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SECTION II.—GENERAL METEOROLOGY.

HAIL IN THE UNITED STATES.[1]

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The occurrence of hail at Weather Bureau stations is made a part of the record of precipitation, the principal object sought being to complete the record of precipitation in whatever form it may have occurred. While the printed record does not distinguish between a damaging and a harmless hailstorm, yet such distinction is made in the manuscript records and a very brief account of damaging hail is kept under the caption "Meteorological notes." These latter have not been printed and it is not possible, therefore, to compile statistics of damaging hailstorms except by the expenditure of a large amount of time and labor in examining the manuscript records. The compilation of hail statistics on which this paper is based was undertaken because of the immediate necessity for a knowledge of the approximate frequency of hail throughout the United States. The printed records will be found in the series of annual reports of the Chief of Weather Bureau (Annual Meteorological Summaries).

A previous attempt made in 1898 (MONTHLY WEATHER REVIEW, 1898, **26**: 546), was not wholly successful because the data then available were incomplete.

The phenomenon of hail is even more local in its distribution than precipitation, hence one of the great difficulties in determining its frequency over areas of considerable size.

Director A. Angot, of the French meteorological service, has stated[2] that about 1,000 stations would be necessary for an area of 4,050 square miles in order to study the distribution of hail in sufficient detail. Such distribution of stations, if uniformly made, would require *one station for every 4 square miles*, or in a State the size of Iowa, for example, nearly 14,000 stations.

The total number of records used in the preparation of the present paper and included in Table 1 is 167 for an area of 3,026,789 square miles, or, if uniformly distributed, *one station for every 18,124 square miles*, or one station for an area the size of New Hampshire and Vermont.

The actual distribution for certain regions is, however, better than the above average. Thus, for example, Iowa, with an area of 56,147 square miles, has six stations within its borders and one separated from it by the Missouri River only, a total of seven, or one for each 8,021 square miles. Five of these stations, however, are massed in the river valleys which bound the State on the east and the west, respectively.

The annual frequency of hail in Iowa, as shown in Table 1, is:

Stations.	Hailstorms.
Sioux City	3.3
Omaha (Nebr.)	2.8
Des Moines	3.8
Charles City	2.8
Dubuque	2.8
Davenport	2.9
Keokuk	2.4

[1] Accompanied by five figures forming charts XLV-28 to XLV-32, inclusive.
[2] See this REVIEW, March, 1914, 42: 167, column 1, last paragraph.

The above figures mean simply that, on the average, hail falls about three times each season. While the figures give no information as to the intensity of the storms, it is a matter of common experience that many hailstorms are harmless and that damaging hailstorms are not numerous, at least in many portions of the country.

One hail insurance company of Iowa states that in the last 24 years it has paid a total of $1,860,633.04 in hail losses, or an average of $77,526.40 per year. Naturally the losses in some years are greater than in others. The losses sustained by this one company for 1915 were $225,219 and in 1916 were $135,204. From these figures there is no way of arriving at the number of acres damaged or the extent of the damage, whether total or only partial in each case. What is needed is an accurate statement of the number and extent of damaging hailstorms in each quarter section of the State for at least 10 years. The magnitude of the problem is thus apparent.

It is clear from the figures of Table 1 that the frequency of hail as a meteorological phenomenon varies sometimes within the limits of a single State; thus the frequency of hail is greater in western Kansas and Nebraska than in the eastern portions of the same States, and according to Section Director George M. Chappel, of Des Moines, Iowa, mutual hail insurance companies of that State charge a higher rate for hail risks in northern than in southern counties. The average cost of $1,000 hail insurance for a period of 5 years according to a prominent company was for northern counties $18.10 and for southern counties $17.70. This difference is not great, and more detailed data might easily change the ratio, since there is seemingly no reason for a greater frequency in northern than in southern counties, but it would not be surprising to find a diminution of storms in an eastward direction, since the region of infrequent storms lies east of the Mississippi River. In Kansas hail insurance costs as much as 10 per cent in the extreme northwestern counties and about 4 per cent in extreme eastern counties.

Geographic distribution.

The chart of annual hail frequency shows that the region of most frequent occurrence, four or more storms per year, is in southeastern Wyoming and eastward therefrom, including the western portions of Kansas, Nebraska, and Oklahoma. Adjoining this region of maximum frequency, especially to the eastward, the average number of storms per annum decreases to three. Roughly speaking, the region of the occurrence of at least three hail storms on an average per annum includes practically all of South Dakota, Nebraska, Kansas, the western and central portions of Iowa, northwestern third of Missouri, all of Colorado, and the southeastern portion of Wyoming. These two districts having three and four storms per annum may be considered as the chief hail regions of the United States. East of the Mississippi the annual average is two storms or less per annum. A second region of hail frequency comprises a portion of southwestern Montana and southern Idaho and the mountain districts of northern New Mexico and northern Arizona. (See fig. 5, XLV-32.) The occurrence of hail in the foregoing named regions is a phenomenon of late Spring and Summer. Winter hail is frequent along the Pacific coast from San Francisco northward, particularly at the mouth of the Columbia River. Hail also occurs in Winter, but rather infrequently in the East Gulf States, extreme northeast Texas, northern Louisiana, northern Mississippi, northern Alabama, northern Georgia, and southwestern North Carolina. In general, there is an absence of hail at all seasons along the Gulf and Atlantic coasts.

Seasonal distribution.

Hail in the United States is, in general, a phenomenon of the warm season, the only notable exception being along the immediate Pacific coast from San Francisco northward. On that strip of coast hail occurs chiefly from November to March, a season that is substantially the same as that of the rains in that part of the United States.

According to District Forecasters Beals and Willson of Portland, Oreg., and San Francisco, Cal., respectively, the hail of Winter and Spring on the Pacific coast is soft hail or graupel. True hail, of sufficient size to injure crops, rarely occurs. Mr. Beals is able to recall the occurrence of but a single destructive hailstorm in Oregon in the 17 years of his residence in that State, and, likewise, Mr. Willson recalls a damaging hailstorm in California in September, 1916. In both States hail is associated with thunderstorms. The latter are not uncommon in Oregon and Washington, but are very rare in the lowlands of California, although they occur with some frequency on the higher mountains beyond the level of agricultural lands.

Hail also occurs infrequently, it is true, in the Gulf States during the cold season; the region of most frequent occurrence is, however, some distance inland from the coast, viz, in the hilly regions of northern Alabama, northern Georgia, and southwestern North Carolina, particularly. Winter hail in the United States occurs in connection with the movement of LOWS from the Pacific inland, and again when LOWS of whatever place of origin move across the Gulf States. (See fig. 4, XLV–31.)

In the warm season the occurrence of hail is very closely associated with thunderstorm and tornadic phenomena. The writer has pointed out elsewhere that tornadoes occur in Spring a short distance inland from the Gulf coast and that as the season progresses the region of greatest tornadic activity seems to spread northward over the Great Plains States. A development and movement closely paralleling that of tornadoes is observed in hail storms, the last-named are most frequent in Oklahoma in March, for example. As the season advances the region of greatest frequency is found to the northward in Kansas, and the month of greatest frequency is May instead of March. In western Kansas and southeastern Wyoming the month of greatest frequency is June. (See fig. 1, 2. XLV–29–30.)

Damage to crops by hail.

Practically no damage to agricultural crops by hail is possible in the Pacific Coast States and only small damage is possible in the Gulf States both by reason of the infrequency of the phenomenon and the absence of crops at the time of greatest frequency. In Kansas, Nebraska, South Dakota, western Iowa and northwestern Missouri, hail falls at a time when destruction of crops is possible.

Distribution of hail in general.

Hailstorms over both land and water occur most frequently in temperate latitudes, the belt of greatest frequency being between the 35th and the 60th parallels in both hemispheres. They are infrequent in the Tropics, especially over the lowlands. In Arctic and Antarctic regions while hail occurs more frequently than was once supposed, lack of precise observations makes it somewhat conjectural whether the hail reported is graupel or true hail.

The geographic distribution of hail and its destructive effects on crops have been studied in Europe in great detail.

Württemberg.—Dr. Anton Bühler, of Zurich, has discussed in great detail the damage by hail in Württemberg during the 60 years 1828–1887.[3] The number of hail days during the 60 years averaged 13 and ranged from a maximum of 28 days in 1852 to but 4 days in 1867 and 1879. The smallest superficial area damaged in any one year was 1,627 hectares (4,020 acres) and the greatest was 32,133.7 hectares (79,402 acres).

India.—Although records of hail frequency and damage in India are not available for so long a period as in some European countries, yet much valuable information has already been collected and is summarized in Indian Meteorological Memoirs, volume 6, from which the matter below has been abstracted.[4]

Hailstorms occur in India almost exclusively during the dry or northeast monsoon. In the first half of this period or during the cold weather, they are restricted to northwestern and central India and occur in connection with and during the passage of cyclonic storms across India.

The prevailing winds are of continental origin and the air is hence comparatively dry, more especially in Rajputana and Central India, where hailstorms chiefly occur. During the second half of the dry monsoon, or the hot-weather months, March, April, and May, hailstorms usually occur under different conditions from those which give rise to hailstorms in the cold weather and also occur chiefly in areas where these storms are of rare occurrence in the preceding cool months. Hailstorms in the hot-weather months invariably accompany thunderstorms or, as it would be more correct to state, they are severe local thunderstorms, the precipitation in part of the area occurring as hail.

Thunderstorms and hailstorms hence occur chiefly at the period when convective action is most vigorous. The conditions which accompany and appear to be essential to their formation are: High temperature, large diurnal range of temperature. The large ascensional movement necessary for the formation of hailstones appears to be provided either:

(1) By exaggerated hot-weather conditions in the open plains, giving rise to unusually vigorous convectional movement.

(2) By a strong, dry land current advancing seaward and passing under a sea current and forcing the latter upward.

(3) By air movement from the plains across lines of hills.

In the Assam Valley the Assam Hills, and the Cachar hailstorms appear to be the result of forced ascent of sea winds in hot weather, blowing across the Bengal coast into east and central Bengal and across the Assam Hills into Assam.

In Bengal they appear to be due chiefly to the second action, the dry, westerly winds of the Gangetic Plains working under and forcing upward the southerly sea winds prevailing in that area at the time.

Hailstorms rarely occur in India south of latitude 16°.

Cold-weather hailstorms in India.

The general inference suggested from the statistics of hail frequency is probably correct, viz, that hailstorms are most frequent in Central India and Rajputana, area through which the primary depressions of the cold-weather storms almost invariably pass and that they are much less frequent in the northwestern provinces to the north of their general line of movement and the central provinces to the south of it.

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[3] Die Hagelbeschädigungen in Württemberg. Stuttgart, 1890.
[4] Hailstorms in India during the period 1883–1897. *J. Eliot*, Meteorological Reporter to the Government of India. (Ind. Met'l. mem., v. 6.)

Hailstorms of the second class, viz, hot-weather or summer thunderstorms, occur chiefly during the hot-weather months of March, April, and May and in districts in which convectional air movement (or forced ascent) due to thermal action, is large and vigorous, and also generally where the lower air strata are comparatively damp, as is the case in the maritime provinces of Bengal, Bombay, and Madras and in the Assam River Valley.

THEORIES OF HAIL.

Many theories of the formation of hail have been advanced within the last 100 years and the subject has been discussed from a number of slightly different viewpoints. There appears to be unanimity of opinion upon the following:

(1) Hailstorms (in temperate latitudes at least) are almost invariably associated with thunderstorms in which a display of electrical action is a prominent feature. While this association is an intimate one there does not appear to be any relation such as cause and effect between the two phenomena.

In the United States the region of greatest thunderstorm frequency does not coincide with the region of greatest hail activity. This fact is strikingly illustrated by a comparison of the average number of days with hail and with thunderstorms at two points representing, respectively, the region of greatest hail frequency and the greatest thunderstorm frequency. In this connection see W. H. Alexander's paper in this REVIEW, 1915, **43**:322, for tables and charts of thunderstorm frequency. The two points selected are: For hail, Cheyenne, Wyo., and for thunderstorms, Montgomery, Ala.

In the table below will be found the average number of days with hail and thunderstorms, respectively, for these two places.

Average number of days with hail and with thunderstorms.

Montgomery, Ala.

	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.	Annual.
Hail	0.1	0.2	0.2	0.4	0.1	0.3	0.1	0	0	0	0	0	1.4
Thunderstorms	1.6	2.7	3.8	4.4	7.3	11.5	11.4	10.1	6.4	1.1	1.4	0.7	62.4
Ratios	*1:16*	*1:13*	*1:19*	*1:11*	*1:73*	*1:38*	*1:114*	.....	.....	.....	.....	.....	*1:44*

Cheyenne, Wyo.

	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.	Annual.
Hail	0	0	0.1	0.4	1.4	3.2	1.4	1.5	1.2	0.2	0	0	9.4
Thunderstorms	0	0	0.2	2.5	7.5	11.9	14.0	11.2	4.9	0.6	0	0	52.8
Ratios	.....	.....	*1:2*	*1:6*	*1:5*	*1:4*	*1:10*	*1:7*	*1:4*	*1:3*	.....	.....	*1:6*

At Montgomery, Ala., the period of maximum *hail* is in the months February, March, and April, with a second maximum in June; but the latter may be more apparent than real, due probably to the local distribution of hail. Statistics for other stations in Alabama (Table 1) show that there is practically no hail along the Gulf coast after May, but that with distance inland from the coast and the slight increase of elevation, in the northern part of the State, as at Birmingham, the season of maximum hail falls in April and May. At Jacksonville, Fla., the chief hail maximum falls in June, thus tending to confirm the secondary maximum in June at Montgomery, Ala.

The period of maximum *thunderstorm* activity at Montgomery, Ala., falls in the summer, June, July, and August, while hail ceases after July. The ratio of hail to thunderstorms is greatest in April, 1:11, and least in July, 1:114.

The ratios "hail to thunderstorms" given above for the two stations Montgomery and Cheyenne show that the ratio hail to thunderstorm is much greater in Cheyenne than in Montgomery and it also may be interpreted as emphasizing the infrequency of hail with thunderstorms in the Gulf States.

The director of the French meteorological service in a recent paper [5] states that the cause of the production of hail can not be seen in the electric manifestations that accompany it.

The view that all hailstorms are merely intense thunderstorms in which a part of the precipitation is in the solid form—enunciated first, I believe, by Eliot in discussing the hailstorms of India—has much to commend it.

(2) That a prerequisite to the formation of hail is an ascending current of sufficient strength to carry drops of water or small balls or bunches of moist snow upward into the colder air strata there to be frozen. There are several lines of argument in favor of the origin of hail in a strong ascensional current, viz:

(*a*) The constitution of hailstones—concentric layers of ice or of ice and snow of different texture—points to repeated condensations and freezings suggesting the existence of a strong ascensional current.

(*b*) The evidence of cumulo-nimbus clouds also strongly points toward the existence of a strong vertical uplift and the measured height of these clouds in the warm season provide further confirmation, if confirmation is necessary, of the fact that their summits extend well into the region of ice clouds.

(*c*) The tops of these clouds must therefore be chilled by expansion, by radiation, by evaporation into the dry air, and by their contact with the colder air strata. Whether the cloud particles will freeze on passing through the isotherm of 0°C. or whether they will pass into a state of "subcooling" is of course a matter of speculation; but in any event it seems clear that the origin of hail is to be found connected with the changes that are taking place within great cumulo-nimbi. Prof. William Ferrell held the view that a hailstorm is simply a tornado in which the ascending currents are so strong and reach up so high that raindrops are carried up into the cold regions above and there frozen into hail.

Hail is generally associated with tornadoes, yet the writer much doubts whether the fundamental conditions for the formation of a tornado are always present in a hailstorm. Rather it should be recognized that just as there are degrees of intensity in thunderstorm phenomena, so there must be degrees of intensity in the conditions that produce hail. It is a fact worthy of mention that the region of greatest thunderstorm frequency in the United States does not coincide with the region of greatest hail frequency. Hail occurs with greatest frequency in southeastern Wyoming and over the Plains region immediately to the eastward, also in elevated regions of New Mexico and Arizona. It is conceivable that an ascending air current starting from the elevated regions of New Mexico and Arizona will not only be cooler initially, but will also sooner reach the isotherm of 0°C. than will an ascending current starting, say, in Florida or the Southeastern States where thunderstorms during the summer months are of almost daily

[5] *A. Angot* in Compt. rend., Acad. agric. de France, 2 (1916), No. 31, pp. 912-913; *transl.* in this REVIEW, Dec., 1916, 44:679.

occurrence. It also seems reasonable to suppose that an ascending current that originates, say, in the lee of the Rocky Mountains will require less initial ascensional energy to penetrate the colder upper strata than would be required in regions where the isotherm of 0°C. is found at a greater elevation. Kite and balloon observations made by the Weather Bureau at Mount Weather, Va., show that the isotherm of 0°C. is at its greatest altitude [6] in the months of July, August, and September.

Another reason for the absence of hail in the lower latitudes is the likelihood that even should hail occasionally form there, it will be melted before reaching the earth. Hail observed at great altitudes in the Tropics is invariably small.

It has been computed that a hailstone 6 millimeters (nearly a quarter of an inch) in diameter can not fall through the air at a speed greater than 5.42 meters per second. If then, the origin of the hail be placed at 5 kilometers—a not unusual altitude—a little more than nine minutes would be consumed in falling to the ground. There is ample reason to believe that at air temperatures which prevail during thunderstorms in lower latitudes, any hail which might be formed would probably be melted before it reached the surface of the earth.[7]

Elsewhere [8] the writer has expressed the opinion that thunderstorms in the Southeastern States are less violent than in the Northern States. The freedom from hail in the South seems to confirm the opinion heretofore expressed.

I have been assisted in the preparation of this paper by Mr. Bertrand W. Bailey of the River and Flood Division.

TABLE 1.—*Average number of days with hail, 1906–1915.*

Pacific Coast.

Stations.	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.	Annual.
Washington.													
Tatoosh Island	0.4	0.6	0.5	0.5	0.1	0	0	0	0	0.7	1.9	0.9	5.6
North Head	1.4	0.8	1.1	0.9	0.1	0	0	0	0	0.3	0.9	0.6	6.1
Seattle	0	0	0.6	0.3	0.2	0.4	0	0	0.2	0.3	0.4	0.2	2.6
Tacoma	0.7	0.5	0.4	0.9	0.5	0	0	0	0.2	0.4	0.5	0.1	4.2
Spokane	0.0	0.1	0.7	0.7	1.0	0.7	0.2	0	0.3	0.1	0	0	3.8
Walla Walla	0.2	0	0.4	0.5	0.1	0	0	0	0	0.1	0.1	0	1.4
Oregon.													
Portland	0	0.4	1.0	0.8	0.7	0.3	0	0	0.2	0.2	0.2	0.3	4.1
Baker City	0	0.1	0.1	0.3	0.5	0.9	0.5	0.1	0.3	0.1	0	0	2.9
Roseburg	0.1	0	0.6	0.4	0.2	0.3	0	0	0.1	0	0.1	0	1.8
California.													
Eureka	1.2	1.1	1.2	0.3	0.2	0	0	0	0	0	0.4	0.5	4.9
Mount Tamalpais	1.2	0.3	0.9	0	0.2	0	0	0	0	0	0.3	0.5	3.4
San Francisco	0.9	0.6	0.7	0	0	0	0	0	0	0	0.1	0.3	2.6
San Diego	0.1	0.2	0.5	0.3	0	0	0	0	0	0	0.2	0.3	1.6
Red Bluff	0.3	0.2	0.5	0	0.6	0.3	0	0	0	0	0	0.2	2.1
Sacramento	0.6	0.3	0.2	0	0	0	0	0	0	0	0	0	1.1
Fresno	0.2	0.4	0.4	0.2	0.1	0	0	0	0	0	0.1	0	1.4
San Luis Obispo	0.3	0.4	0.3	0	0	0	0	0	0.1	0	0	0.1	1.2
Los Angeles	0.1	0.1	0.3	0	0	0	0	0	0	0	0	0.1	0.6

[6] Bulletin, Mount Weather Observatory, 6: 179.

[7] See also in this connection R. Russell on "Hail," p. 133.

[8] *A. J. Henry.* Loss of life in the United States by lightning. Washington, 1901. 8°. p. 15, fig. (Weather Bureau bulletin No. 30.)

TABLE 1.—*Average number of days with hail, 1906–1915*—Continued.

Great Basin.

Stations.	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.	Annual.
Idaho.													
Lewiston	0	0	0.3	0.3	0.3	0.1	0.3	0	0.2	0.1	0	0	1.6
Boise	0.1	0	0.3	0.6	0.9	0.4	0.1	0.1	0	0.2	0.2	0.1	3.0
Pocatello	0	0.3	0.6	0.8	0.9	1.1	0.6	0.4	0.6	0.1	0	0.2	5.6
Utah.													
Salt Lake City	0.1	0.2	0.4	0.2	0.7	0.4	0	0.2	0.2	0	0.2	0.1	2.7
Modena	0.1	0.1	0.3	0.7	0.9	0.5	0.4	0.7	0.3	0.1	0	0	4.1
Nevada.													
Reno	0	0	0.1	0.2	0.8	0.1	0.2	0.2	0.1	0.1	0.1	0	1.9
Tonapah	0	0.1	0	0	0.4	0	0.1	0.1	0.1	0	0	0	0.8
Winnemucca	0.1	0.1	0.1	0.1	0.3	0.4	0.1	0	0.1	0	0	0	1.3
Arizona.													
Flagstaff	0.1	0	0	0.3	0.2	0.4	1.5	1.2	0.9	0.3	0	0	4.9
Phoenix	0	0.4	0.3	0.2	0.1	0	0.1	0	0	0.1	0	0	1.2
Yuma	0	0	0.1	0	0	0	0	0	0	0	0	0	0.1

Rocky Mountains.

Stations.	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.	Annual.
Montana.													
Kalispell	0	0	0	0	0.4	0.5	0.2	0.6	0.1	0.1	0	0	1.9
Havre	0	0	0	0.2	0.4	1.0	0.4	0.1	0	0	0	0	2.1
Helena	0	0	0	0.1	1.0	1.3	1.2	0.3	0.3	0.1	0.3	0	4.6
Miles City	0	0	0.1	0	0.6	0.5	0.2	0.5	0	0	0	0	1.9
Wyoming.													
Yellowstone Park	0	0	0	0	0.5	1.5	0.8	1.1	0.4	0.1	0	0	4.4
Lander	0	0	0.2	0.6	0.1	0.4	0.1	0.3	0	0	0	0	1.7
Cheyenne	0	0	0.1	0.4	1.4	3.2	1.4	1.5	1.2	0.2	0	0	9.4
Colorado.													
Grand Junction	0	0.1	0.3	0.8	0.5	0.6	0.1	0	0.4	0	0.1	0	2.9
Denver	0	0	0	0.3	0.8	1.2	0.3	0.3	0.2	0	0	0	3.1
Pueblo	0	0	0.1	0.7	0.6	1.1	0.6	0.2	0.1	0	0	0	3.4
New Mexico.													
Santa Fe	0.1	0	0.7	0.8	1.1	1.0	1.0	0.2	0.3	0.6	0	0	5.8
Roswell	0	0.1	0	0.5	0.8	0.2	0	0	0.1	0	0	0	1.7

Plains.

Stations.	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.	Annual.
North Dakota.													
Williston	0	0	0	0	0.5	0.1	0.5	0.5	0.3	0.1	0	0	2.0
Devils Lake	0	0	0	0.1	0.5	0.4	0.6	0.1	0.1	0.1	0	0	1.9
Bismarck	0	0	0	0.4	0.6	0.7	0.4	0.3	0	0	0	0	2.4
South Dakota.													
Rapid City	0	0	0	0.1	0.4	0.6	1.2	0.5	0.2	0	0	0	3.0
Pierre	0	0	0	0.3	0.4	0.8	0.4	0.5	0.1	0.1	0	0	2.6
Huron	0	0	0	0.3	0.9	1.0	0.6	0.1	0.3	0.1	0	0	3.3
Yankton	0	0	0.2	0.4	0.8	0.6	0.7	0.3	0.2	0	0	0	3.2
Nebraska.													
Valentine	0.2	0.1	0.1	0.2	0.8	0.3	0.7	0.6	0.2	0.1	0.1	0	3.4
North Platte	0	0.2	0.1	0.5	1.0	0.5	0.9	0.7	0.1	0	0	0	4.0
Omaha	0	0	0.1	0.9	0.8	0.2	0.3	0.1	0.3	0	0.1	0	2.8
Lincoln	0	0	0.5	0.7	0.7	0.5	0.4	0.3	0.2	0	0.2	0	3.5
Kansas.													
Dodge City	0	0	0.2	0.6	0.7	1.4	0.3	0.5	0.1	0.4	0.3	0	4.5
Topeka	0.2	0.1	0.3	0.5	0.8	0.5	0.1	0.1	0.4	0	0	0	3.0
Concordia	0	0	0	0.6	1.1	0.5	0.4	0.1	0.4	0.4	0.1	0	3.6
Iola	0	0.1	0.5	1.0	0.7	0.5	0	0	0.1	0.2	0.2	0.1	3.4
Wichita	0	0.2	0.3	1.2	1.3	0.5	0	0	0.1	0	0.1	0	3.7
Oklahoma.													
Oklahoma City	0	0.2	0.8	1.5	1.0	0.3	0	0	0.1	0.1	0.1	0	4.1

TABLE 1.—*Average number of days with hail, 1906–1915*—Continued.

Mississippi Valley.

Stations.	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.	Annual.
Minnesota.													
Duluth	0	0	0	0.1	0.7	0.2	0.6	0.1	0.1	0.2	0.1	0	2.1
Moorhead	0	0	0	0	0.2	0.3	0.1	0.5	0.1	0	0	0	1.2
St. Paul	0	0	0	0.2	0.4	0.3	0.1	0.2	0.2	0	0	0	1.4
Iowa.													
Sioux City	0	0.1	0	0.7	0.9	0.7	0.4	0.2	0.3	0	0	0	3.3
Charles City	0	0	0.1	0.2	0.9	0.7	0.3	0.3	0.1	0.2	0	0	2.8
Dubuque	0	0	0.2	0.6	0.6	0.3	0.2	0.3	0.2	0.1	0.3	0	2.8
Des Moines	0	0	0.3	0.6	1.2	0.3	0.3	0.2	0.5	0.4	0	0	3.8
Davenport	0	0.1	0.2	0.9	0.6	0.6	0.1	0.1	0.2	0	0.1	0	2.9
Keokuk	0	0	0.4	0.4	0.8	0	0.3	0.3	0	0.1	0.1	0	2.4
Illinois.													
Chicago	0	0	0.2	0.5	0.2	0.5	0.2	0.3	0	0	0	0.1	2.0
Peoria	0	0.1	0.4	0.5	0.4	0.2	0.2	0.1	0.2	0.1	0.1	0	2.3
Springfield	0	0	0.7	0.8	0.3	0.3	0.1	0	0.1	0	0.1	0.1	2.5
Cairo	0.1	0.1	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0	0.1	0	1.2
Missouri.													
Kansas City	0	0.1	0.5	0.9	0.9	0.6	0.2	0.1	0.2	0.4	0.2	0.1	4.2
Columbia	0.2	0	0	1.1	0.5	0.6	0.1	0	0.3	0.5	0.2	0	3.5
Hannibal	0.2	0.2	0.3	0.8	0.7	0.4	0	0	0	0.1	0.1	0	2.8
St. Louis	0.1	0	0.4	0.6	0.6	0.2	0.4	0	0.2	0.1	0.1	0	2.7
Springfield	0	0.3	0.1	0.5	0.7	0.1	0	0.1	0	0.1	0.2	0.1	2.2
Arkansas.													
Fort Smith	0.2	0.3	0.3	0.6	0.4	0.5	0.1	0	0	0	0.1	0	2.5
Little Rock	0.1	0.4	0.1	0.4	0.3	0.4	0.1	0	0.1	0	0.1	0.1	2.1

Gulf Region.

Stations.	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.	Annual.
Texas.													
Amarillo	0	0.2	0.1	0.5	0.8	0.5	0.2	0.2	0	0.2	0.2	0	2.9
Abilene	0	0.2	0.6	0.6	1.5	0.2	0.2	0.1	0	0.1	0.1	0.1	3.7
El Paso	0	0.1	0.1	0.3	0.3	0.3	0.1	0	0.3	0.1	0.2	0.1	1.9
Del Rio	0	0	0.1	0.1	0.3	0	0.1	0	0	0	0.1	0	0.7
San Antonio	0	0.3	0.1	0.5	0.5	0	0.1	0	0.1	0	0	0	1.6
Fort Worth	0.1	0.3	0.3	0.8	0.5	0.4	0.1	0	0.1	0	0.1	0.1	2.8
Palestine	0.2	0.2	0	0.3	0.6	0.1	0	0	0.1	0	0.1	0.1	1.7
Corpus Christi	0	0	0.1	0.3	0.4	0	0	0	0	0.1	0	0.1	1.0
Galveston	0	0.1	0.3	0.2	0	0	0	0	0	0.1	0.2	0	0.9
Louisiana.													
Shreveport	0.1	0.5	0	0.2	0.1	0.1	0	0.1	0.1	0	0.1	0.1	1.4
New Orleans	0.2	0.2	0.2	0.5	0.3	0.1	0.1	0.1	0.1	0	0.1	0	1.9
Mississippi.													
Vicksburg	0.2	0.4	0.2	0.5	0.2	0.2	0	0.1	0.3	0	0.1	0.1	2.3
Meridian	0	0.1	0	0.7	0.1	0	0	0.1	0	0	0	0	1.0
Alabama.													
Birmingham	0.1	0.4	0.1	0.4	0.4	0.2	0.4	0.1	0.1	0.1	0	0	2.3
Montgomery	0.1	0.2	0.2	0.4	0.1	0.3	0.1	0	0	0	0	0	1.4
Mobile	0.1	0	0.1	0.6	0.4	0	0.1	0	0	0	0.1	0	1.4
Florida.													
Pensacola	0	0.2	0.3	0.4	0.3	0	0	0	0	0	0	0.2	1.4
Jacksonville	0	0	0.1	0.2	0.4	0.6	0	0	0.1	0	0	0	1.4
Tampa	0	0	0	0	0.1	0	0	0.1	0	0	0	0	0.2
Jupiter	0	0	0	0.1	0.1	0	0	0	0	0	0	0	0.2
Key West	0	0	0	0	0	0	0	0	0	0	0	0	0.0

Great Lakes Region.

Stations.	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.	Annual.
Wisconsin.													
Green Bay	0	0	0.2	0	0.1	0.1	0.2	0	0.1	0.1	0.1	0	0.9
La Crosse	0	0	0.2	0.6	0.9	0.5	0.3	0.2	0.2	0	0.1	0	3.0
Madison	0	0	0.1	0.6	0.5	0.3	0.3	0	0	0	0.2	0	2.0
Milwaukee	0	0.1	0	0.3	0.7	0.1	0.2	0.1	0.2	0.2	0.1	0	2.0
Michigan.													
Marquette	0	0	0.1	0	0.2	0.3	0.3	0	0.1	0	0	0	1.0
Escanaba	0	0	0	0.2	0.5	0.5	0.4	0.4	0	0	0	0	2.0
Sault Ste. Marie	0	0	0	0.1	0	0.1	0.3	0.1	0	0	0	0	0.6
Alpena	0	0	0.3	0	0.3	0.1	0.2	0.1	0.3	0	0.1	0	1.4
Grand Haven	0	0	0.2	0.2	0.6	0.1	0.1	0	0	0.3	0.1	0	1.6
Grand Rapids	0	0	0.1	0.4	0.3	0.1	0.2	0.1	0.3	0.2	0.1	0	1.8
Detroit	0	0	0	0.6	0.3	0.8	0.1	0.1	0	0.1	0.1	0	2.2
Houghton	0	0	0.1	0.1	0.2	0.3	0.1	0.2	0	0	0	0	1.0
Port Huron	0	0	0.1	0.3	0.3	0.2	0.1	0.1	0.1	0	0	0	1.2

TABLE 1.—*Average number of days with hail, 1906–1915*—Continued.

Ohio Valley.

Stations.	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.	Annual.
Indiana.													
Indianapolis	0.1	0.1	0.2	0.2	0.5	0.3	0.4	0	0.2	0.1	0	0	2.1
Evansville	0.1	0.3	0.3	0.5	0.7	0	0.2	0.1	0.1	0.1	0.2	0	2.6
Ohio.													
Toledo	0	0	0.2	0.4	0.2	0.3	0.3	0.1	0	0.1	0.1	0	1.7
Sandusky	0	0	0.3	0.4	0.2	0.2	0.3	0.1	0	0.1	0	0	1.6
Cleveland	0.1	0	0.1	0.5	0.2	0.3	0.2	0	0.2	0.2	0	0	1.8
Columbus	0	0	0.3	0.3	0.3	0.1	0.3	0.1	0.1	0	0.1	0	1.6
Cincinnati	0	0	0.1	0.4	0.3	0.3	0.2	0	0	0.1	0	0	1.4
West Virginia.													
Parkersburg	0.1	0.2	0	0.5	0.6	0.7	0	0	0	0.2	0	0.1	2.4
Elkins	0	0.1	0.2	0.6	0.6	0.4	0	0.1	0.1	0	0.1	0.1	2.3
Kentucky.													
Louisville	0.1	0	0.3	0.3	0.2	0.2	0.5	0	0.2	0	0.3	0.1	2.2
Lexington	0	0.1	0.3	0.4	0.1	0.4	0.1	0.1	0.1	0.1	0	0	1.7
Tennessee.													
Nashville	0	0.1	0.4	0.2	0.5	0.4	0.2	0	0	0	0	0.1	1.9
Knoxville	0.1	0.2	0.2	0.5	0.1	0.2	0.3	0.2	0.1	0	0.1	0	2.0
Chattanooga	0	0.2	0.3	0.7	0.3	0.2	0.1	0.1	0	0	0	0.1	2.0
Memphis	0.1	0.6	0.2	0.4	0.2	0.3	0	0	0	0.2	0	0.2	2.2

New England.

Stations.	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.	Annual.
Maine.													
Eastport	0.2	0	0.1	0.1	0	0	0.1	0	0	0.1	0	0.1	0.7
Portland	0	0	0.1	0.1	0.2	0	0.1	0.1	0.1	0	0	0	0.7
New Hampshire.													
Concord	0.1	0	0.1	0.1	0.3	0.1	0.3	0.1	0	0.2	0.1	0	1.4
Vermont.													
Northfield	0	0	0.1	0	0.1	0.4	0.2	0	0	0.1	0	0	0.9
Massachusetts.													
Boston	0	0	0	0	0	0	0.1	0	0.1	0	0.1	0	0.3
Nantucket	0	0	0.2	0	0.1	0	0	0	0.1	0.1	0.2	0.1	0.8
Rhode Island.													
Providence	0	0	0.1	0	0.3	0.1	0	0.1	0	0	0	0	0.6
Block Island	0	0	0.3	0.1	0	0	0	0	0	0	0.2	0	0.6
Connecticut.													
Hartford	0	0	0.1	0	0.3	0.2	0.3	0.1	0	0	0.2	0	1.2
New Haven	0	0.1	0.1	0	0.2	0	0.1	0.1	0.1	0	0.1	0	0.8

Middle Atlantic States.

Stations.	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.	Annual.
New York.													
Albany	0.1	0	0.2	0	0.5	0.2	0.3	0.2	0.1	0	0.1	0	1.7
Syracuse	0	0.1	0	0.1	0.3	0.3	0.3	0.1	0	0.1	0	0	1.3
Oswego	0	0	0.1	0.1	0.1	0.3	0.1	0.1	0.2	0.6	0.6	0	2.2
Rochester	0	0	0.1	0	0.1	0.1	0.1	0	0.3	0.2	0	0	0.9
Buffalo	0	0	0.1	0.1	0.3	0.2	0.1	0.1	0	0.1	0.2	0	1.2
Binghamton	0.1	0	0	0.1	0.1	0.4	0.2	0.1	0.1	0.2	0.1	0	1.4
New York City	0.1	0.1	0.1	0	0.2	0.2	0.2	0.1	0	0	0	0	1.0
New Jersey.													
Atlantic City	0	0	0.2	0.1	0.1	0.2	0	0.1	0	0	0	0	0.7
Pennsylvania.													
Erie	0.1	0	0.2	0.3	0	0.4	0.1	0.1	0.3	0.4	0.3	0.1	2.3
Pittsburgh	0.1	0	0.3	0.6	0.3	0.3	0	0.3	0	0	0	0.1	2.0
Harrisburg	0	0.1	0	0.6	0.3	0.2	0.2	0.1	0.1	0.2	0	0	1.8
Scranton	0.1	0	0	0.3	0.3	0.8	0.4	0.1	0	0.1	0	0.1	2.2
Philadelphia	0	0.1	0.1	0	0.1	0.2	0.1	0.3	0	0	0.1	0	1.0
Maryland.													
Baltimore	0.3	0	0.1	0	0	0.4	0	0	0	0	0	0	0.8
District of Columbia.													
Washington	0	0.1	0.2	0	0.1	0.3	0.4	0.1	0.1	0	0.1	0	1.4
Virginia.													
Richmond	0.1	0	0.1	0.5	0.3	0.2	0.1	0.1	0	0.1	0	0.1	1.6
Wytheville	0	0.1	0.2	0.1	0.4	0	0.2	0.1	0.1	0	0	0	1.2
Lynchburg	0.1	0	0	0.1	0	0	0.1	0	0	0	0	0	0.2
Norfolk	0	0.1	0.3	0.2	0.3	0.3	0.1	0	0	0	0	0	1.3

TABLE 1.—*Average number of days with hail, 1906–1915*—Continued.

South Atlantic States.

Stations.	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.	Annual.
North Carolina.													
Raleigh	0	0.2	0.1	0.1	0.2	0	0	0.1	0	0	0.1	0.1	0.9
Asheville	0	0.1	0.1	0	0.2	0.2	0.3	0.2	0	0	0	0	1.1
Charlotte	0.2	0.1	0.5	0	0	0	0.3	0	0	0	0.1	0.5	1.7
Wilmington	0	0	0.3	0.1	0	0.2	0	0	0	0	0	0	0.6
South Carolina.													
Columbia	0.1	0	0.2	0	0.2	0.3	0.1	0.2	0	0	0	0.1	1.2
Charleston	0	0.1	0	0.1	0.1	0	0	0.1	0.1	0	0	0	0.5
Georgia.													
Atlanta	0.1	0.2	0.2	0.1	0.1	0.2	0.1	0.2	0	0.3	0.1	0.3	1.9
Augusta	0	0	0	0	0	0	0.1	0	0	0	0	0	0.1
Macon	0	0	0.2	0.1	0.3	0	0.3	0	0.1	0	0	0	1.0
Savannah	0	0	0	0	0.5	0.1	0	0	0	0	0	0	0.6

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LIGHTNING AND FOREST FIRES IN CALIFORNIA.

By ANDREW H. PALMER, Observer.

[Dated: U. S. Weather Bureau office, San Francisco, Cal., July 14, 1916.]

The inauguration of the fire-weather warning service as a part of the work of the U. S. Weather Bureau has opened another interesting field for investigation in meteorology.[1] New problems have presented themselves for solution. The difficulties encountered to date have been largely the result of a lack of data, the absence of normals, and the want of precedent. Though forest fires doubtless occurred long before man appeared on the earth, a systematic record as to their causes extends over comparatively few years. In the United States the matter was not given serious attention until 1880, when a table of forest-fire statistics was prepared as a part of the Tenth Census. The investigation of the relation of weather to forest fires is of even more recent date, while the fire-weather warning service was inaugurated in the Pacific Coast States in 1913 on the recommendation of District Forecaster E. A. Beals.

With reference to their origin, forest fires may be divided into two groups, those caused by man and those caused by nature. While those caused by man are the larger of the two groups, it is not the purpose of this paper to discuss them in detail. Those caused by nature may be subdivided into three groups, (1) those caused by "spontaneous" combustion, (2) those caused by volcanic eruptions, and (3) those caused by lightning.

"Spontaneous" combustion is a direct cause of forest fires only in rare instances, and as an observed source there are few cases on record. However, of the many forest fires of unknown origin it is believed that some, at least, were thus produced. The exudation of oils and other mineral matter from the ground, or the close packing of damp leaves and grass on the forest floor may at times produce chemical reactions which might result in combustion. Forest fires caused by volcanic eruptions had not been recognized in the United States until May 19, 1915, when an eruption of Lassen Peak in northeastern California was accompanied by a blast of superheated gases which kindled two forest fires in that vicinity.[2] As natural causes of forest fires spontaneous combustion and volcanic eruptions must therefore be considered rare in the United States. The third natural cause, lightning, and its relation to forest fires, is the subject of this discussion.

[1] Concerning the fire-weather warning service see this REVIEW, March, 1916, 44: 133–139.—EDITOR.

[2] *Palmer, A. H.* An eruption of Lassen Peak. MONTHLY WEATHER REVIEW, October, 1916, 44: 571–572.

LIGHTNING AND FOREST FIRES IN THE UNITED STATES.

On the national forests of the United States during the five-year period 1911–1915, inclusive, fires were caused as follows: Railroads, 14.4 per cent; campers, 15.6 per cent; brush burning, 7.9 per cent; lumbering, 1.8 per cent; lightning, 29.5 per cent; incendiary, 8.7 per cent; miscellaneous, 5.2 per cent; and unknown, 16.8 per cent. Lightning is a more important factor in causing forest fires than it is in causing fires in cities, the proportion being in the ratio of 7 to 1.

The relation of lightning to forest fires in the United States was studied in 1912 by Mr. Fred G. Plummer, of the United States Forest Service.[3] The more important conclusions reached by Mr. Plummer may be briefly summarized as follows:

Trees are the objects most often struck by lightning, because: (*a*) They are the most numerous of all objects; (*b*) as a part of the ground, they extend upward and shorten the distance to a cloud; (*c*) their spreading branches in the air and spreading roots in the ground present the ideal form for conducting an electrical discharge to the earth. Any kind of tree is likely to be struck by lightning. The greatest number struck in any locality will be the dominant species. The likelihood of a tree being struck by lightning is increased: (*a*) If it is taller than surrounding trees; (*b*) if it is isolated; (*c*) if it is on high ground; (*d*) if it is well (deeply) rooted; (*e*) if it is the best conductor at the moment of the flash; that is, if temporary conditions, such as being wet by rain, transform it for the time from a poor conductor to a good one. Lightning may bring about a forest fire by igniting the tree itself or the humus at its base. Many forest fires caused by lightning probably start in the humus. Other things being equal, trees growing in different soils differ slightly in susceptibility to lightning stroke. One study gave these results: Loam, 23 per cent; sand, 18 per cent; clay, 17 per cent; and others, 42 per cent. Zones of marked hazard from lightning—due partly to soil variations, partly to mineral deposits, and partly to altitude—are recognized throughout the West. The conductivity of wood is governed by its moisture content and its temperature. Electricity traverses wood more easily in the longitudinal direction of its fibers than across them. About 2 per cent of trees struck by lightning are ignited. While trees do not differ greatly as to their susceptibility to lightning, they do differ greatly as to inflammability.

LIGHTNING AND FOREST FIRES IN CALIFORNIA.

In California there are 18 national forests in which are included a total area of 19,575,000 acres. Not all of this land is timbered, but there are about 17,400,000 acres of standing timber in the State. These 18 national forests, which are separate and distinct from the national parks, are shown in outline in figure 1. As California is a large State containing 5 per cent of the total area of the country, and as it has within its borders a great variety of topography, soil, and climate, its trees include 125 of the 500 to 600 species growing in the United States. An

[3] *Plummer, Fred G.* Lightning in relation to forest fires. Washington, 1912. (Forest Service Bulletin 111.)

Fig. 1. Average Number of Days with Hail. Spring, 1906-1915.

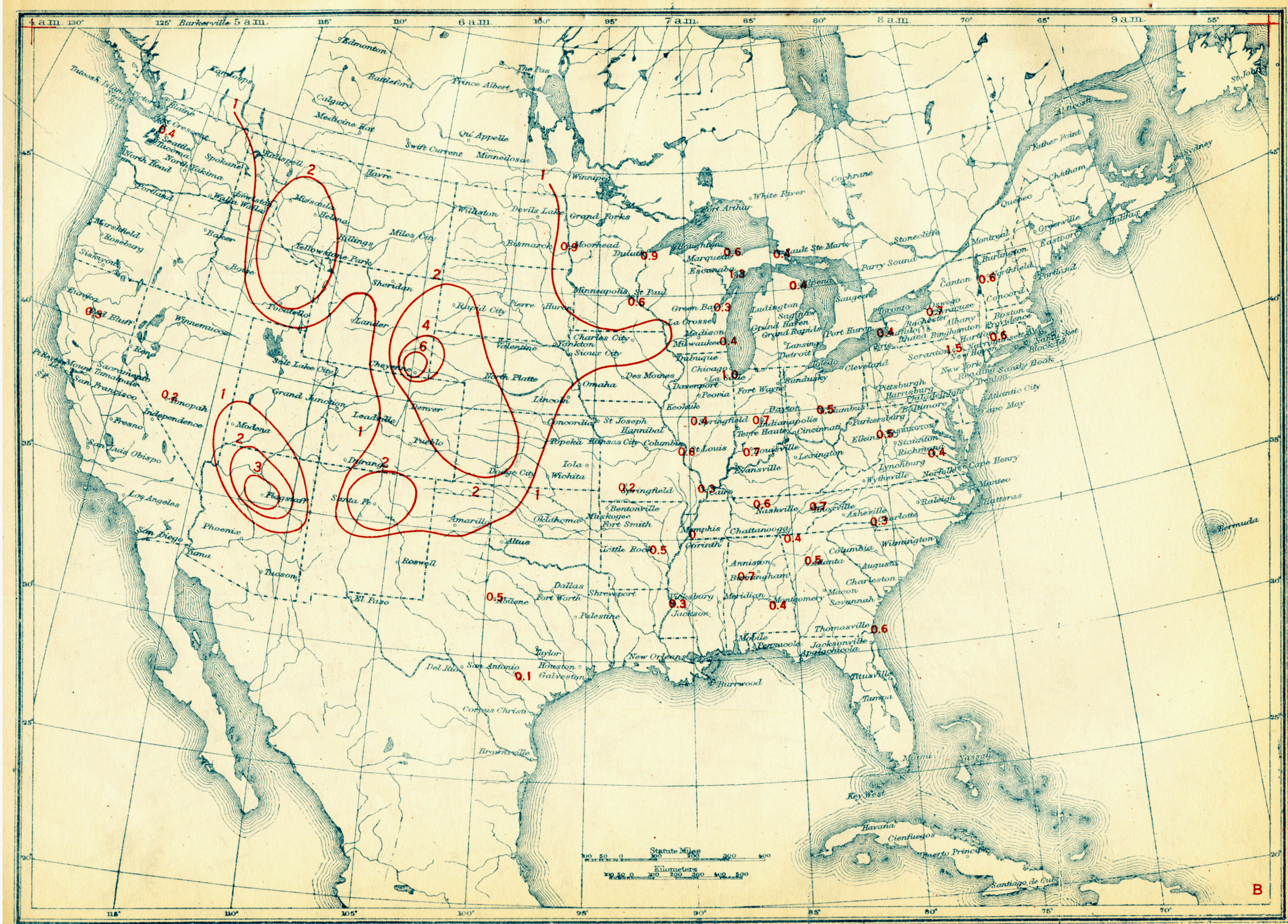

Fig. 2. Average Number of Days with Hail. Summer, 1906-1915.

Fig. 3. Average Number of Days with Hail. Autumn, 1906-1915.

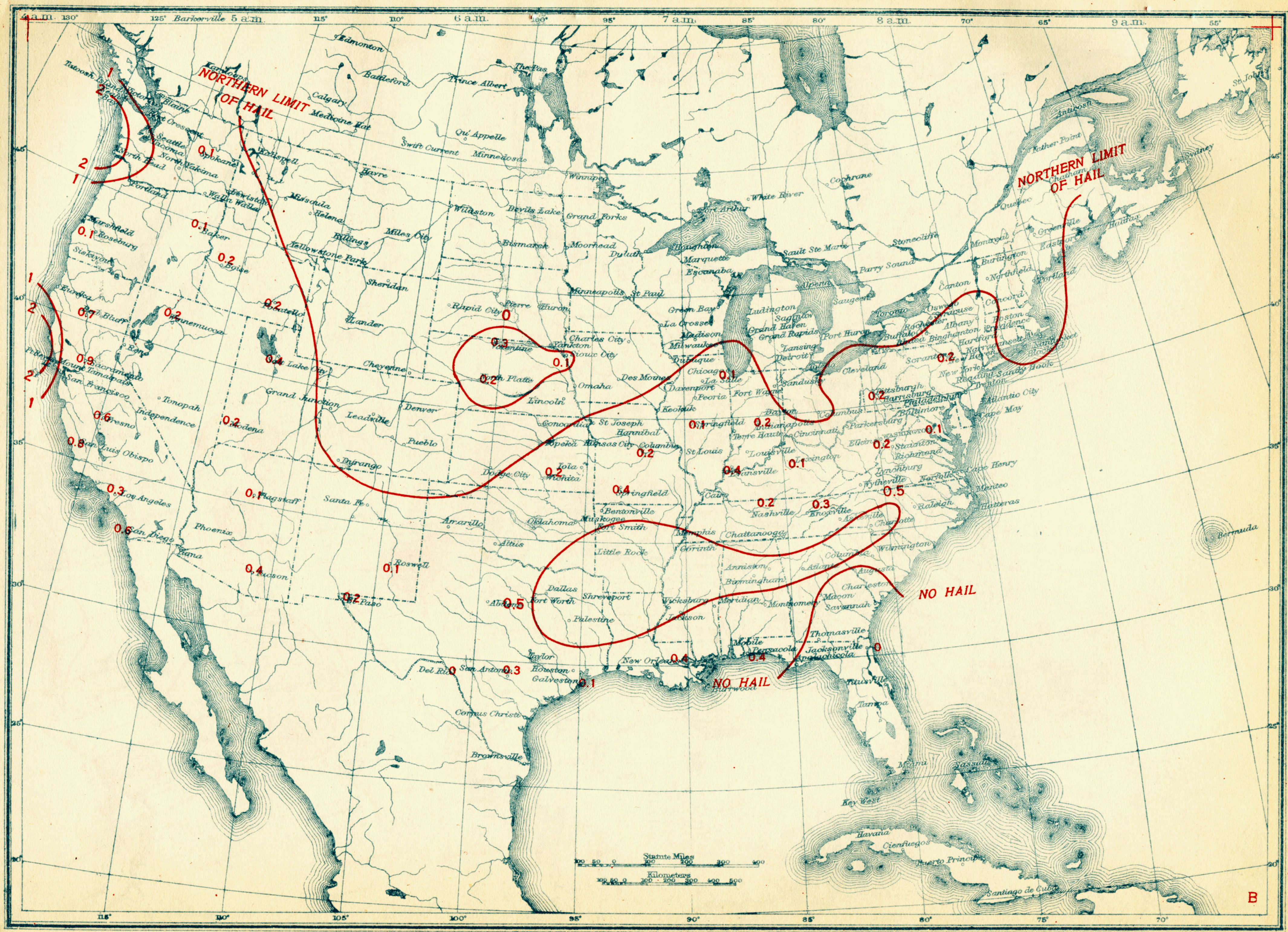

Fig. 4. Average Number of Days with Hail. Winter, 1906-1915.

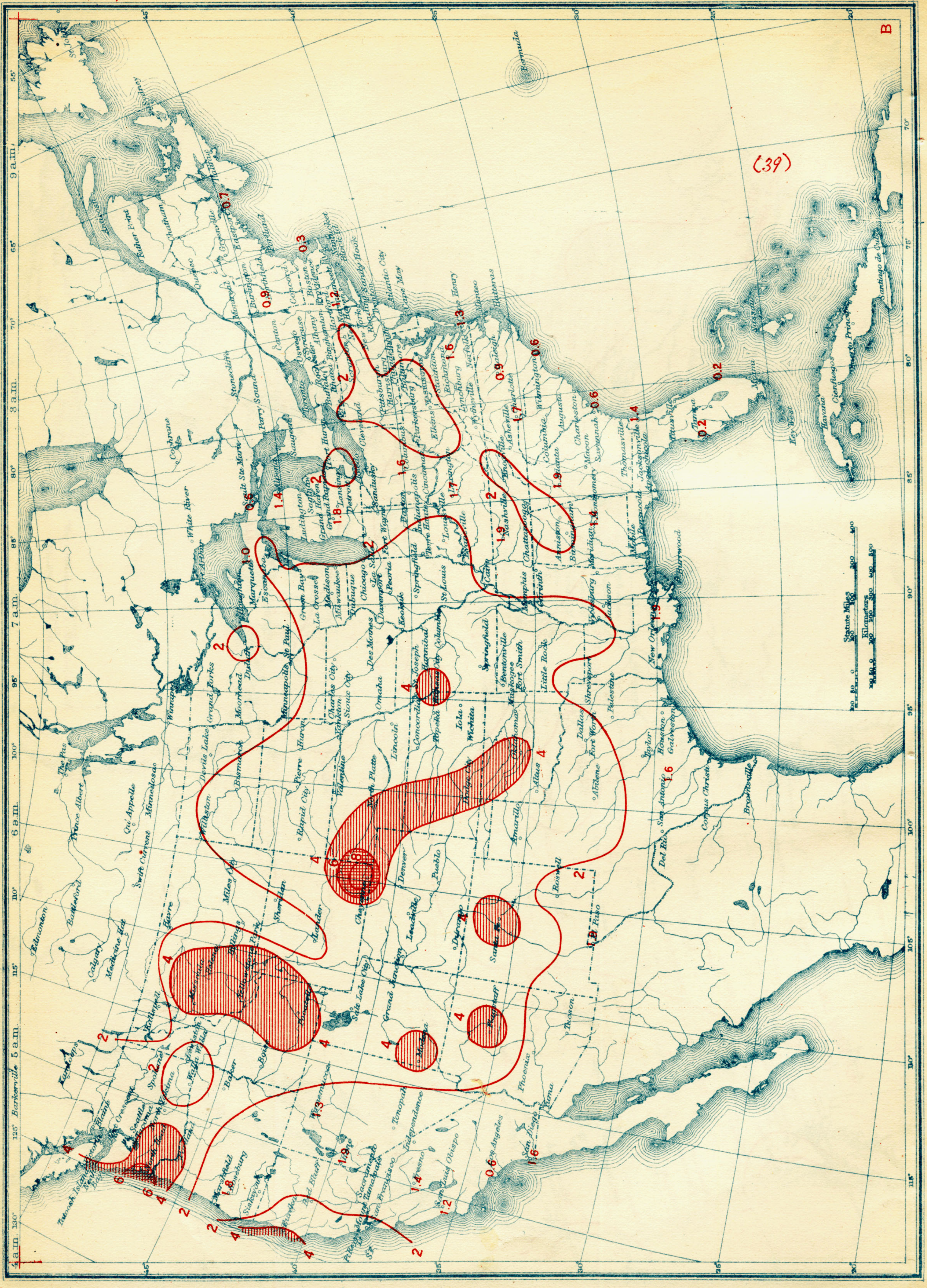

Fig. 5. Average Number of Days with Hail. Year, 1906-1015.