable hydrologic analysis.

40. Autumn precipitation is know to influence the volume and peak of streamflow in the following season, through its effect on soil moisture. Evaluation of this effect is part of the unsolved problem of the total duration of precipitation which significantly affects the seasonal peak flow.

41. In addition to the duration-area-depth function expressed in terms of the mean annual precipitation, further study would probably result in a refinement on the basis of elevation, distinction between proporations of rain and snow in each storm, latitude, normal seasonal variation during the year, and other parameters.

42. The meteorological phenomenon of evapo-transpiration from the snow-covered portions as well as other portions of the basin, during the long period antecedent to each year's flood peak, deserves far more study than available time has permitted. Lack of knowledge of its magnitude requires the assumption that the evaporation loss is either negligible or average, thus including it as a small but probably safe margin in the estimate of the optimum meteorological conditions.

43. In a general way, much of the basin is meteorologically homogeneous, and conditions observed in one place reflect conditions existing in other places having comparable elevation, orientation, forest cover, and other exposure characteristics. However, it is a fact that more extreme weather can exist for short periods and over small areas, than for long periods and over large areas. The optimum season for the entire basin above The Dalles would require more general distribution of snow and of melting conditions than could occur with the concentration required for the maximum possible flood on one of the tributaries.

Chapter IV

MELTING CONDITIONS

44. Air Temperature as Index. For the Columbia Basin above The Dalles, and for many of the sub-basins, it has been observed that the peak rate of streamflow bears a fairly close relation to the seasonal volume. It has further been observed that variations in this relation are related to variations in observed mean temperature for short periods prior to each flood peak. It is recognized that air temperature is only one of the factors influencing rates of heat supply, and that the available temperature record is probably inadequate as a sample of the temperature of the air passing over the basin. However, in lieu of anything better at this time, temperature observations must be regarded as an index to rate of heat supply.

45. Comparison of temperature observations during the melting seasons, following winter seasons of varying magnitude of snow deposit, indicates that a cover of extremely deep snow in the Columbia Basin could be followed by extremely high temperatures. Variations, from year to year, of temperature change in the air passing over the basin show practically no correlation with volume of discharge.

46. One of the requirements of the maximum possible flood is synchronous contribution from major tributaries. It is believed that, while temperature is influenced by latitude, the difference in normal progress of the melting season due to the extreme north-south extent of basin can be overcome by unusual temperature distribution. The greatest variation of temperature in the basin is associated with difference in elevation. This has two important hydrologic consequences. One is the variation in length of the snow-cover season with elevation, and the other is the variation in size, shape, and location of the area contributing runoff during the snow-melt season. While in general the snow-accumulation season for most of the basin may be about seven months, there is no one date on which the snow pack has accumulated over the entire basin and is all ready to melt.

47. It has not been possible to determine adequately the optimum variation of temperature with elevation. Further meteorological research may disclose the possibility of an approach to isothermal conditions over the entire basin for long periods, thus providing wider melting zones than occur with the normal decrease in temperature with elevation.

48. Figure 27 shows the maximum and minimum monthly mean temperature of record for five stations in the Columbia Basin, in terms of departure from mean annual. These stations were selected on the basis of areal representation and adequacy of record. The figure shows a smooth variation from month to month of both maximum and minimum temperatures. It is to be noted that the extremes for individual stations are not greatly different from one another. The record indicates that for periods as long as a month, marked temperature anomalies prevail over large areas, widely scattered stations frequently experiencing their extremes of record during the same periods.

49. Figure 28 shows tentative estimates of highest and lowest mean temperatures, for 7- and 30-day periods, in terms of departure from mean annual. The curves resulted from envelopment of values such as those in figure 27. This envelopment of extreme station-record value represents a tentative estimate of possible extreme temperatures for large areas. It has not been possible to determine extreme mean temperatures by transposition, extrapolation of controlling elements, or any other method analogous to those used with maximum precipitation. Table II shows the same estimate of extreme possible temperatures as figure 28, with the addition of other durations and areas of other sizes for greater ease in interpolation.

50. Further study might show that duration and area do not adequately define the relation of temperature to snow melt and that refinement would probably include such parameters as elevation, aspect, and forest cover.

51. Optimum Temperature Sequence. A cold fall and spring, with winter temperatures near freezing, will permit the maximum possible depth of accumulated precipitation, and will permit the greatest possible portion of the precipitation to occur as snow. Further, a cold spring will delay the melting until the higher temperatures can occur. Hydrologic analysis may determine the optimum time of year for the occurrence of the maximum temperature for that time of year. This optimum time is a function of the area-elevation curve of the basin, and one of the isssues involved is the possible occurrence of extreme melting conditions at a time when the area of melting snow is at a maximum.

52. The lower part of figure 26 shows a suggested critical sequence of monthly mean temperatures taken from figure 28 and table II, for the hypothetical area of 50,000 square miles. October and April are the coldest possible, the intervening months having temperatures near freezing. June and July are the hottest possible; May is normal, but could have any temperature between the limits shown in fugure 28 and table II. The time at which the basin air temperature should rise sharply is determined by the location of the snow line for maximum volume of water to be melted from the snow.

53. For periods shorter than one month, and for areas less than 50,000 square miles, the mean temperature for any size of area and for any duration may be determined in a manner explained earlier for distribution of precipitation. That is, the temperature for areas of all sizes and for all durations must be within the limits set by figure 28 and table II for those areas and durations.

54. An important question to consider is the rate at which the temperature can increase in the spring. In April 1936, in the Columbia Basin, the mean temperature for the third week of the month was about 30 F higher than for the first week of that month. It has not been possible to examine the record completely or to study the possibilities exhaustively, but at this time there is no apparent reason why a late spring month of maximum possible temperature could not follow a month of lowest possible temperature for that time of year. It also appears possible for the maximum weekly mean temperature to follow the minimum with only one near-normal week intervening.

TABLE II

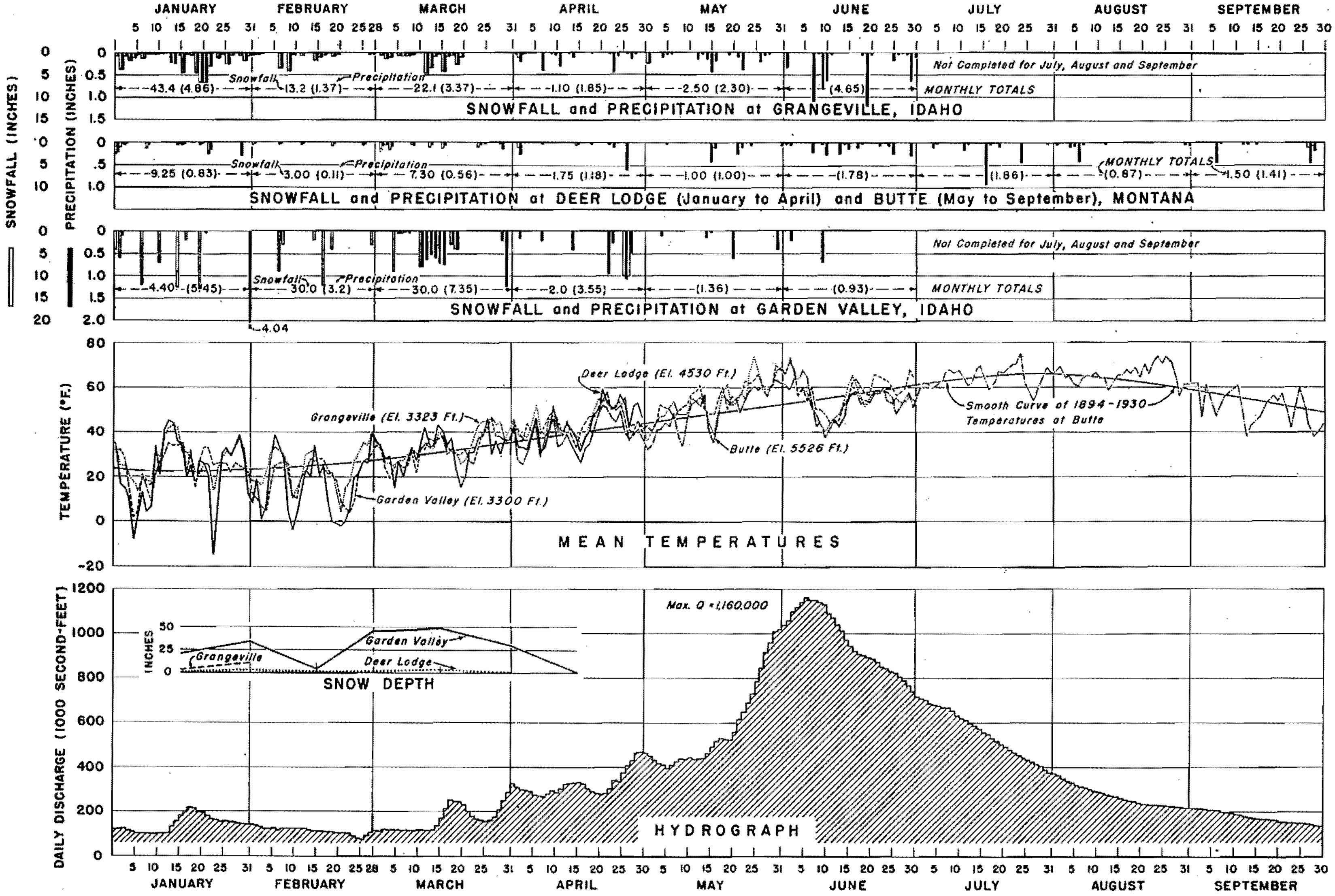
TENTATIVE ESTIMATE OF HIGHEST AND LOWEST POSSIBLE SURFACE-AIR TEMPERATURES DEPARTURE FROM MEAN ANNUAL

(°F)

	Month Area Sq.Mi.	O	N	D	J	F	M	A	M	J	J	A	S
							Maximum						
Week	2,000	19	8	0	-4	0	8	20	30	36	38	36	28
	10,000	18	7	-2	-6	-2	6	18	28	34	36	35	27
	50,000	16	6	-3	-8	-3	5	17	26	33	35	34	26
14 Days	2,000	15	5	-3	-7	-4	4	15	24	31	34	32	24
	10,000	14	4	-4	-8	-5	3	14	23	30	34	32	24
	50,000	14	3	-5	-9	-6	2	13	22	30	33	31	23
Month	2,000	11	1	-6	-10	-8	-1	10	19	26	31	28	21
	10,000	11	1	-6	-10	-8	-1	10	19	26	31	28	21
	50,000	11	1	-6	-10	-8	-1	10	19	26	31	28	21
							Minimum						
Week	2,000	-28	-44	-54	-57	-53	-34	-19	-7	0	3	1	-10
	10,000	-26	-42	-52	-55	-51	-33	-18	-6	2	5	4	- 7
	50,000	-23	-39	-50	-53	-49	-32	-16	-5	3	7	6	- 4
14 Days	2,000	-18	-32	-44	-50	-46	-29	-15	-3	4	8	6	- 4
	10,000	-16	-31	-43	-49	-45	-28	-14	-3	5	10	8	- 2
	50,000	-15	-30	-42	-48	-44	-28	-13	-3	6	11	9	0
Month	2,000	- 7	-21	-34	-43	-40	-24	-10	0	8	14	12	3
	10,000	- 7	-21	-34	-43	-40	-24	-10	0	8	14	12	3
	50,000	- 7	-21	-34	-43	-40	-24	-10	0	8	14	12	3

1894 FLOOD: COLUMBIA RIVER AT THE DALLES, OREGON

HYDROGRAPH AND CONCURRENT METEOROLOGICAL DATA



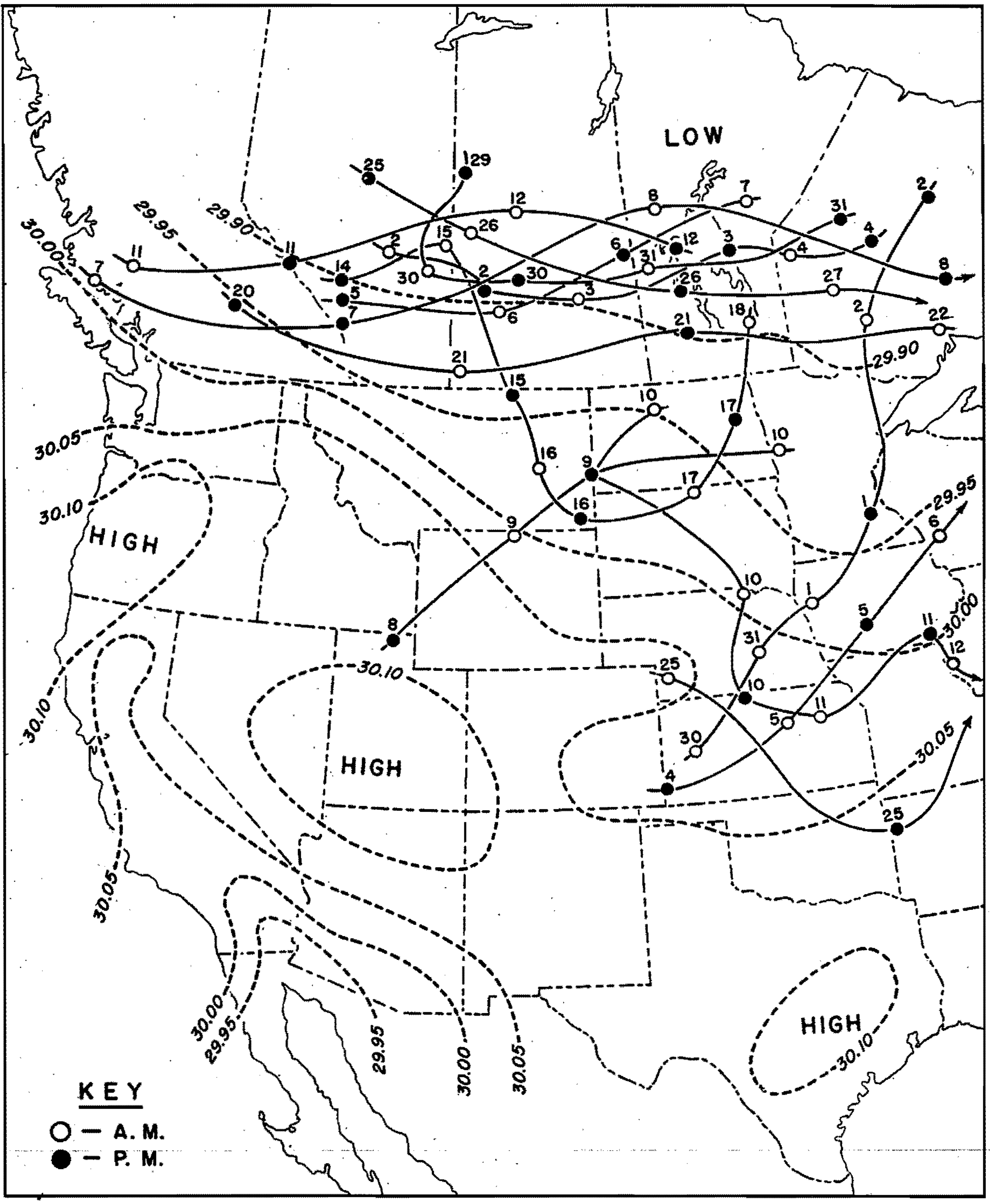
FILE 44119

FIGURE 1

U.S. DEPARTMENT OF COMMERCE WEATHER BUREAU HYDROMETEOROLOGICAL SECTION

MEAN PRESSURE PATTERN AND TRACKS OF LOW PRESSURE CENTERS

October 1893



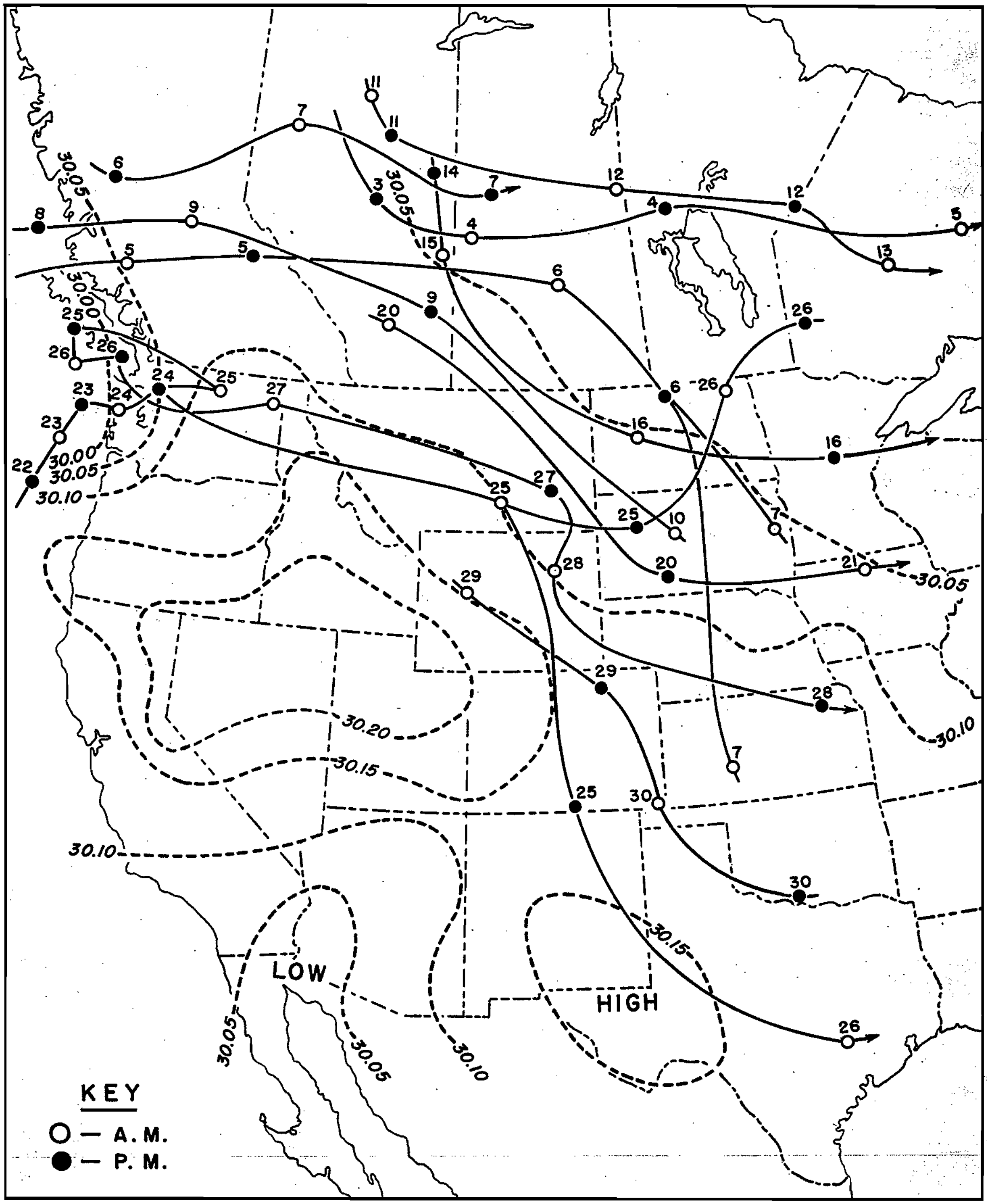
FILE 44121-10

FIGURE 2

U.S. DEPARTMENT OF COMMERCE WEATHER BUREAU HYDROMETEOROLOGICAL SECTION

MEAN PRESSURE PATTERN AND TRACKS OF LOW PRESSURE CENTERS

November 1893



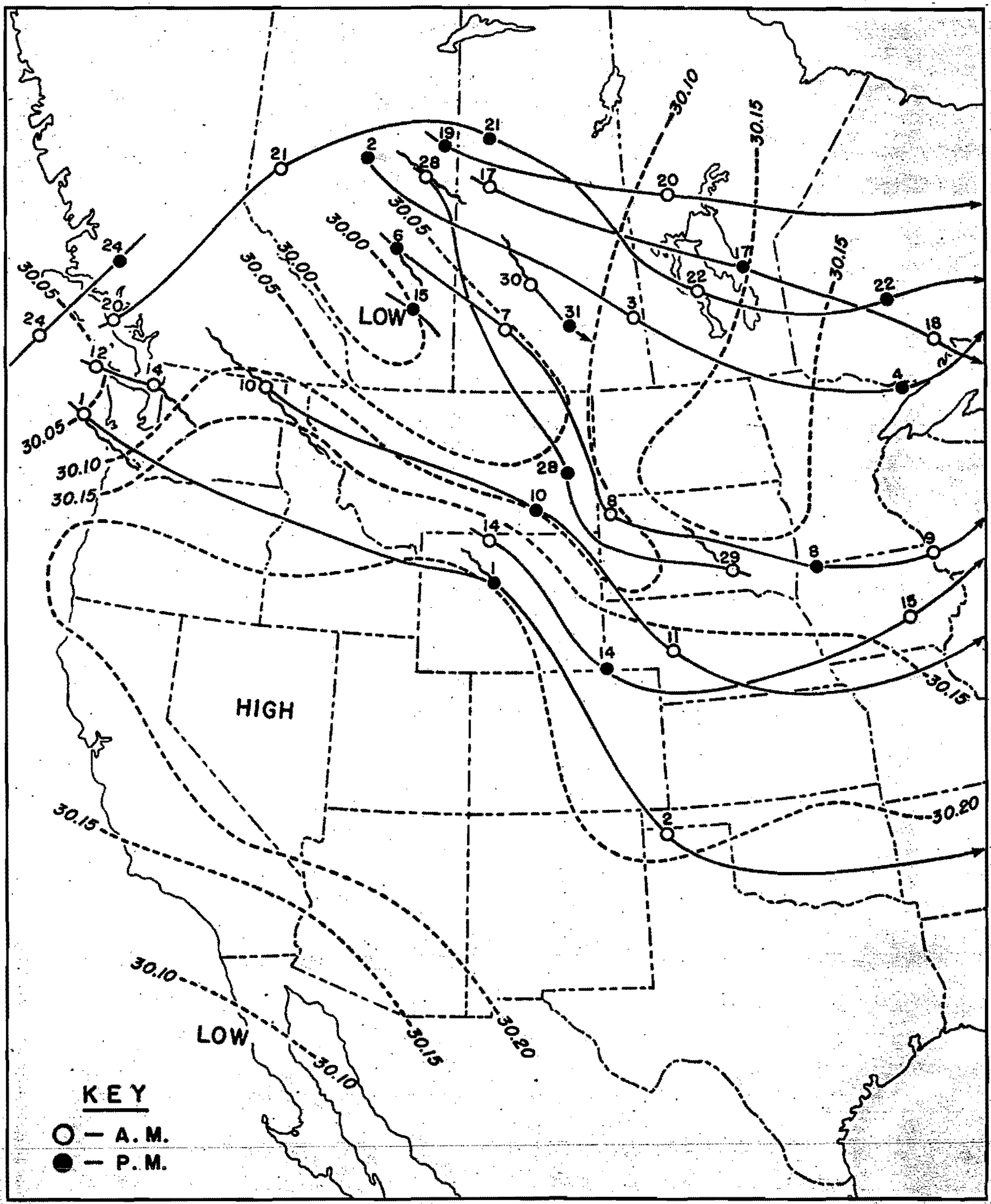
FILE 44121-11

FIGURE 3

U.S. DEPARTMENT OF COMMERCE WEATHER BUREAU HYDROMETEOROLOGICAL SECTION

MEAN PRESSURE PATTERN AND TRACKS OF LOW PRESSURE CENTERS

December 1893

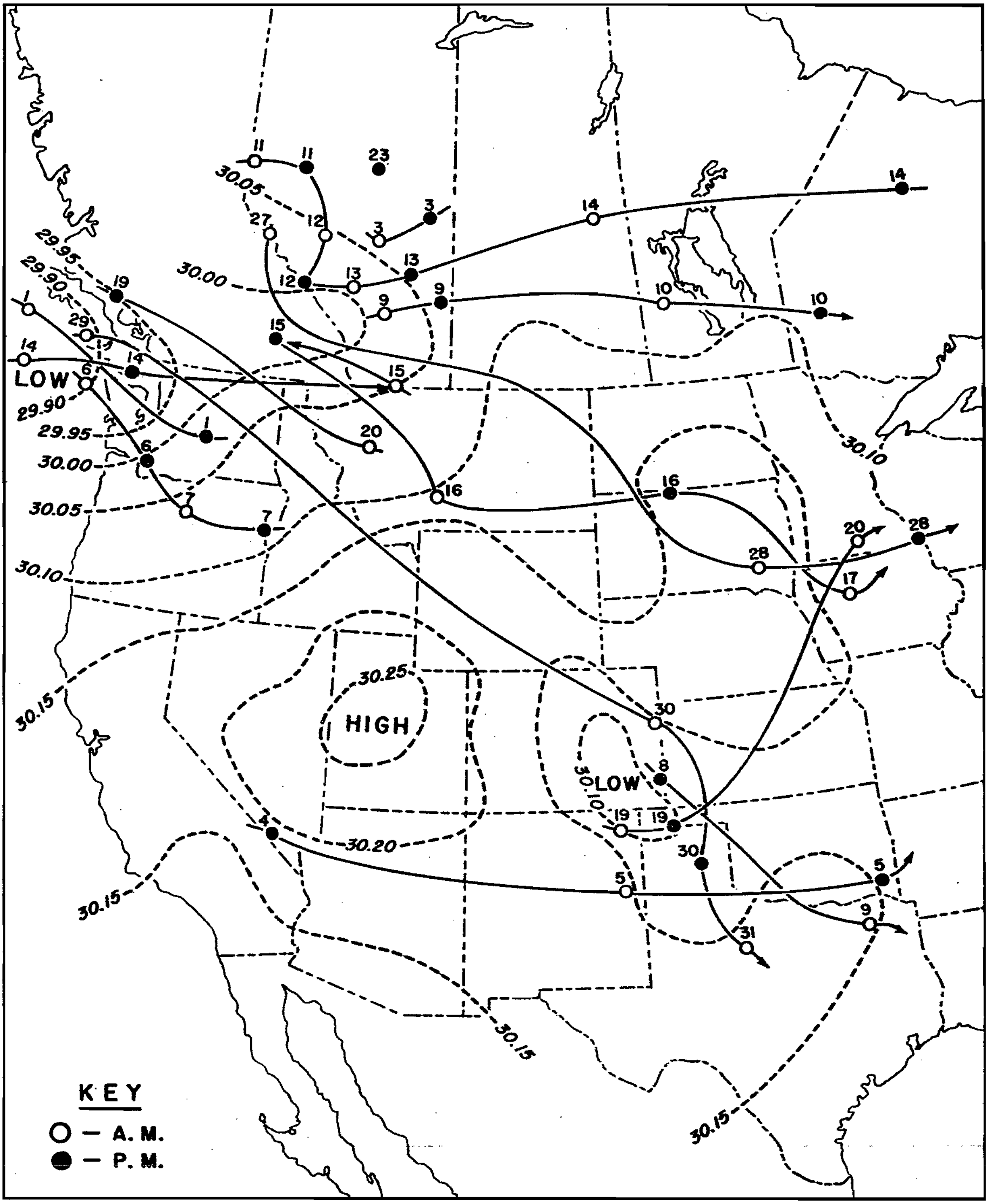


FILE 44121-12

FIGURE 4

MEAN PRESSURE PATTERN AND TRACKS OF LOW PRESSURE CENTERS

January 1894



MEAN PRESSURE PATTERN AND TRACKS OF LOW PRESSURE CENTERS

February 1894

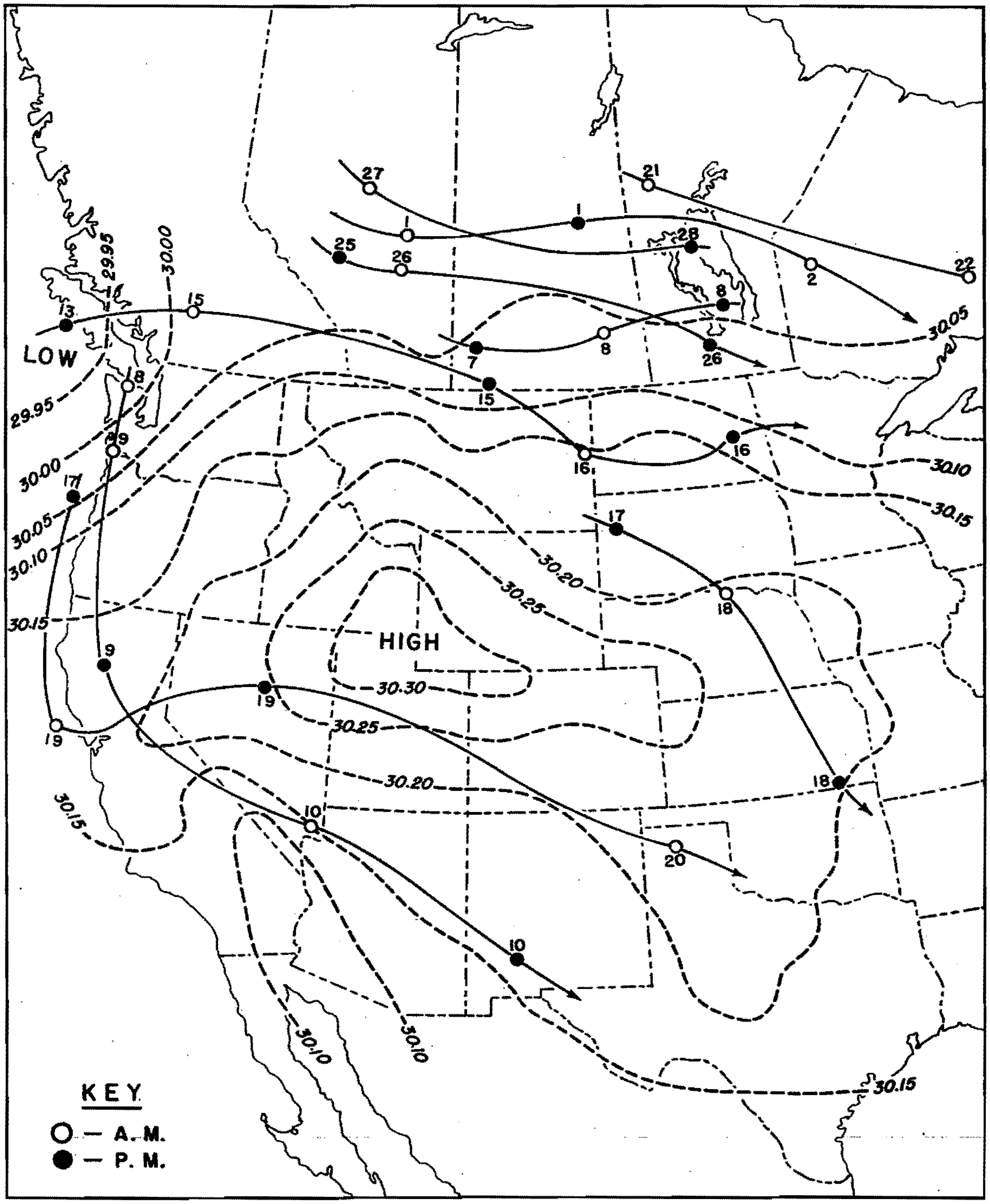


FIGURE 6

MEAN PRESSURE PATTERN AND TRACKS OF LOW PRESSURE CENTERS

March 1894

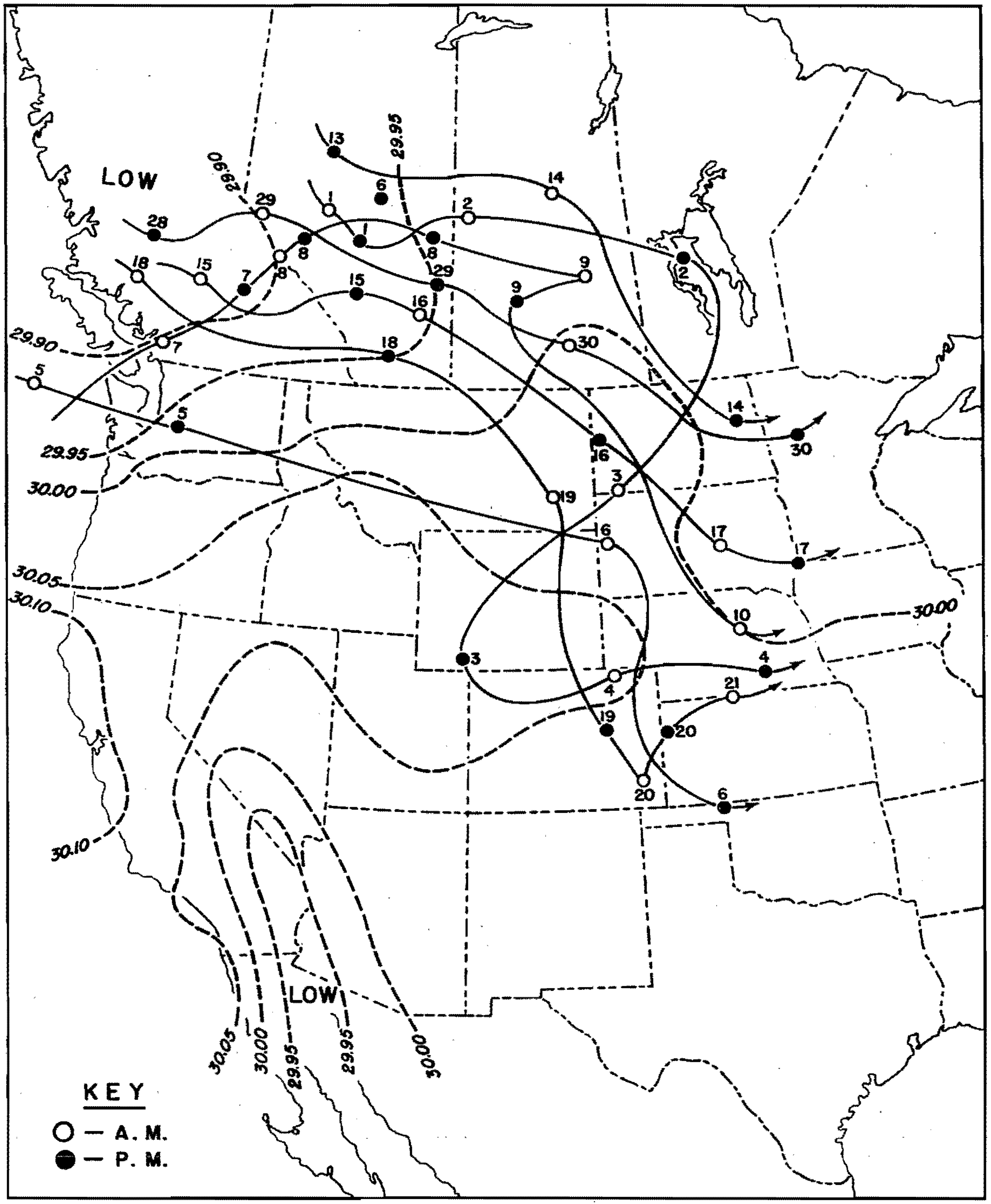


FIGURE 7

MEAN PRESSURE PATTERN AND TRACKS OF LOW PRESSURE CENTERS

April 1894

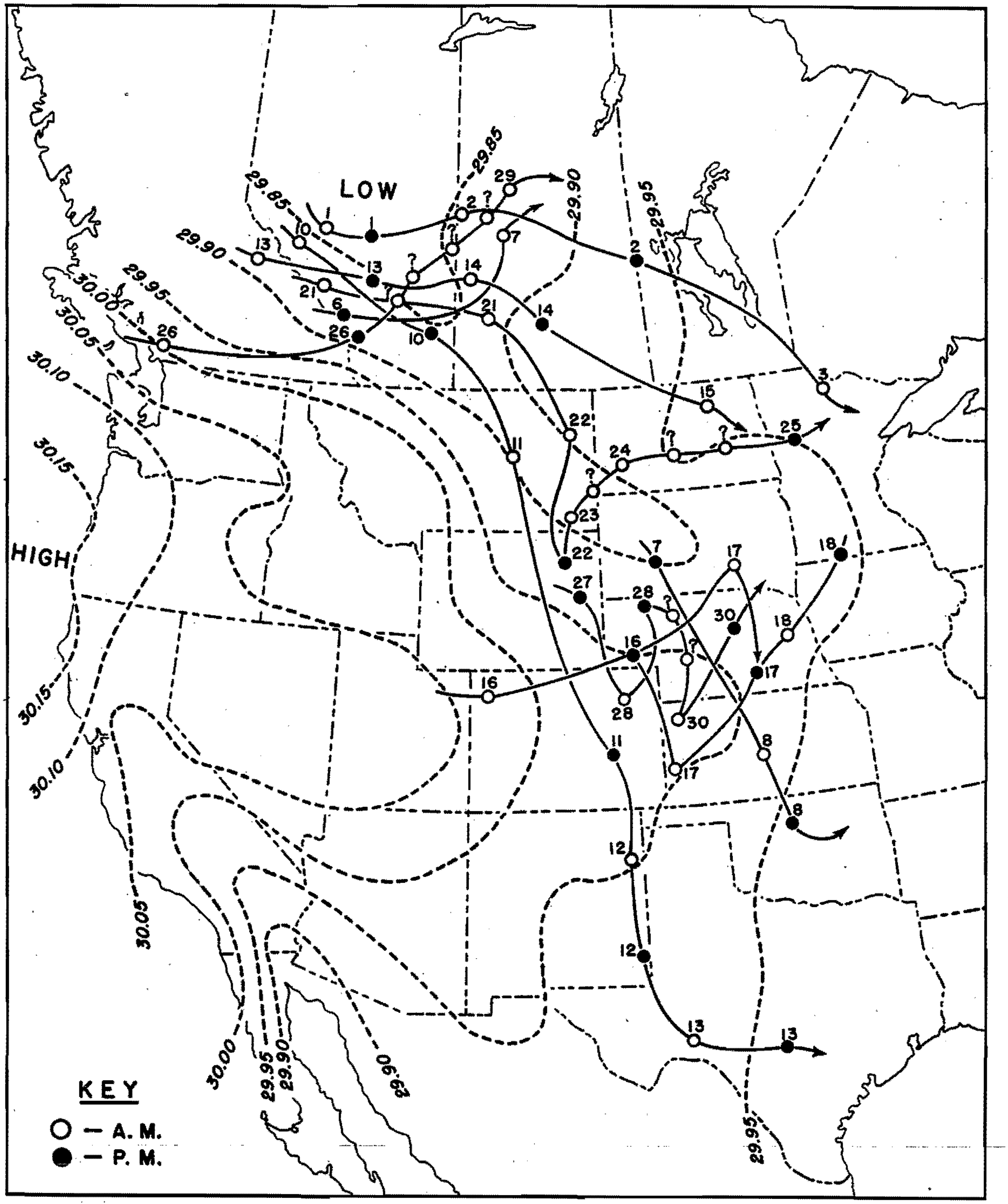


FIGURE 8

MEAN PRESSURE PATTERN AND TRACKS OF LOW PRESSURE CENTERS

May 1894

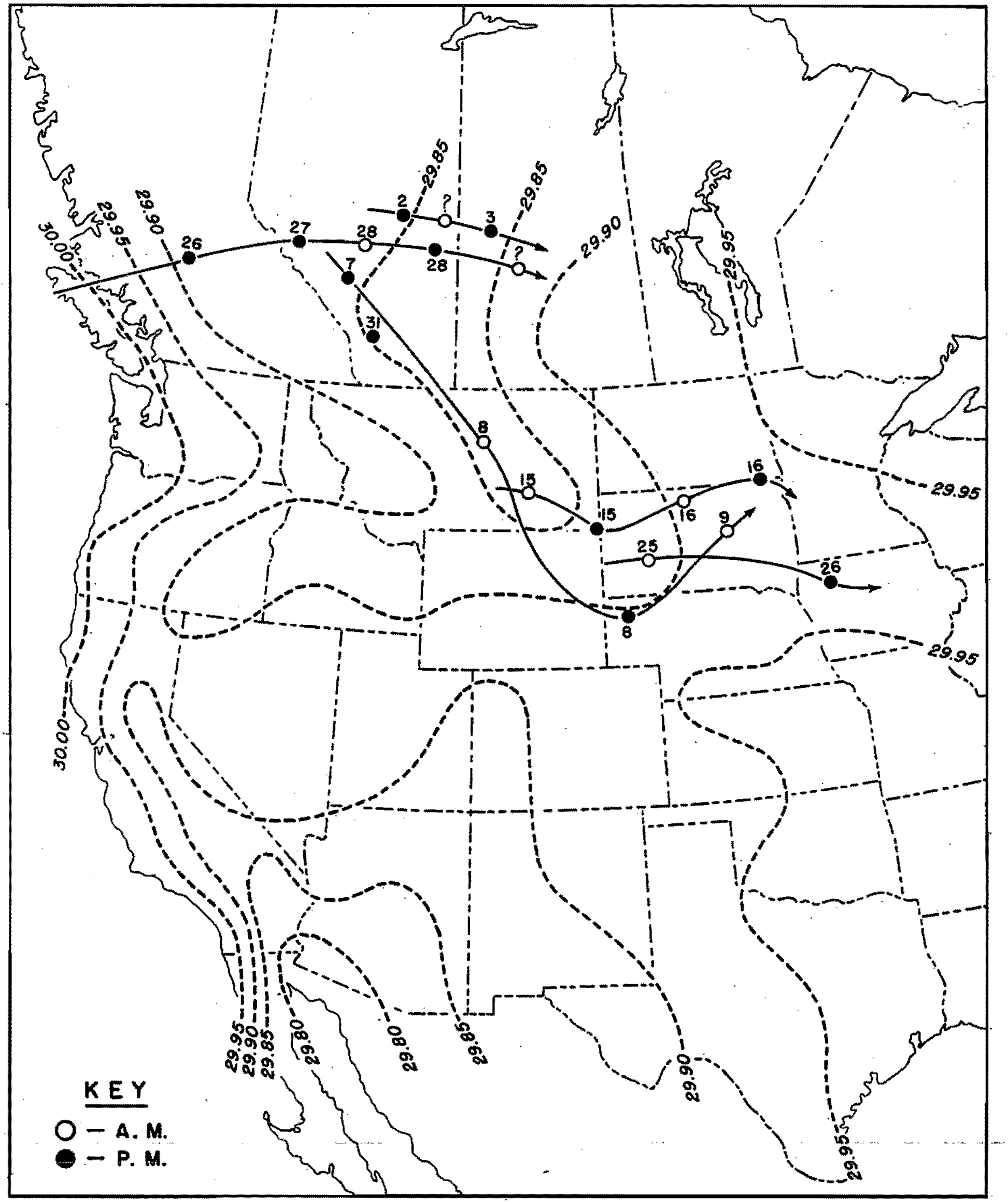


FIGURE 9

MEAN PRESSURE PATTERN AND TRACKS OF LOW PRESSURE CENTERS

June 1894

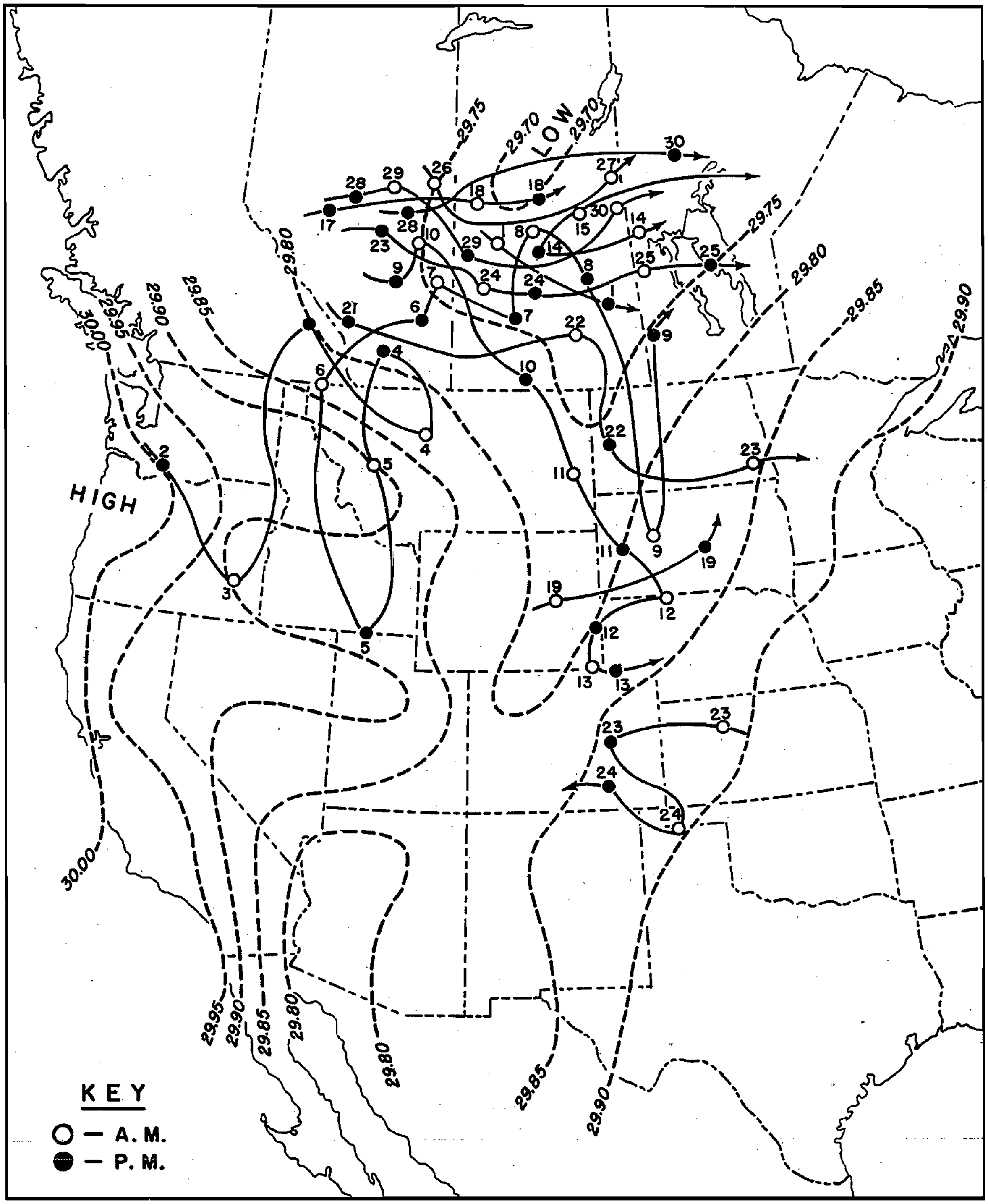


FIGURE 10

DEPARTURES FROM NORMAL PRESSURES (INCHES)
October 1893

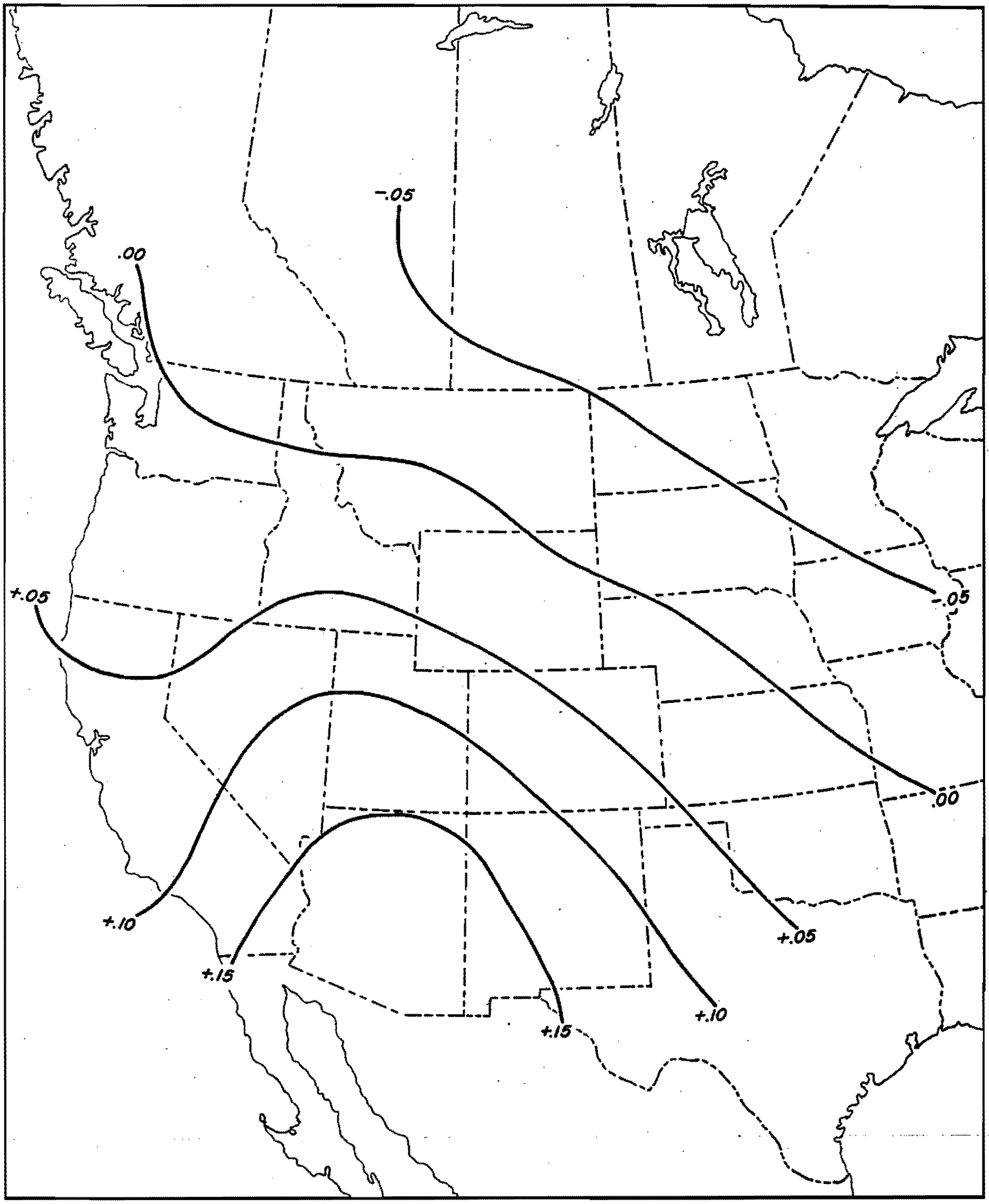


FIGURE 11

DEPARTURES FROM NORMAL PRESSURES (INCHES)

November 1893

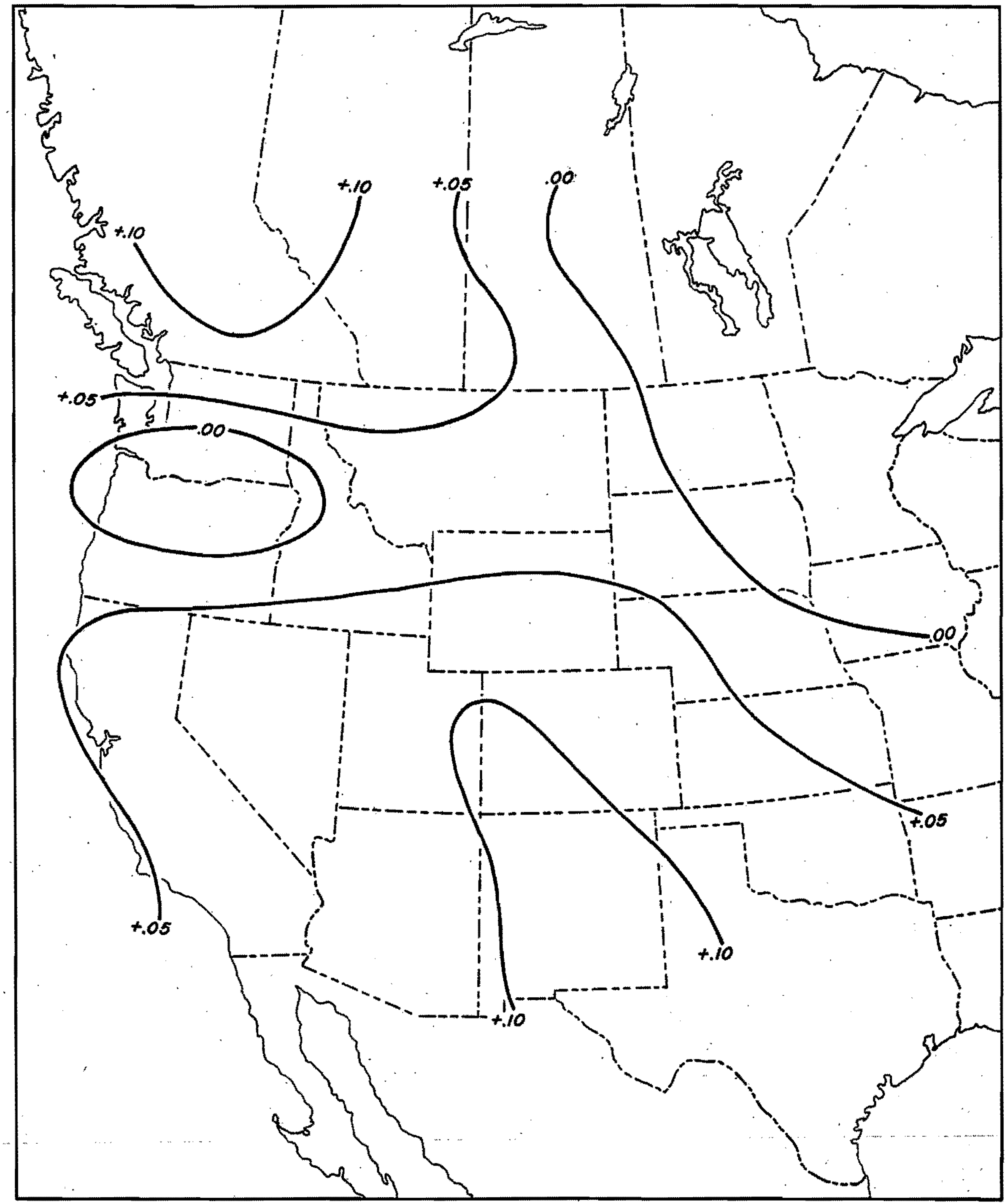


FIGURE 12

DEPARTURES FROM NORMAL PRESSURES (INCHES)

December 1893

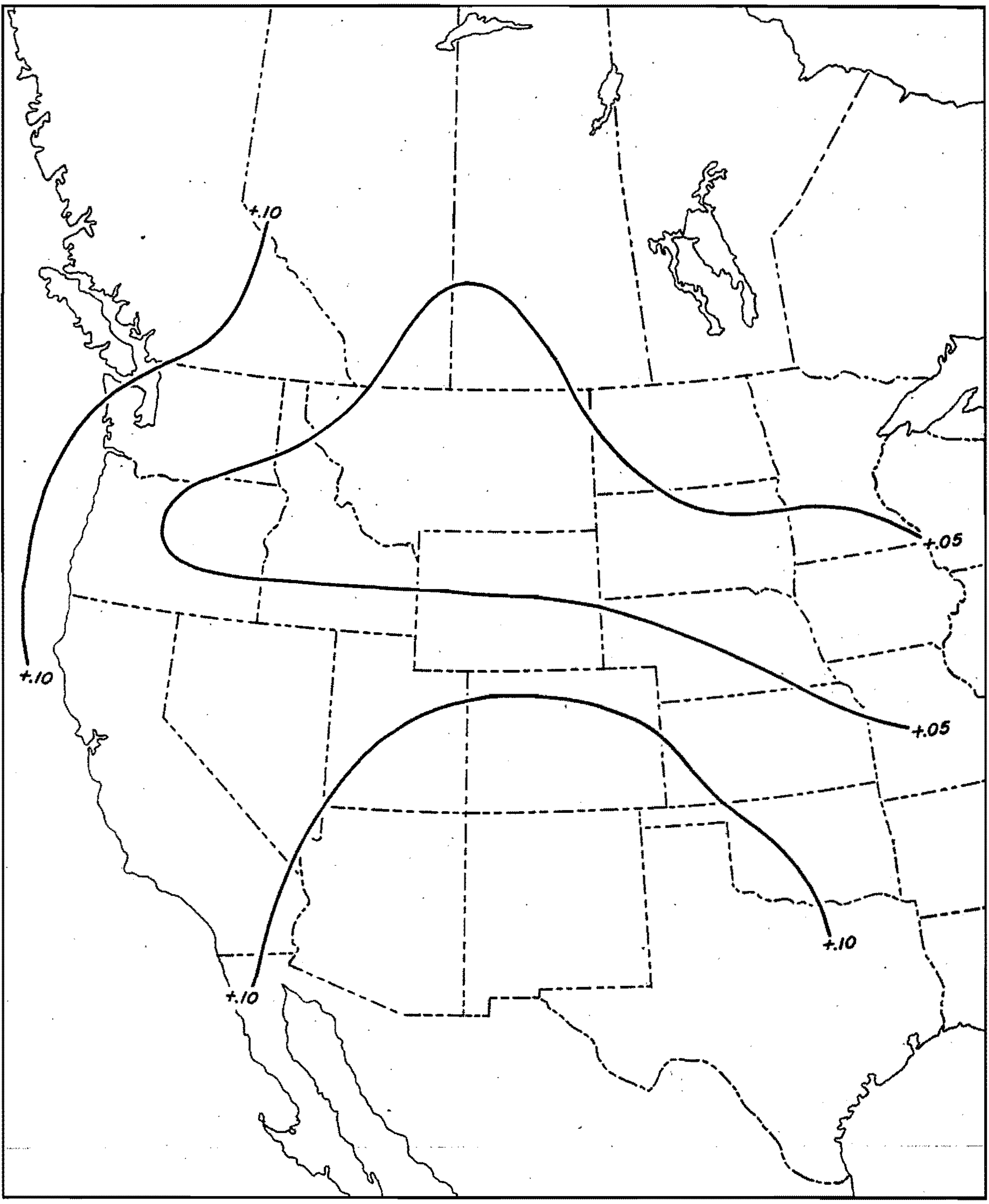


FIGURE 13

DEPARTURES FROM NORMAL PRESSURES (INCHES)

January 1894

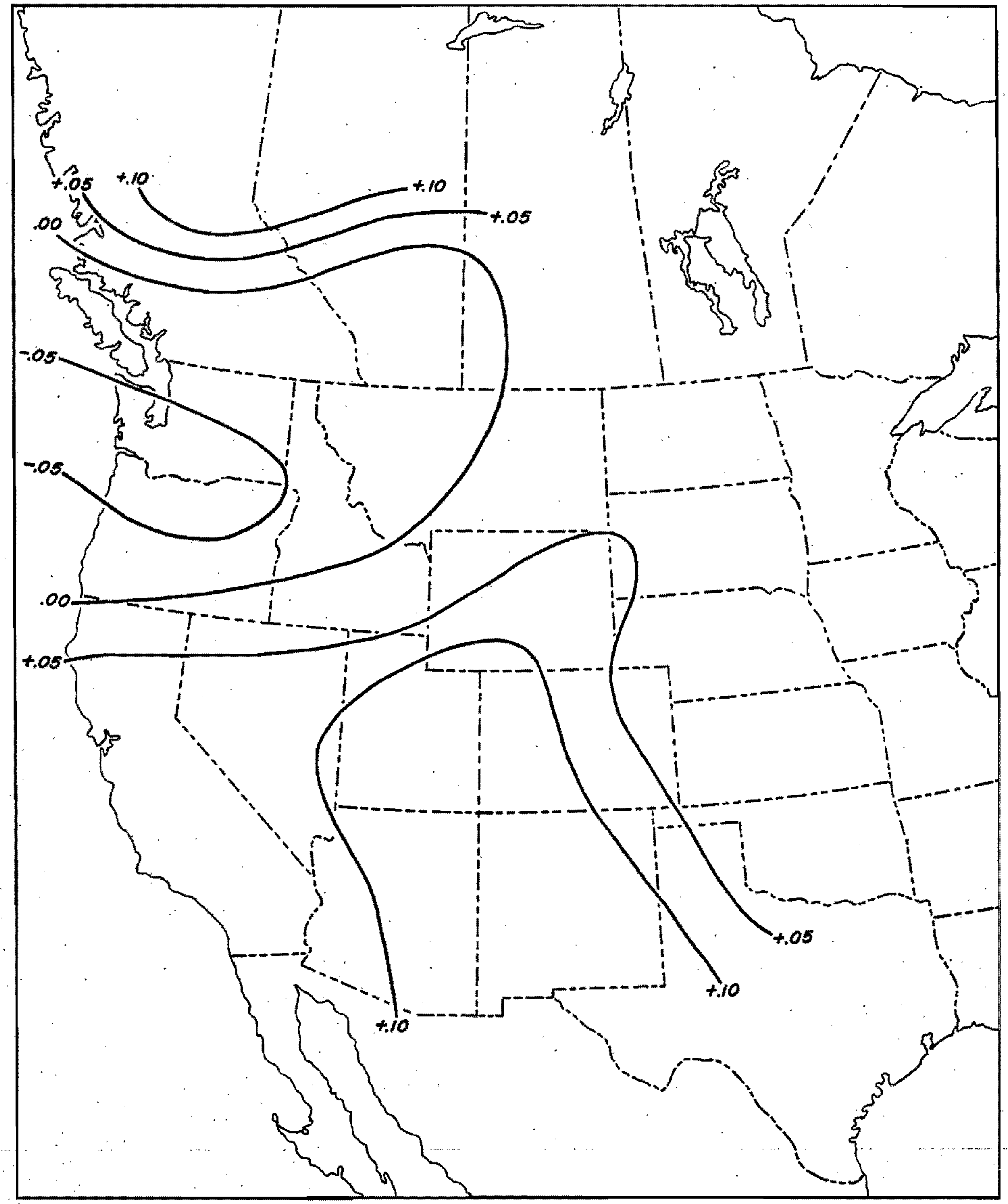
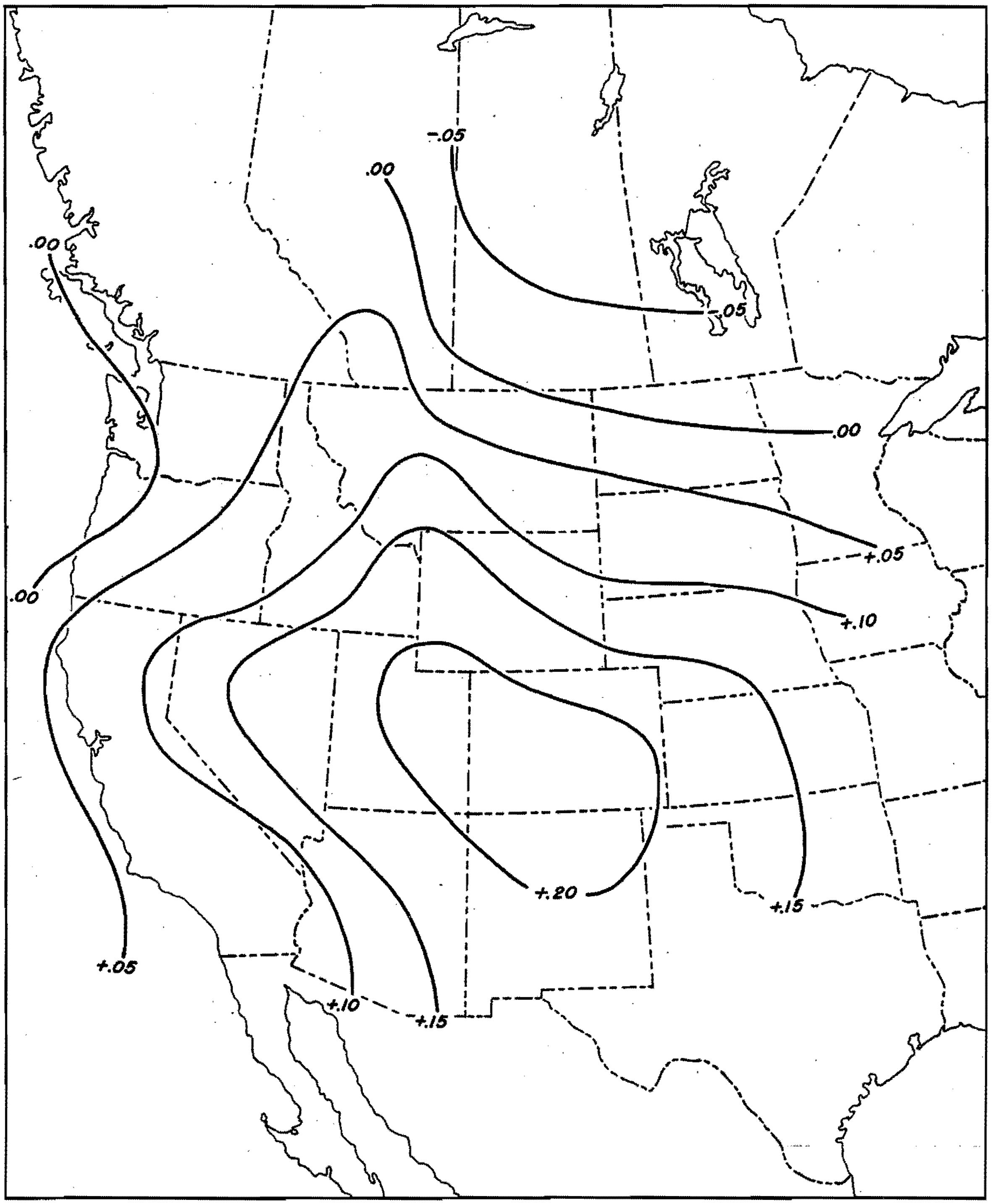


FIGURE 14

DEPARTURES FROM NORMAL PRESSURES (INCHES)

February 1894

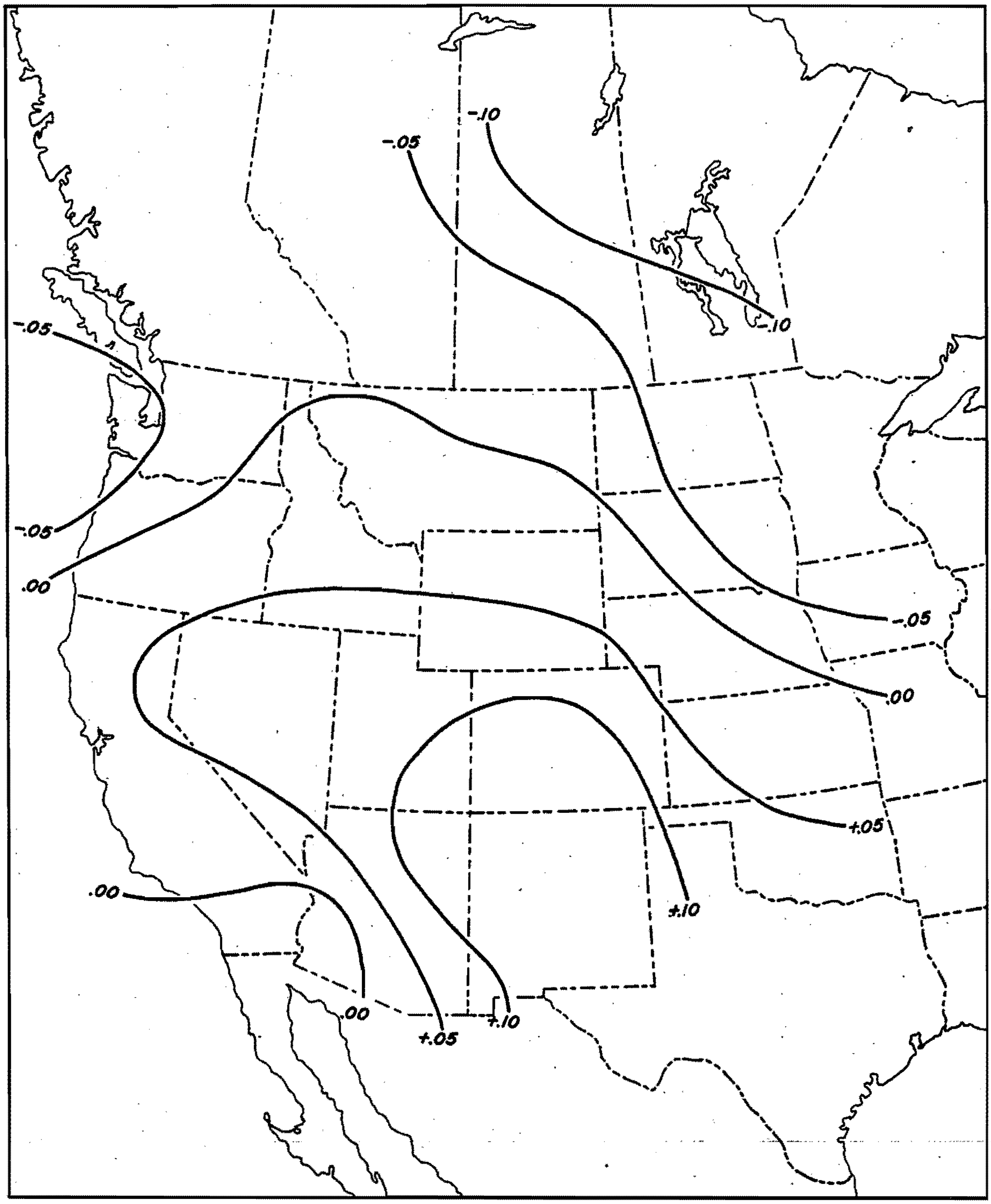


FILE 44121-5

FIGURE 15

DEPARTURES FROM NORMAL PRESSURES (INCHES)

March 1894

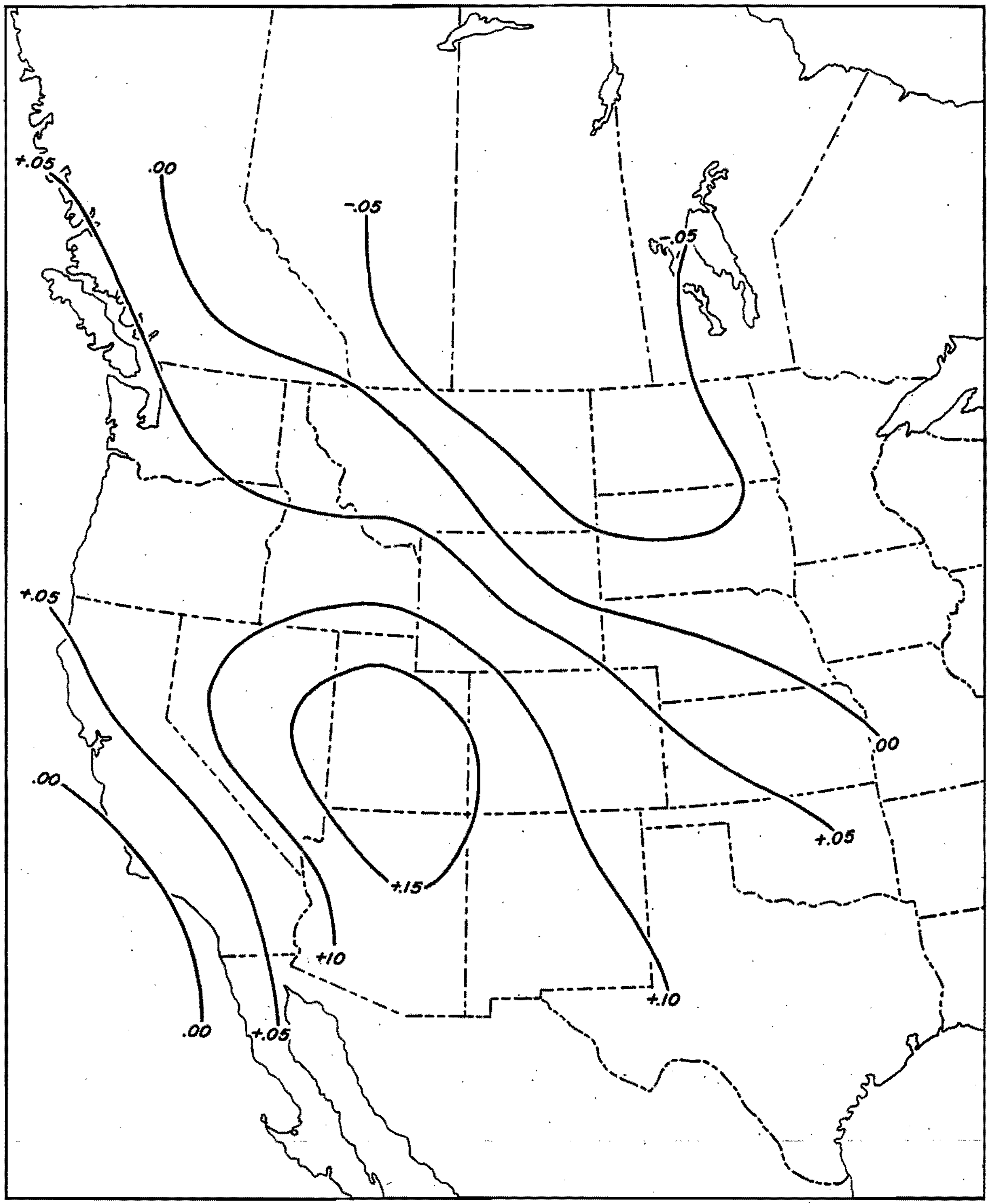


FILE 44121-6

FIGURE 16

DEPARTURES FROM NORMAL PRESSURES (INCHES)

April 1894



DEPARTURES FROM NORMAL PRESSURES (INCHES)

May 1894

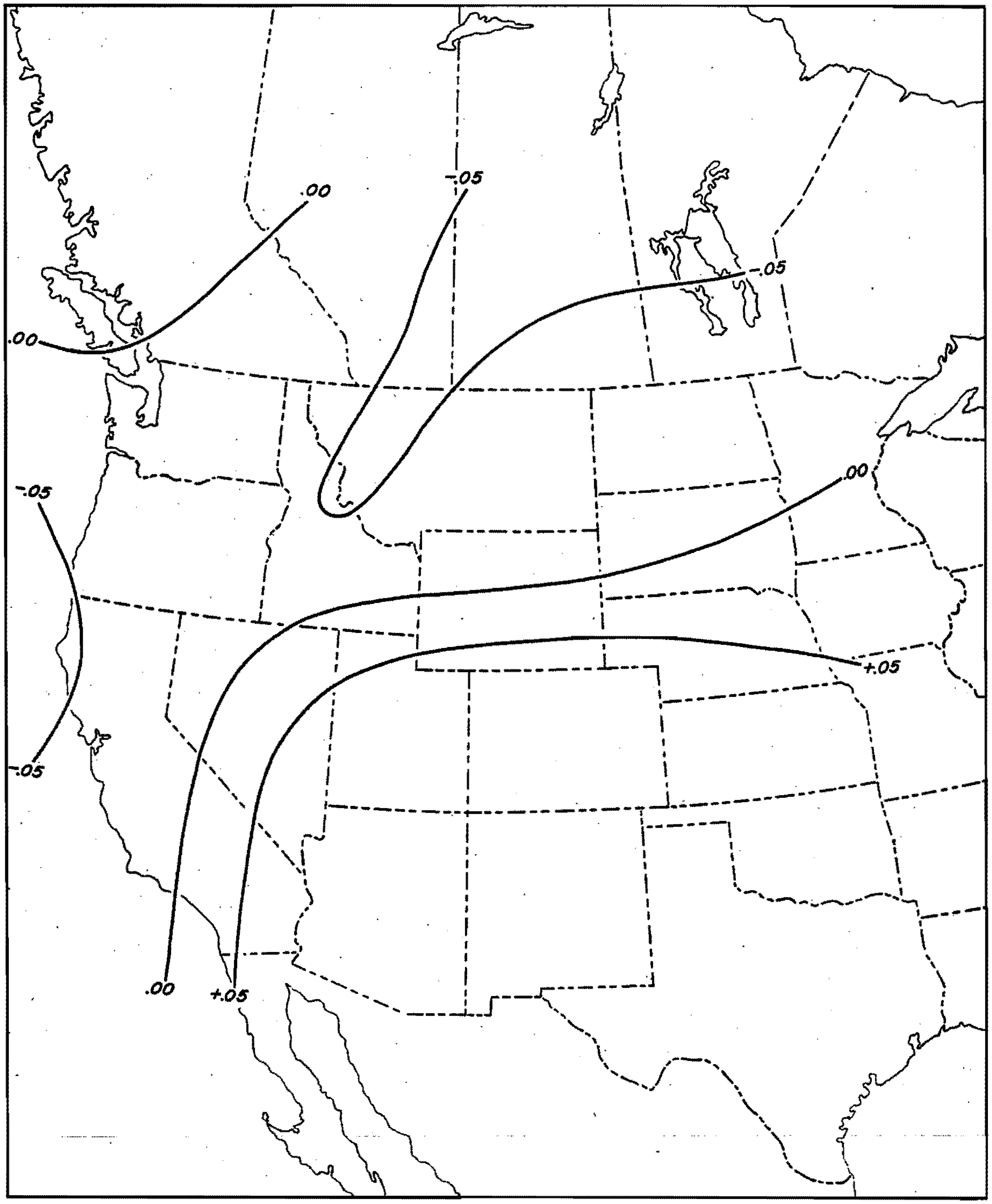
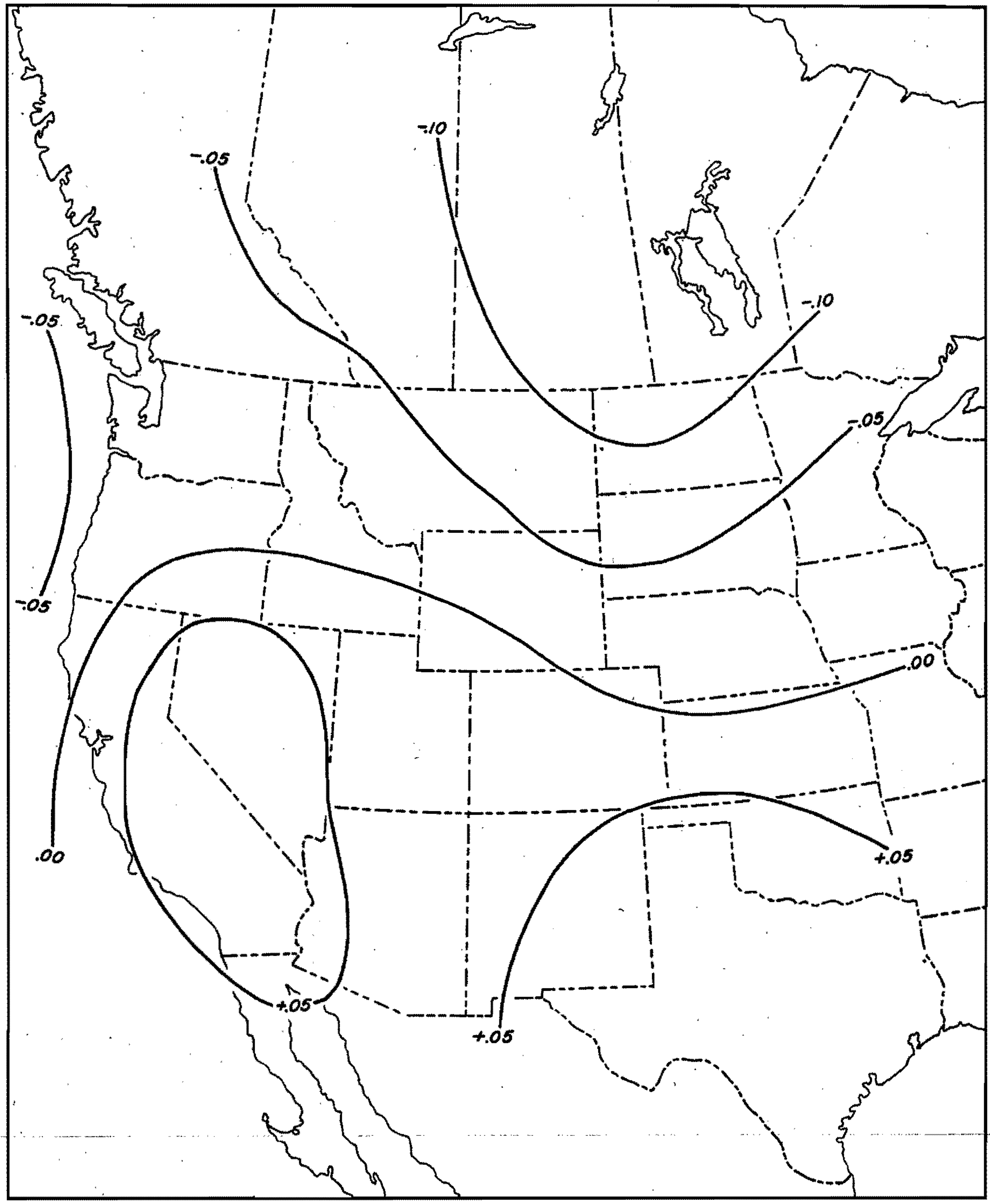


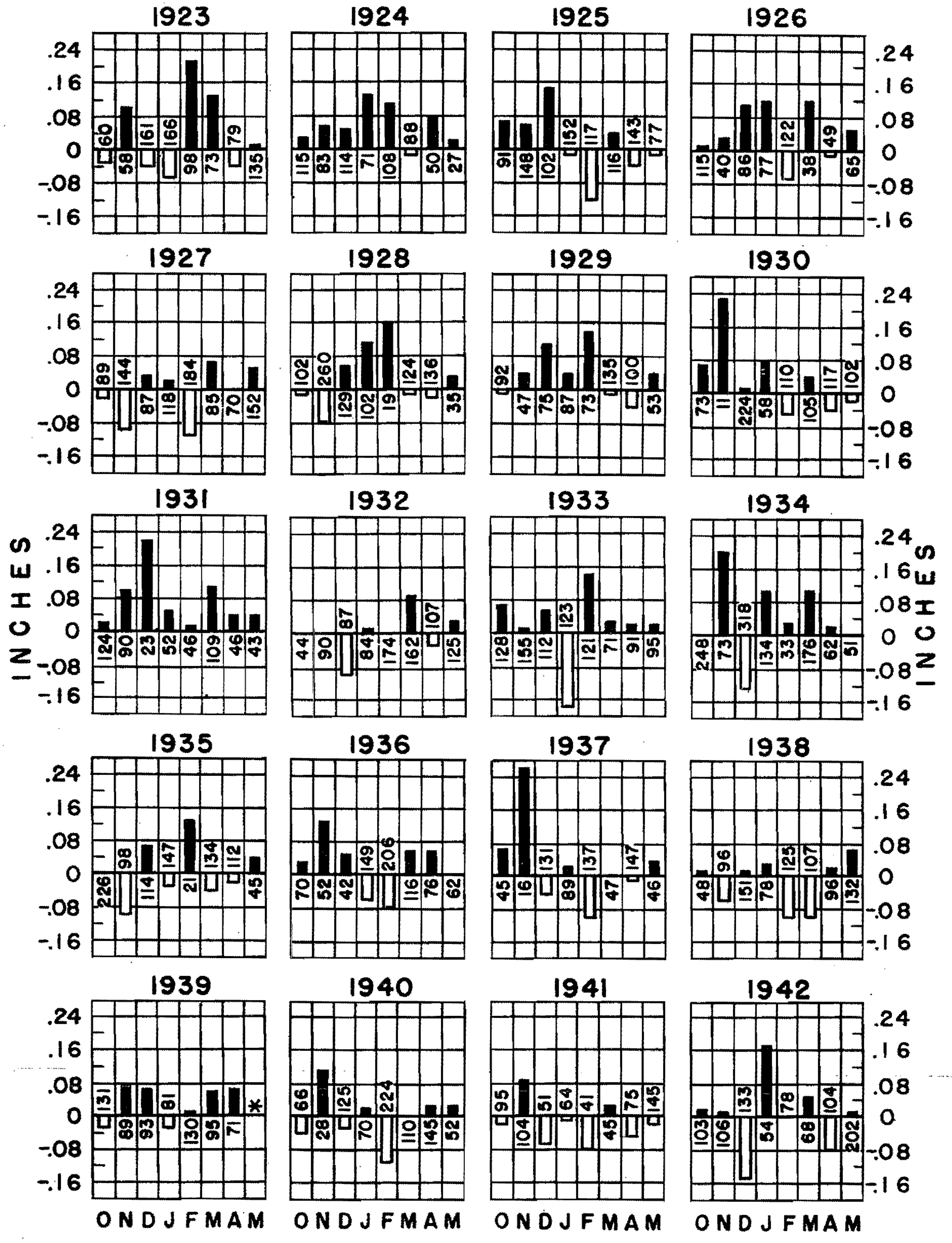
FIGURE 18

DEPARTURES FROM NORMAL PRESSURES (INCHES)
June 1894



U.S. DEPARTMENT OF COMMERCE   WEATHER BUREAU   HYDROMETEOROLOGICAL SECTION

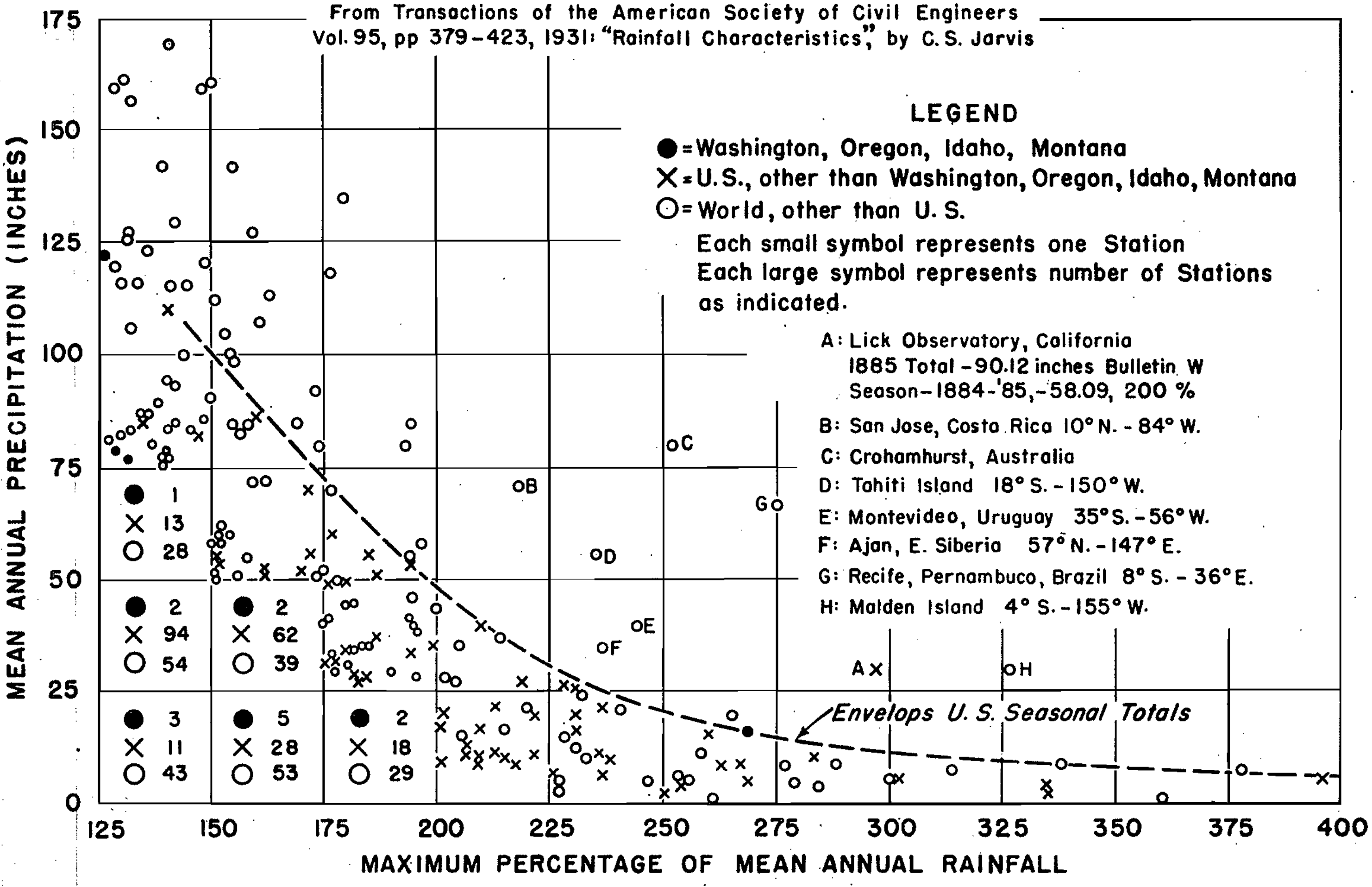
MONTHLY MEAN PRESSURE DEPARTURE FROM NORMAL
WASHINGTON, OREGON, IDAHO AND WESTERN MONTANA
(WATER YEARS)



NOTE: Figures show per cent of normal monthly precipitation for Montana west of the Continental Divide.   * Incomplete data

FILE 44131   FIGURE 20

MAXIMUM RECORDED ANNUAL PRECIPITATION AT WORLD-WIDE STATIONS IN PERCENT OF MEAN ANNUAL PRECIPITATION, AS A FUNCTION OF MEAN ANNUAL PRECIPITATION


From Transactions of the American Society of Civil Engineers
Vol. 95, pp 379-423, 1931: "Rainfall Characteristics," by C. S. Jarvis

MAXIMUM AND NORMAL RECORDED ANNUAL PRECIPITATION BY SECTIONS

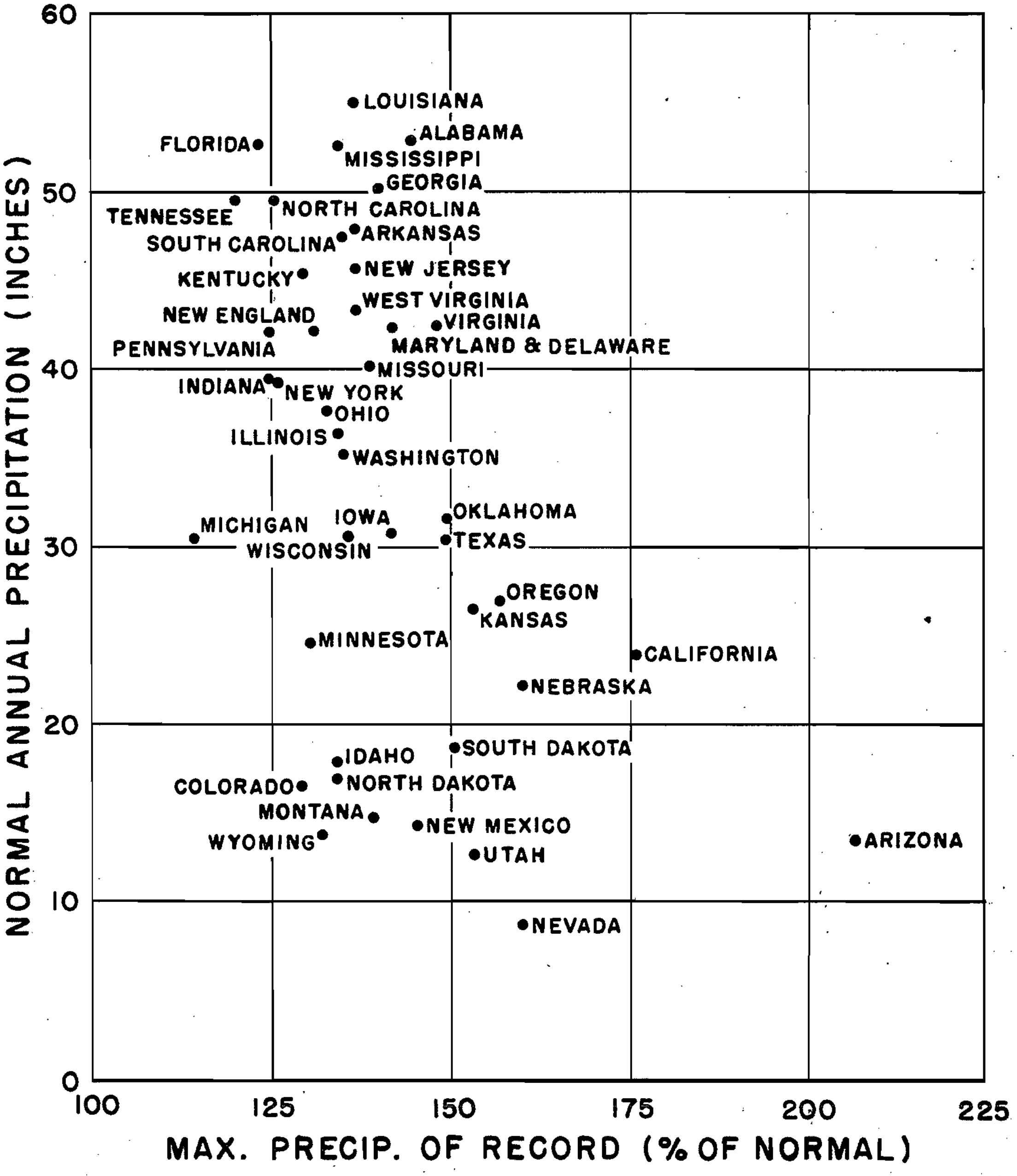


FIGURE 22

MAXIMUM OBSERVED MONTHLY PRECIPITATION IN PERCENT OF MEAN ANNUAL

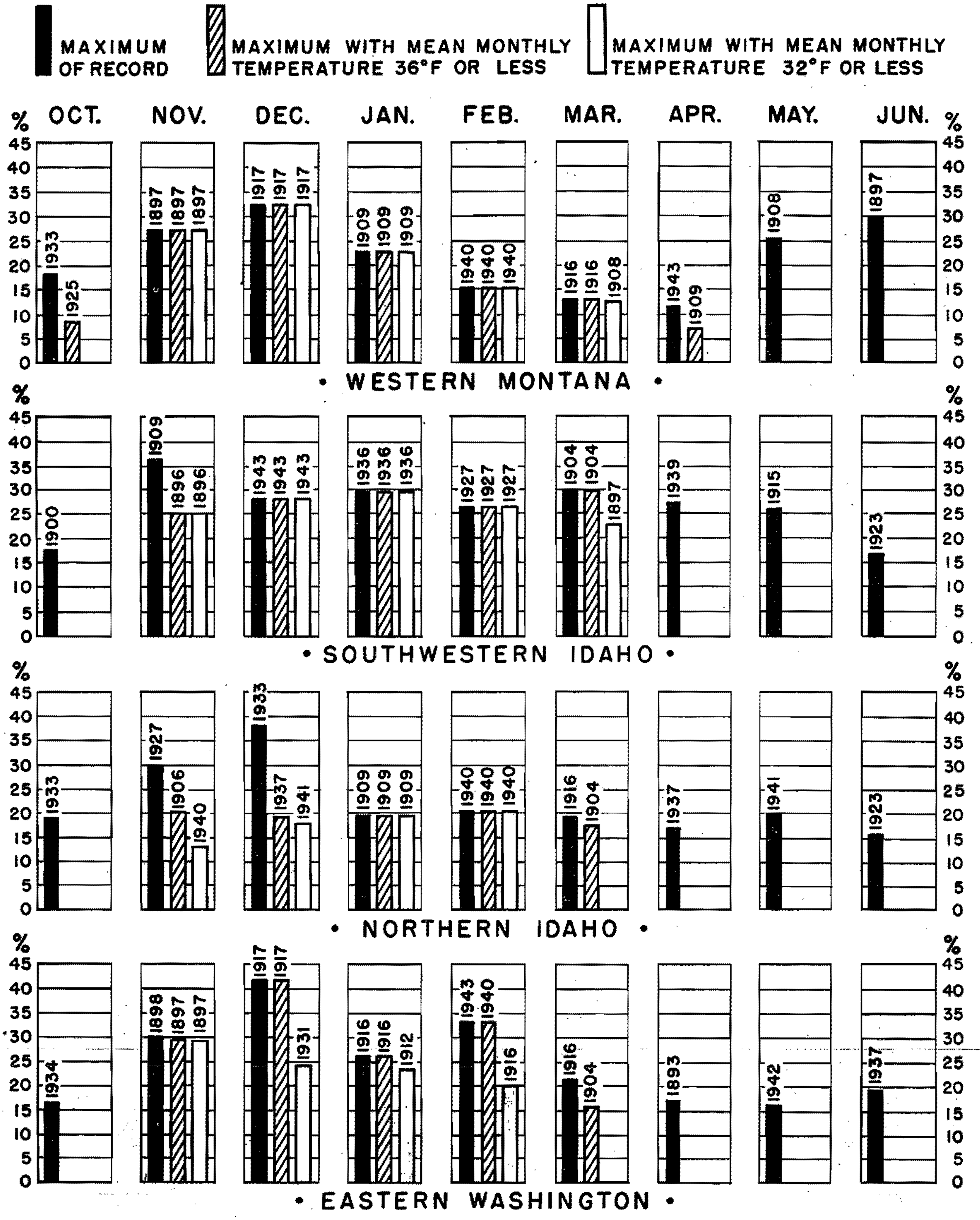


FIGURE 23

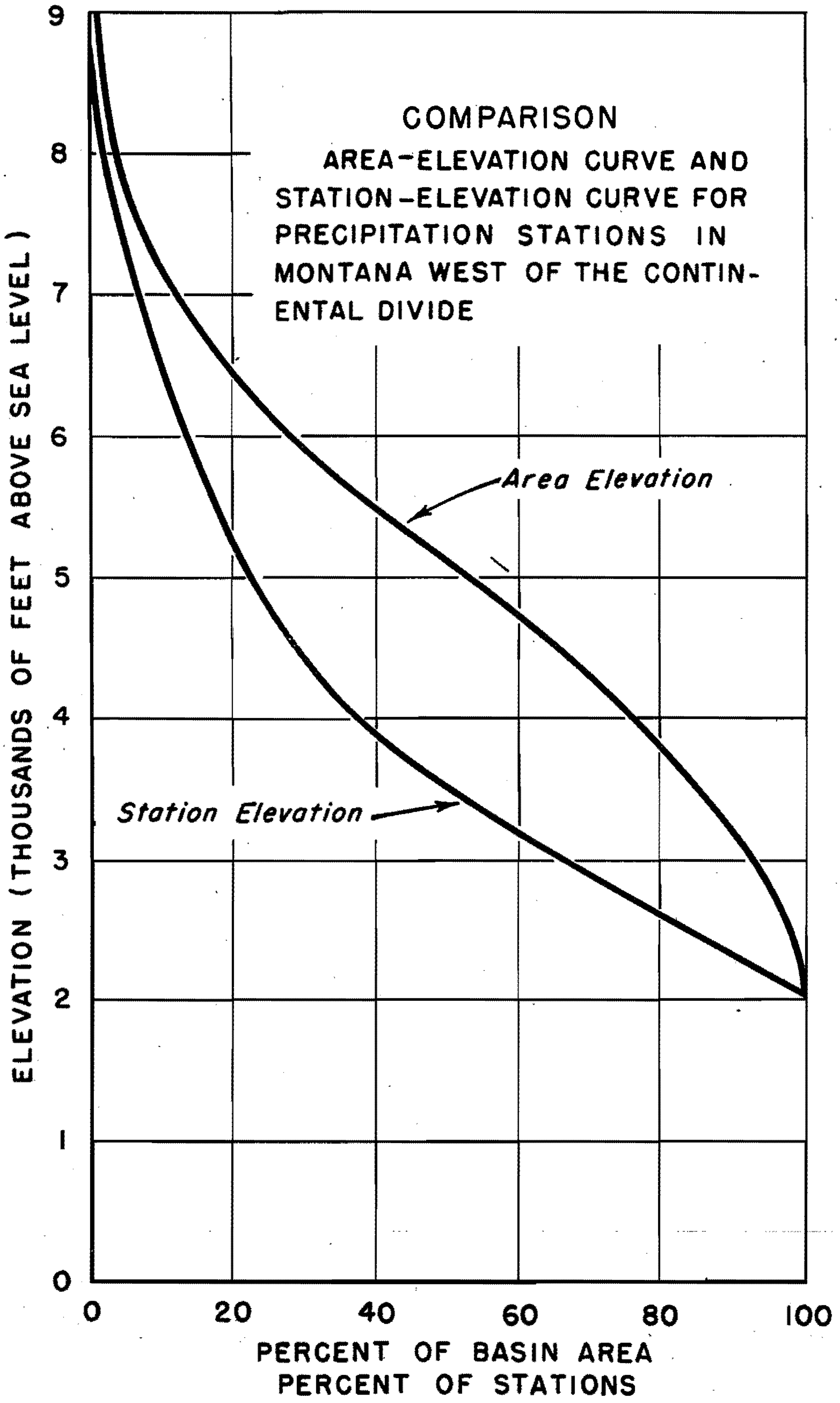
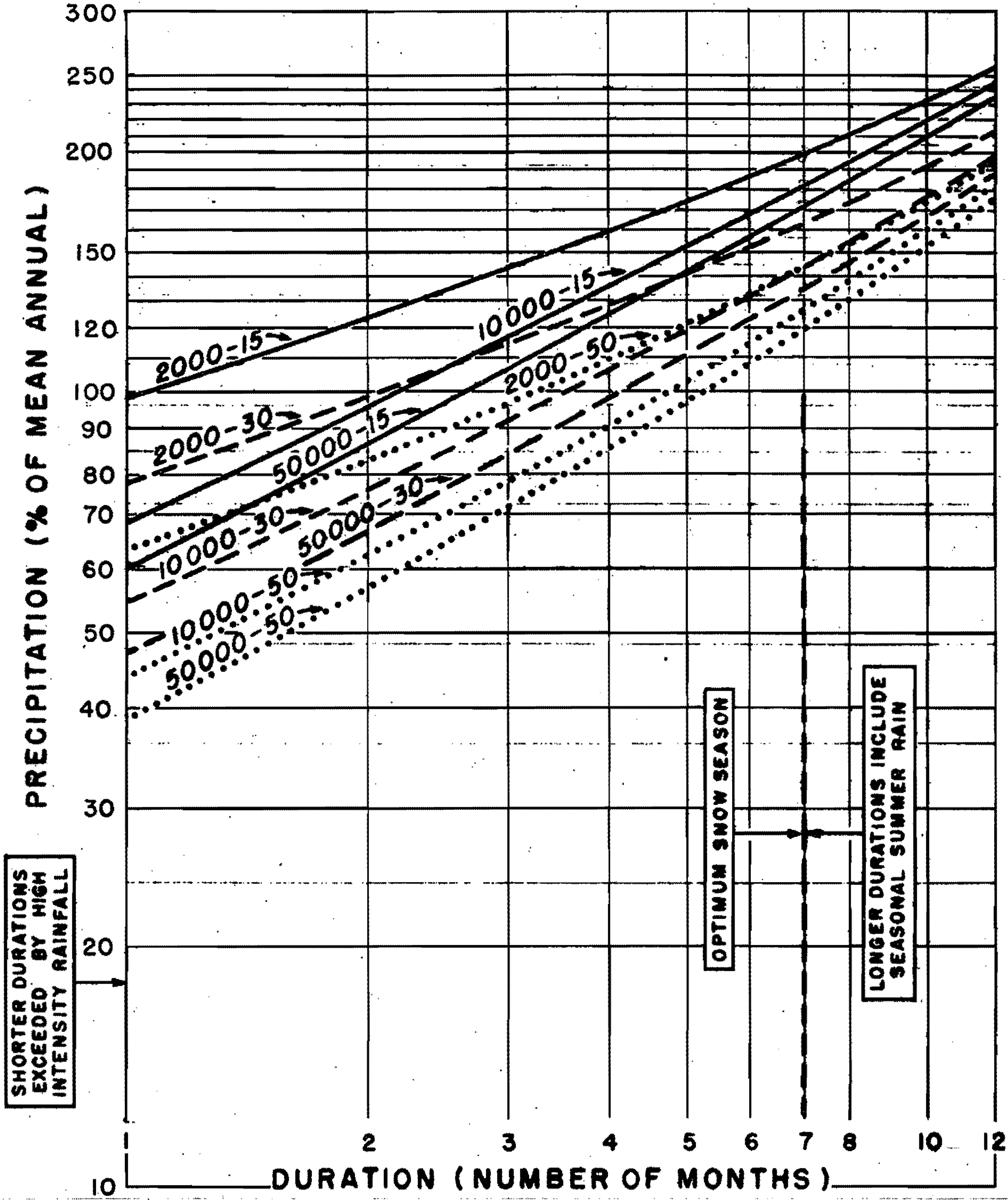

COMPARISON
AREA-ELEVATION CURVE AND STATION-ELEVATION CURVE FOR PRECIPITATION STATIONS IN MONTANA WEST OF THE CONTINENTAL DIVIDE
Area Elevation
Station Elevation
ELEVATION (THOUSANDS OF FEET ABOVE SEA LEVEL)
0
1
2
3
4
5
6
7
8
9
0
20
40
60
80
100
PERCENT OF BASIN AREA
PERCENT OF STATIONS

FIGURE 24

COLUMBIA BASIN
TENTATIVE ESTIMATE OF PRECIPITATION



Maximum Possible Precipitation over Areas of 2000, 10000 and 50000 Square Miles for Zones having Mean Annual Precipitation of 15, 30 and 50 Inches.

COLUMBIA BASIN

SYNTHETIC SEASON OF MAXIMUM POSSIBLE PRECIPITATION AND MELTING TEMPERATURE

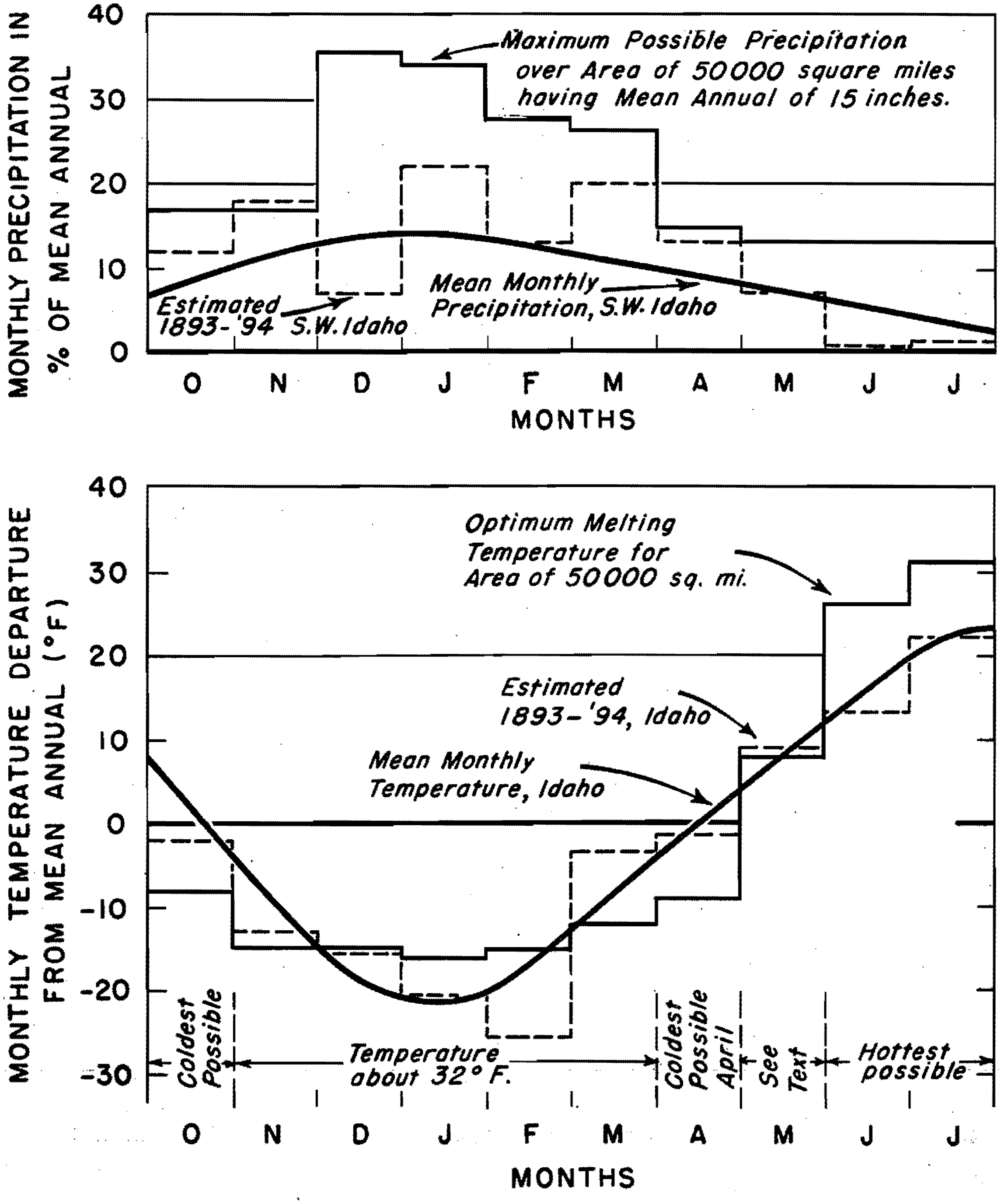
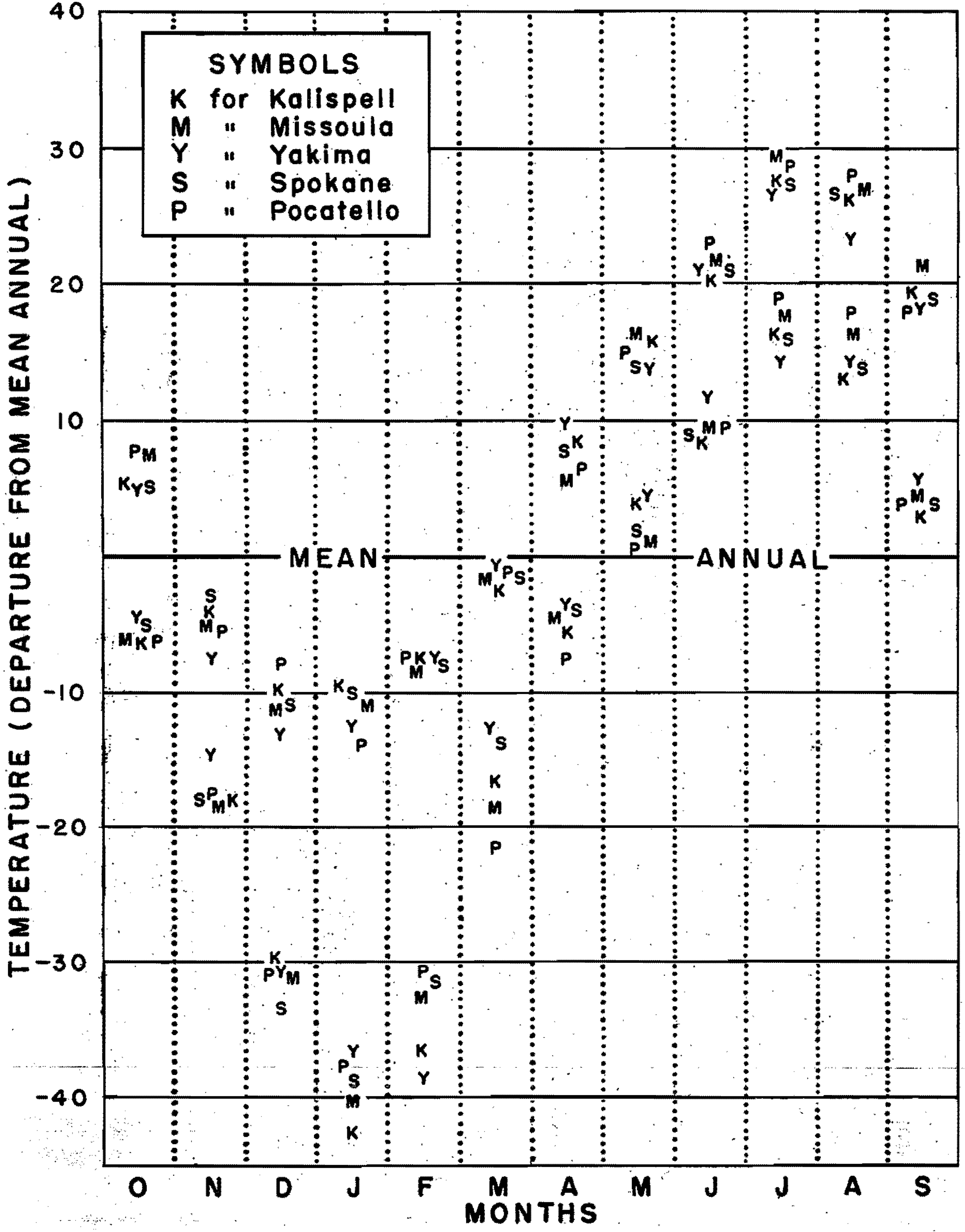


FIGURE 26

RECORD MAXIMUM AND MINIMUM MONTHLY MEAN TEMPERATURES FOR SELECTED STATIONS



FILE 44120

FIGURE 27

COLUMBIA BASIN

TENTATIVE ESTIMATE OF HIGHEST AND LOWEST POSSIBLE SURFACE AIR TEMPERATURES

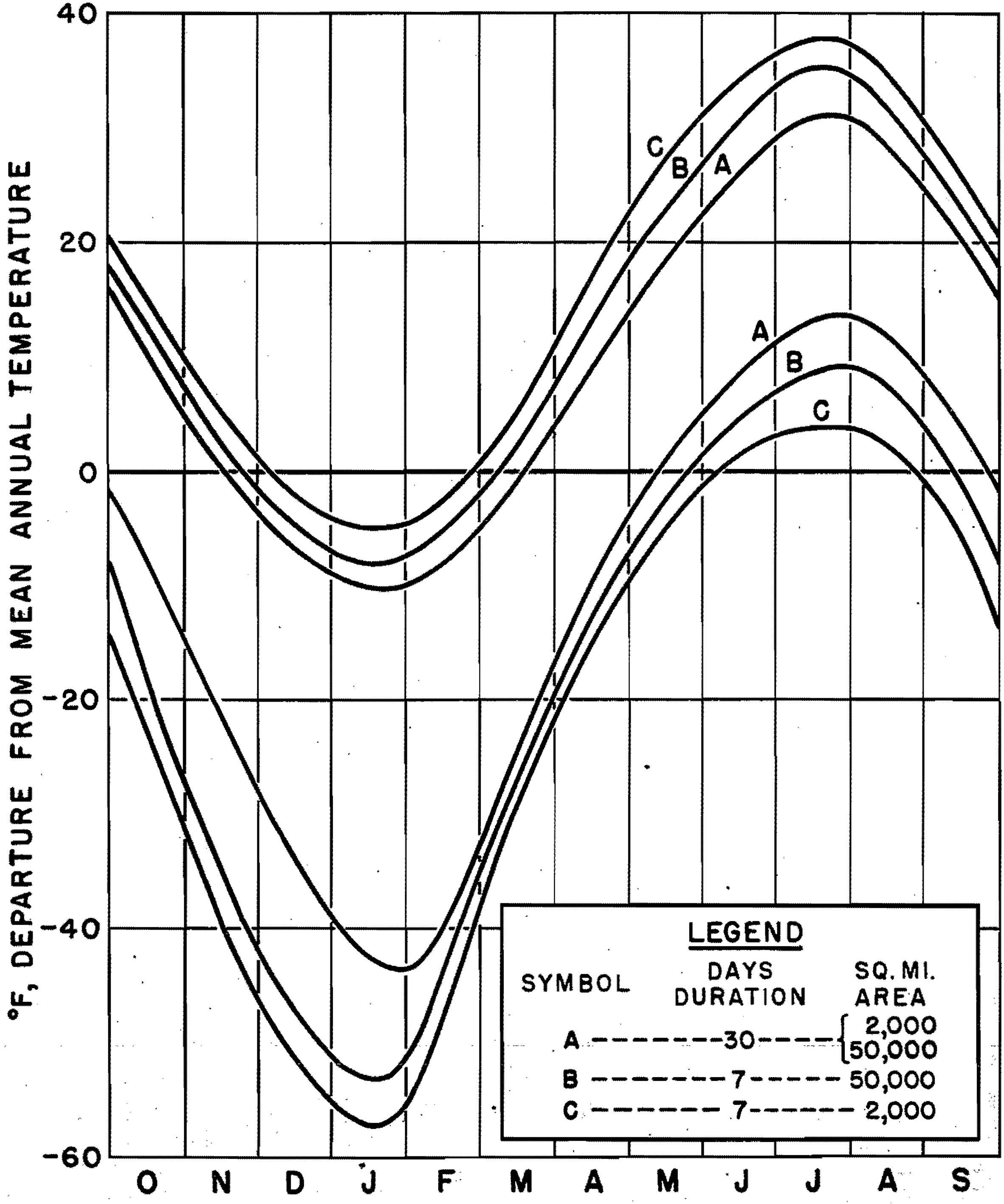


FIGURE 28