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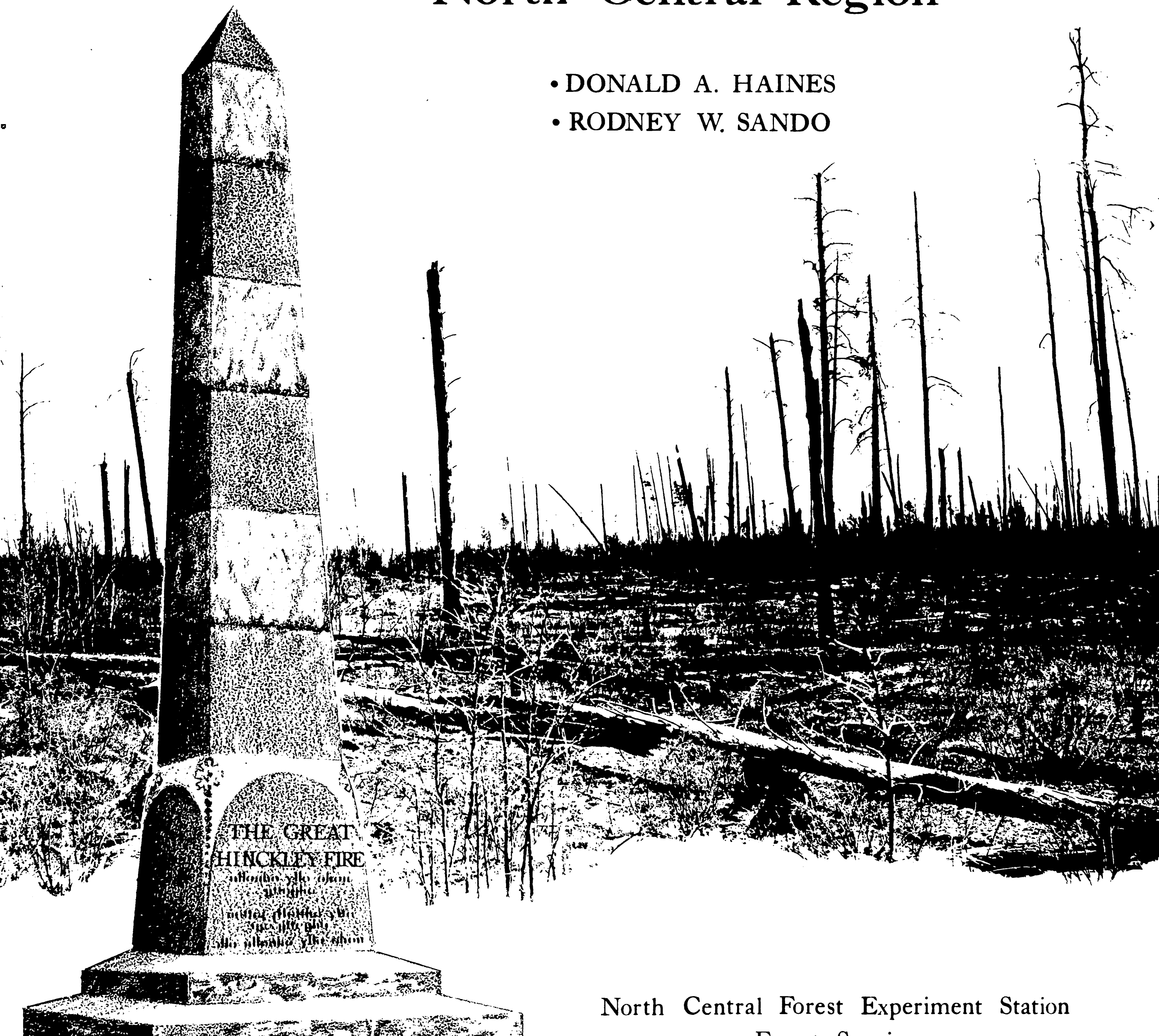

North Central Forest Experiment Station
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Donald A. Haines and Rodney W. Sando

Weather conditions that increase the threat of forest fires are well known. Low precipitation and humidity, coupled with high temperature and maximum solar radiation, lower the forest fuel moisture and therefore increase the fire potential. Winds also play a part in this drying process. After ignition, wind force and direction are of great concern; high, variable winds make suppression difficult, and sometimes impossible.

The specific importance of each meteorological factor is not known for the climatic periods that preceded historically large fires. But we do know, for example, that drought — a condition induced by a combination of meteorological factors — has generally helped set conditions for large fires. Unfortunately, its exact role is unknown, for the term is usually used in a vague and qualitative sense. Palmer (1965) has compiled a partial list of definitions that have been used in drought studies, and he thereby points out the problem. Drought has been defined as:

1. A period with precipitation less than some small amount such as 0.10 inch in 48 hours (Blumenstock 1942).
2. A period of more than some particular number of days with precipitation less than some specified small amount (Great Britain Meteorological Office 1951).
3. A period of strong wind, low precipitation, high temperature, and unusually low relative humidity (Condra 1944).
4. A day on which the available soil moisture was depleted to some small percentage of available capacity (van Bavel and Verlinder 1956).
5. Monthly or annual precipitation less than some particular percentage of normal (McGuire and Palmer 1957).

The same problem of vague definition is evident in our knowledge of the relative importance of the other climatic parameters associated with large fires. Seasonal meteorological conditions leading to these events of the past are usually described by such phrases as: "The summer of 1881 was excessively dry and the drought had done its work . . . hot, dry August . . ." (Bailey 1882). "The summer had been deficient in rainfall. High temperatures, dry air, and light wind for almost 4 months previous" (Guthrie 1936). Holbrook (1960) presents some quantitive data in describing the climatic conditions before the 1894 Hinckley fire, but usually he uses descriptive terms for the other periods analyzed. As an example: "A drought had laid on the land from early May through September, with only one rain, 'a smart shower,' on July 8 to break it." Davis (1959), in reviewing 10 major historical fires, gives brief, definitive information in two cases, but usually describes a situation as: "Extremely hot and dry summer. No rain for months. Hot days with only moderate winds at time of fire." Wells (1968), in his book on the Peshtigo fire, analyzes some of the 1871 records at Milwaukee but finds the information less than satisfactory as it applies to the fire area and summarizes prefire conditions by ". . . it can be accepted that there was a serious drought and that the woods were unusually susceptible to fire."

Little detailed information exists on the characteristics of climatic conditions occurring before historical forest fires. In this paper we will attempt to quantitatively assess the "drought" conditions that preceded a number of great fires and to determine the climatic extremes referred to by such terms as "hot summer" and "low humidity." Sunshine records will also be examined, when available, and in some cases the general wind conditions and synoptic situations that immediately preceded these fires.

PROCEDURE

Selection of Fire Cases

For the purposes of this study, selected fires were restricted to Illinois, Michigan, Minnesota, and Wisconsin. This area is relatively homogeneous; the topography is mostly level, and during summer and autumn weather patterns are generally uniform.

Seven historically great fires were selected from the period 1870 to 1920 (table 1). No earlier fires were considered because of insufficient weather records. The Signal Service's[1] weather

[1] *The Signal Service preceded the Weather Bureau (until 1891) as the designated weather information agency of the U.S. Government (Whitnah 1961).*

Table 1. — The fires and their effects

Name of fire	Date	Acres burned	Lives lost	Reference
Peshtigo (Wis.)	Oct. 8, 1871	1,280,000	1,300	Wells 1968
Chicago (Ill.)	Oct. 8, 1871	1/2,240	200	Lincoln Library 1965
Lower Michigan	Oct. 8-10, 1871	2,500,000	--	Holbrook 1960
Michigan Thumb	Aug. 31- Sept. 5, 1881	1,000,000	169	Holbrook 1960
Hinckley (Minn.)	Sept. 1, 1894	2/160,000	418	Plummer 1912
Baudette (Minn.)	Oct. 7, 1910	300,000	42	Plummer 1912
Cloquet (Minn.)	Oct. 12, 1918	250,000+		Holbrook 1960
		or	538	
		1,280,000		Richardson 1919

1/Destroyed 17,450 buildings
2/Only forested acres given.

forecasting service was established in 1870, and such items as daily synoptic charts and monthly maps of United States precipitation totals were not issued prior to that time. Fires after the early 1920's were not included in this study because by that time forest protection became increasingly effective in the Lake States and it would be necessary to include fire control factors in this analysis.

The Chicago fire was also included in sections of this study because Signal Service records are available for most of the 1870-1871 period. The Chicago weather office burned during the Great Fire, but regular observations began at another nearby location just 7 days after the disaster.

All fires occurred during September or early October. Only late-summer fires were selected because the importance of individual climatic features is different during the various seasons. As an example, the presistence of winter snow might play an important part in spring fires. By fall, however, effects of snow cover should be diminished. Even with the fires restricted to September-October, there could still be a seasonal transition bias in the data.

Determining the actual number of acres burned in each of the fires is often difficult. The figures in table 1 are our best estimate from an extensive review of the literature. The 1894 Hinckley disaster destroyed the smallest forested area — 160,000 acres. All others burned a minimum of a quarter million acres. Human lives were lost on all fires — 1,300 at Peshtigo in 1871.

Early Weather Stations and Records

Weather data taken at observation sites in or near the historic fire region were obtained mostly from original records or from published U.S. Weather Bureau climatic material (1932-1936). All data are presented for the season or year of the fire and, in the case of precipitation, for the previous year. The locations of the weather observation sites are shown in figure 1.

Because of the extremely large amount of burned acreage in Lower Michigan during October 1871, we used four State stations to establish the fire-climatic pattern: Detroit, Grand Rapids, Lansing, and Thunder Bay (near Alpena). The fires of 1871 stayed well north of Detroit, but destroyed Holland (less than 25 miles from Grand Rapids) and threatened Lansing and Alpena.

In the Peshtigo region, both Embarrass and Sturgeon Bay had well-kept records during the early 1870's. Embarrass precipitation observations were continuous from 1864 to 1892. However, there appears to be either a local anomaly at the immediate site or there was an instrument exposure problem. Surrounding weather stations — such as Green Bay, Shawano, and New London — have normal precipitation amounts of near 30 inches per year, while Embarrass averaged over 40 inches during its period of record. In order to have a standard record period from which to measure precipitation deviations in the various years, all precipitation data (except for Embarrass) have been based on the period from 1931 to 1960 insofar as possible. Because of the bias in the Embarrass data, this station's deviations are expressed in terms of the period over which the record was kept.

Obtaining temperature data during this early period was more difficult than obtaining precipitation information. Apparently no station had maximum and minimum thermometers during the early 1870's. Average daily temperatures during much of the 1800's were computed from a number of air temperature readings taken at specific times during the day. Because of this fact, the temperatures used in this paper are usually computed as departures from a period of years during which the specific fire occurred.

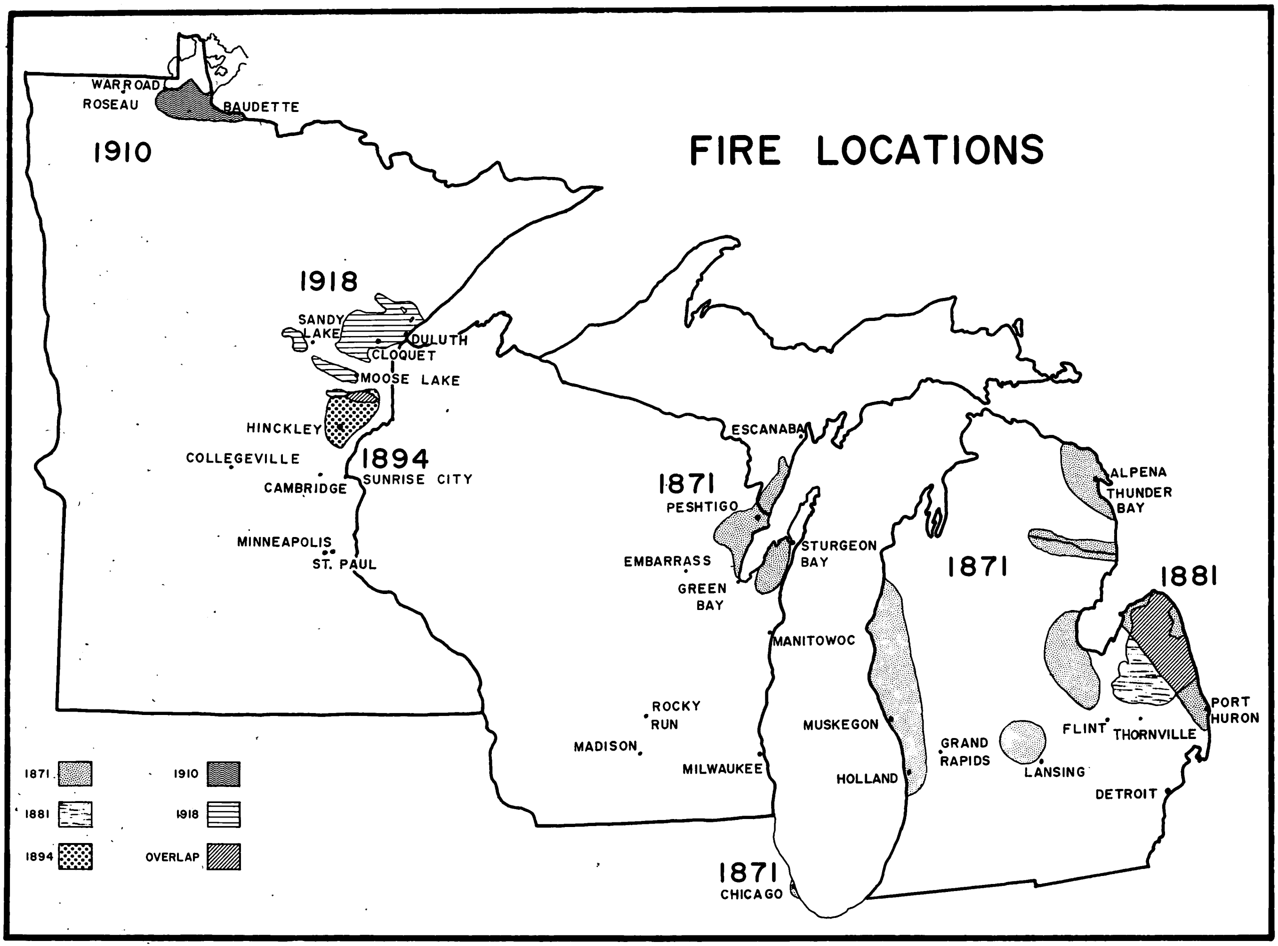

FIGURE 1. — Location of the burned areas and the nearby weather-observation sites operating at the time of the fire. The 1894 and 1918 fire areas overlap, as do the Michigan 1871 and 1881 areas.

Weather records were taken at Thornville and Port Huron for a number of years preceding the 1881 Michigan Thumb fire. Thornville is close to the fire region; Port Huron, although somewhat farther away, provided maximum and minimum temperatures for that period.

By the time of the Hinckley fire of 1894, a number of well-run cooperative weather stations were established in eastern Minnesota. Collegeville, although some distance to the west of the main fire area, and St. Paul, to the south, were included in this study because of the excellence and duration of their observations. Cambridge and Sandy Lake are nearer to the main fire region.

The Baudette fire of 1910 burned the weather station in that city. Therefore, Roseau observations were used to complete the record for October.

The fire of 1918 burned Cloquet, but the cooperative weather station was not lost. Weather observations are therefore continuous for that city. Nearby Duluth was and still is a Weather Bureau first-order station. The more complete instrumentation at this station (i.e., a sunshine recorder, wind equipment, etc.) made possible a more complete reconstruction of the weather conditions preceding and during this fire.

Some data from other weather stations were used in specific instances during the course of this study. As an example, data from Madison, Milwaukee Manitowoc, and Rocky Run, Wisconsin, were used to establish the extent of rainfall departures from normal before the 1871 Peshtigo and Chicago fires, and were also included in the precipitation averages for one graph.

CLIMATIC VARIABLES

Precipitation

Precipitation graphs for 15 stations over a 2-year period are given in figure 2. The stations are

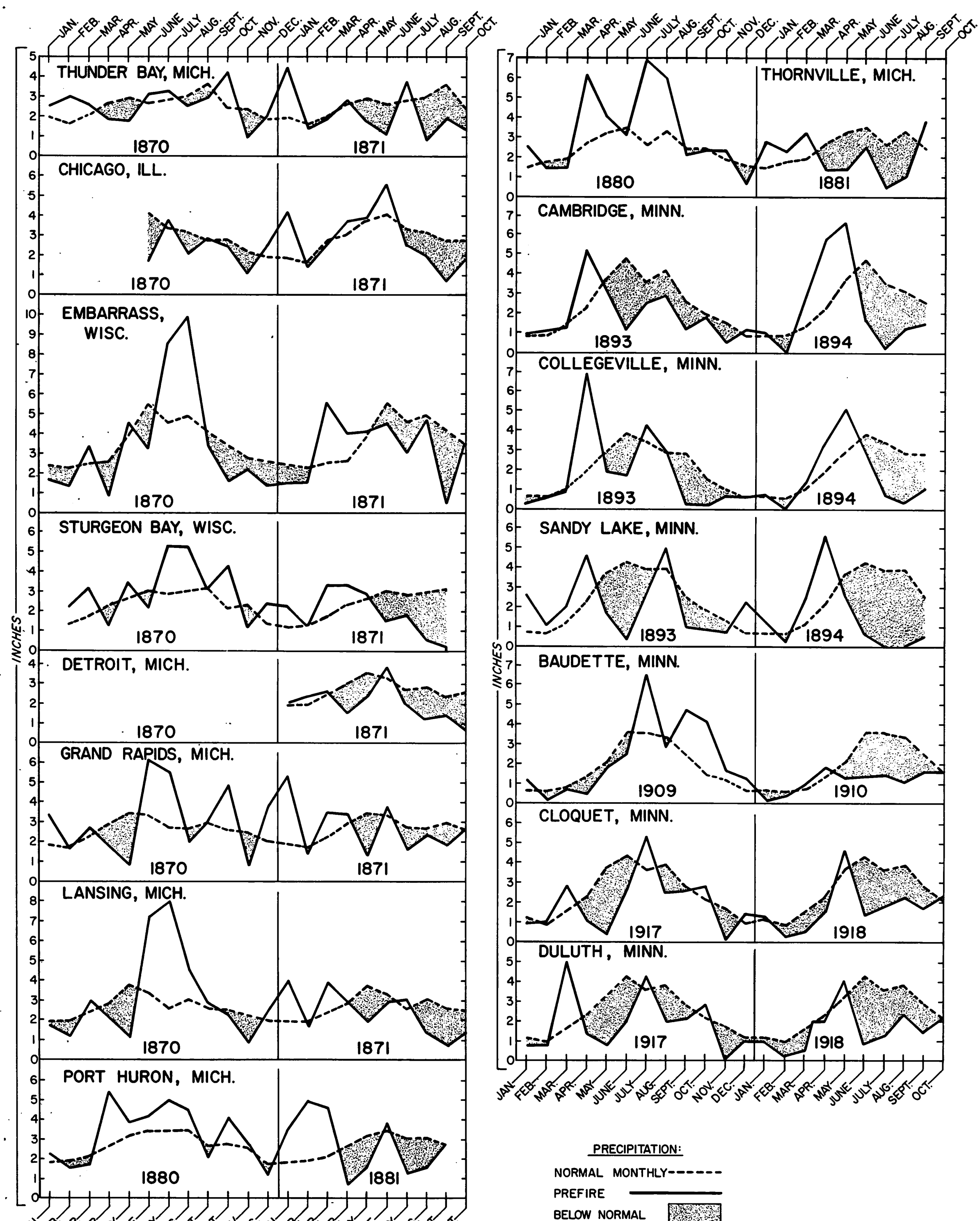

FIGURE 2. — Departure from normal monthly precipitation amount during the 2 years preceding the 1871, 1881, 1894, 1910, and 1918 fires. The normal monthly precipitation is delineated by a broken line, the prefire precipitation by a solid line. Shaded areas represent periods when precipitation was below normal.

arranged in this manner to show the similarities between records in the individual prefire months. Monthly normals are plotted for each station, and superimposed on these normals are the monthly precipitation values during the fire years.

Present-day specialists usually view drought from the standpoint of departure from normal precipitation, as does the American Meteorological Society (Huschke 1959). The rigorous classification scheme of Palmer (1965) is built on a definition of drought as "a prolonged and abnormal moisture deficiency." In our analysis of precipitation preceding large fires, this definition is used as a reference point.

Questions pertinent to this study are: (1) Was the precipitation amount below normal, and, if so, (2) was the abnormal situation prolonged? The first question is answered by simply looking at the graphs; the second is more difficult. In the treatment of agricultural drought, Palmer (1965) showed an example in which his method of evaluation produced incipient to extreme drought from July 1932 to October 1940 in western Kansas. However, the fire drought problem is mostly concerned with moisture loss in dry fuels rather than stress effects upon vegetation growth. Therefore, we will confine consideration of drought to the fire year.

Prolonged and abnormal moisture deficiency began in Lansing and Grand Rapids in May 1871, in Sturgeon Bay in June, and in Chicago in July (fig. 2). It began in Port Huron and Thornville in April 1881, in Sandy Lake in May 1894, in Cambridge and Collegeville in June 1894, and in Baudette in May 1910. In some instances, precipitation was slightly above normal during one month of the period, but the overall seasonal pattern indicates a large precipitation deficit. The beginning of prolonged moisture deficiency is more difficult to establish at the other stations; thus there may be some disagreement on the starting months at these sites.

U.S. War Department (1871) monthly precipitation maps indicate near- or above-normal moisture throughout Michigan in 1870 and early 1871. If we assume that Detroit also experienced these conditions, prolonged moisture deficiency began there in April 1871. Thunder Bay had heavy precipitation in January 1871, then near-normal conditions for 3 months. Fairly low amounts fell in May and June, however, and May was selected as the beginning month of low rainfall.

The Embarrass record shows a dry autumn in 1870 as well as a below-normal winter snowfall. However, March and April had well-above-normal rains. We matched the data with the Sturgeon Bay pattern and designated June as the beginning month of the dry spell. The 1918 Cloquet and Duluth records present a problem, because severe drought may well have begun as early as the autumn of 1916 in that region and continued until the October 1918 fire. To avoid possibly overestimating the importance of moisture deficit, however, we considered only the season in question and assumed an 8-month dry period. Therefore, the periods of prolonged and abnormal departures were as short as 3 months before the Chicago and Hinckley fires, and as long as 8+ months before the Cloquet disaster.

A comparison of the total amount of precipitation that fell during these selected dry periods and the lowest amounts ever recorded for these periods shows that almost all stations (except the Michigan 1871 sites) were near their all-time low precipitation totals during the prefire months (table 2). In fact, five stations recorded their all-time low during these months.

Dividing the length of weather record by the number of times rainfall has been as low or lower than it was in the prefire period gives the return period for the prefire moisture deficient conditions in that area. As an example, Baudette had May through September rainfall totals of less than 6.60 inches only once during its 58-year weather record. Therefore, drought conditions (based on 1910 rainfall amounts) occur on the average of once every 29 years in Baudette. Duluth never experienced a February through September precipitation total less than the 1918 amount of 12.67 inches; therefore, its prefire drought recurrence is 96 years, the weather record length from its beginning through 1968. *It is evident that all but the 1871 Michigan data show one station in each fire region as having a very low recurrence for extreme prefire drought conditions.*

The relative severity of drought conditions preceding each fire is shown in figure 3. The 1894 prefire condition was the most serious and the 1871 Michigan condition the least serious. There is a problem with the intermediate ranking in that it depends on interpreting the importance of time vs. amount of precipitation. But if we total the precipitation for a number of stations for periods of 15, 30, 60, 90, and 150 days preceding the start of a specific forest fire (fig. 4) then the problem can be viewed in a different way. Here the amounts were computed as a departure from normal, and the totals of all stations used in each forest fire situation were added together and averaged for each time period. The usual case was very little rainfall for 15 days before a conflagration. There were, however, some exceptions. Port Huron recorded a total of 0.90 inch and Thornville 0.69 inch of rain on August 31 and September 1 prior to the Michigan Thumb fire. In 1918 Cloquet received light rain on the eighth through the fourth days preceding the fire, but the greatest 24-hour total was 0.15 inch, and the 5-day accumulation amounted to only 0.32 inch. There was no precipitation during the 10-day periods before the other fires.

The problem of trying to determine the severity of prefire climatic conditions when restricted to

Table 2. — Comparison between prefire precipitation and normals

Year	Station	1 Months of drought preceding fire	2 Total precipitation during months of drought	3 Lowest precipitation amount ever recorded during same period of months	4 Number of times total precipitation has been less than amounts given in column 2	5 Length of reliable station record[1/]	6 Normal precipitation amount during months in column 1
			Inches	Inches		Years	Inches
1871	Detroit	6 (April-Sept.)	12.35	10.89	6	96	17.75
	Grand Rapids	5 (May-Sept.)	11.08	7.46	11	96	15.18
	Lansing	5 (May-Sept.)	10.21	8.25	7	103	15.30
	Thunder Bay	5 (May-Sept.)	9.58	8.08	5	96	15.08
	Chicago	3 (July-Sept.)	5.27	4.01	3	96	9.26
	Embarrass	4 (June-Sept.)	12.54	10.98	1	28	18.86
	Sturgeon Bay	4 (June-Sept.)	4.75	4.75	0	80	12.12
1881	Port Huron	5 (April-Aug.)	9.15	7.29	8	92	15.38
	Thornville	5 (April-Aug.)	6.75	6.75	0	90	15.23
1894	Cambridge	3 (June-Aug.)	3.09	2.83	1	75	12.34
	Collegeville	3 (June-Aug.)	4.03	3.19	1	75	10.07
	Sandy Lake	4 (May-Aug.)	3.28	3.28	0	75	15.72
	St. Paul	3 (June-Aug.)	2.00	2.00	0	128	10.85
1910	Baudette	5 (May-Sept.)	6.60	6.36	1	58	14.86
1918	Cloquet	8+ (Feb.-Sept.)	14.20	13.52	1	96	23.19
	Duluth	8+ (Feb.-Sept.)	12.67	12.67	0	96	22.71

[1/] In some cases records at the indicated station were combined with those at a nearby station to fill in missing years and give the longest possible record. As an example, the St. Paul data have been combined with early Fort Snelling records and more recent Minneapolis observations to give the longest historical series of weather records west of the Mississippi River.

evaluation over a rigid time period is illustrated in figure 4. As an example, the departures in five of the six fires very little over 60 and 90 days. But in the sixth case — the Hinckley fire — the departure from normal is much greater than the departures shown for the other fires over these same periods. Conversely, if we examine precipitation records for 150 days preceding the fires, we see that the Hinckley region shows the smallest departure from normal precipitation. A curve showing the average precipitation departure for the six fires is included on the graph, but its usefulness is questionable because of the high variation over any specific time interval among the fires.

Examining departure from normal amount is, of course, only one way to view the contribution of reduced precipitation to large fires. Frequency of precipitation may also be important, because frequent wetting of available fuel should reduce the fire hazard. Consequently, the number of days that had 0.10 inch or more of precipitation was also computed for each fire region. Again, the time intervals examined were 15, 30, 60, 90, and 150 days preceding each fire. The composite results appear random; for instance, the rainfall frequency was extremely low over almost all time intervals before the 1894 Hinckley fire. Rainfall frequency for the 15-day period preceding the Baudette, 1871 Wisconsin, and 1871 Michigan fires was very low, while frequencies for the 60-day and longer periods were more than 50 percent of expected.

Rainfall frequencies preceding the Cloquet and Michigan Thumb fires, except for the 30-day interval at Cloquet, were more than 70 percent of the expected. Apparently there was nothing unusual about the rainfall frequency distributions before these two fires.

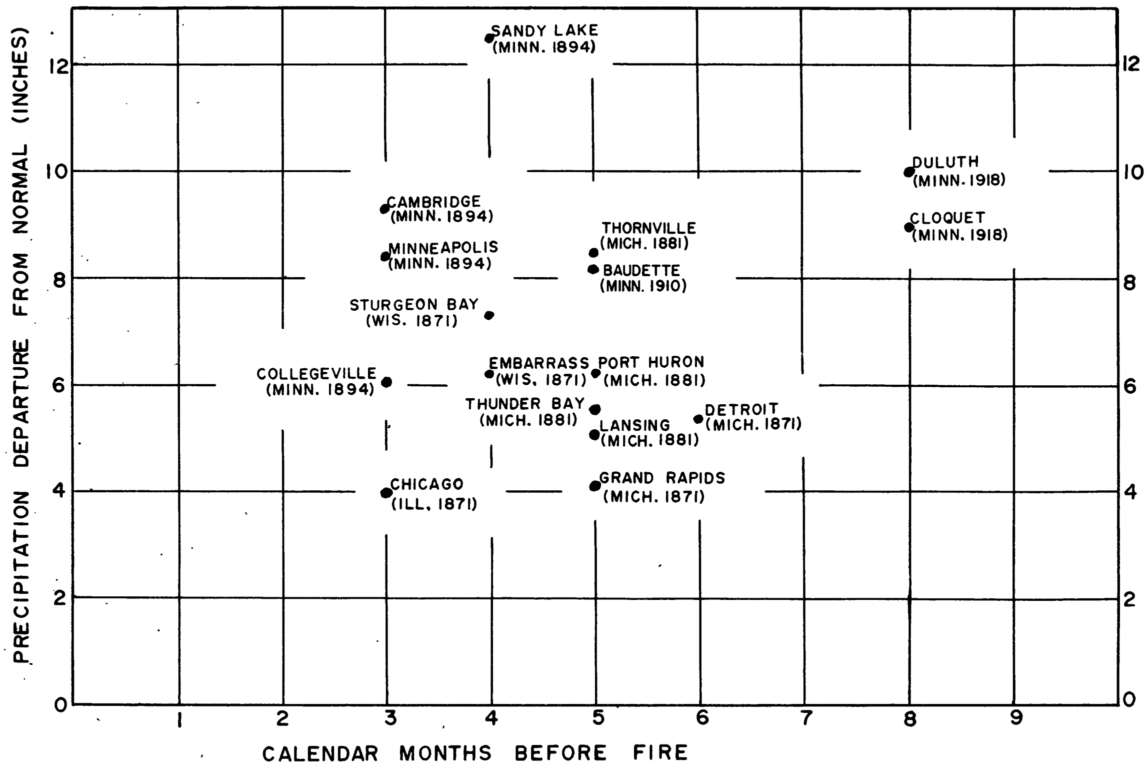

FIGURE 3. — Severity of north-central region fires ranked by prefire precipitation deficit. Sandy Lake, Minnesota, recorded by far the worst conditions preceding the 1894 Hinckley fire. The well-grouped Michigan stations recorded the mildest departure from normal before the 1871 fires.

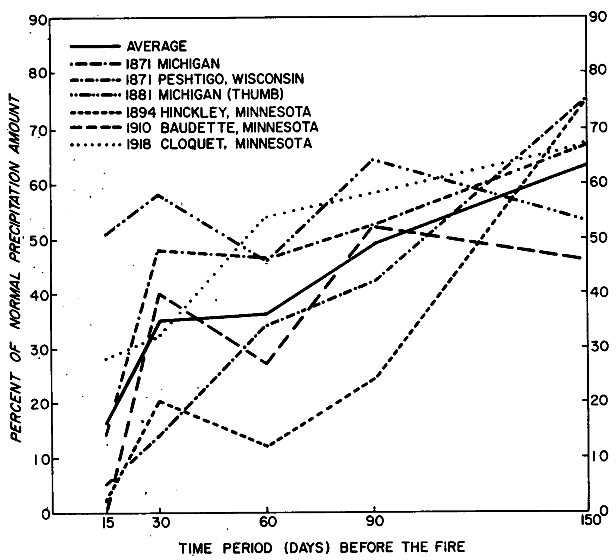

FIGURE 4. — Percent of normal precipitation amount. Data calculated for 15-, 30-, 60-, 90-, and 150-day periods preceding the fire.

Temperature

The literature on climatic conditions preceding large fires may lead one to believe that the terms "hot" and "dry" are nearly synonomous. For instance, Bailey (1882) described the Michigan Thumb region in the following way: "In September no penetrating rain had fallen for almost two months. . . . The swamps had been burned to hard clay by the sun, fiercer in its heat than it had been for years before." However, an examination of the monthly mean departures from normal temperatures at a number of stations preceding the fires shows this contention to be questionable (fig. 5). The U.S. Weather Bureau (1968) considers deviations of more than 0.7° to 1.3° F. to be above or below normal at most Lake States stations during the summer. To be classed as much above or below normal, the deviation must be greater than from 2.5° to 4.7° F. depending on the summer month and station. It is interesting to note that there were above-normal temperatures preceding all the fires, but these often occurred early in the fire year. As an example, strategic regions of Michigan, Illinois, and Wisconsin all had above-normal

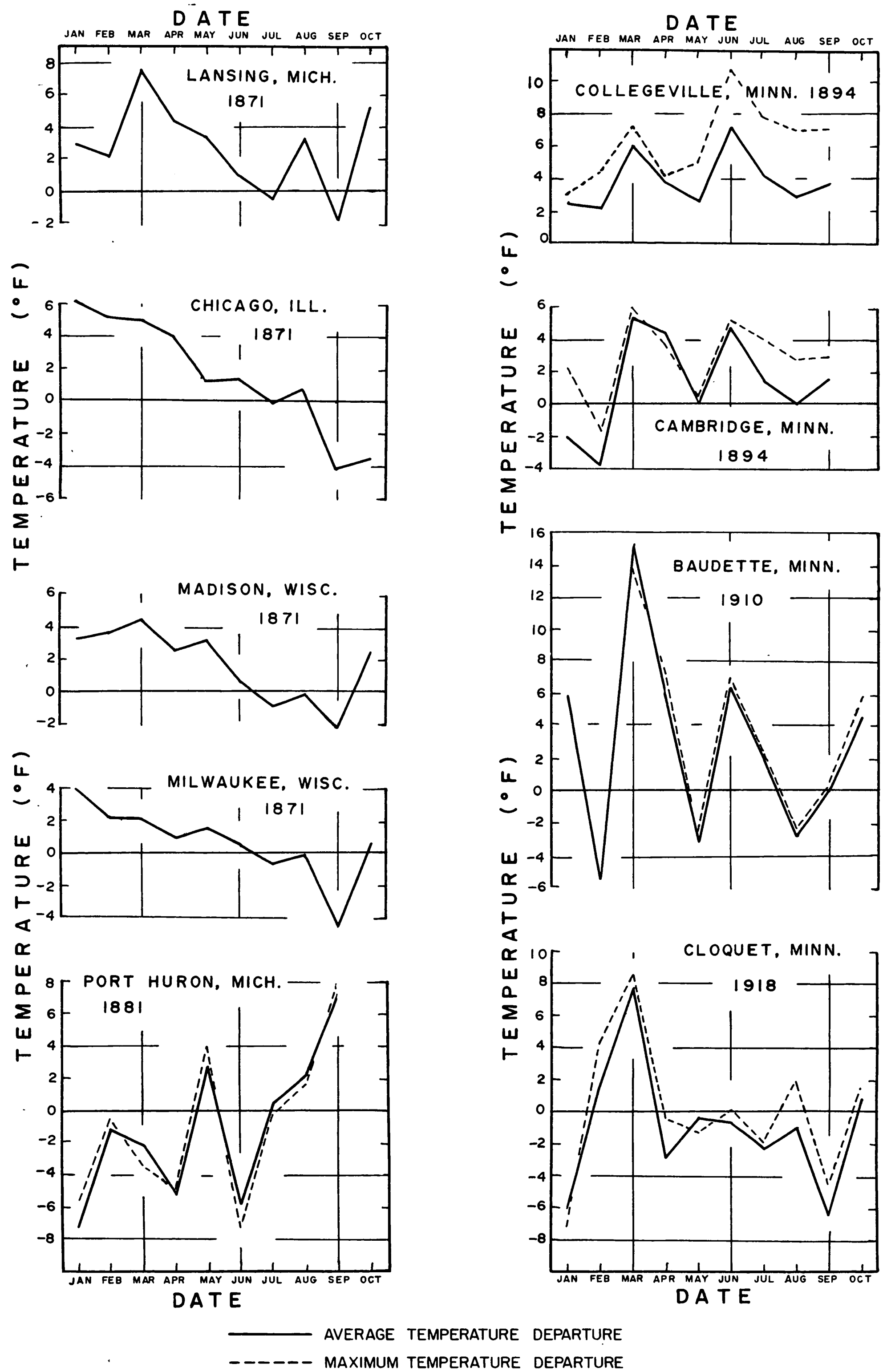

FIGURE 5. — **Departures of monthly temperature from average during the year of the fire.**

temperatures through the first half of 1871. However, their temperatures over the dry period were below normal in most cases (table 3). During the month preceding the fire (table 3), all stations experienced below-normal temperatures in 1871.

The 1894 fire came closest to having a hot-dry prefire climate. As shown in table 2, southeastern Minnesota experienced the lowest June-July-August precipitation total (as observed in St. Paul) throughout a 128-year record. The St. Paul 1894 temperature average for these 3 months has been exceeded only eight times over the length of the station's temperature record (1819 to 1968). Three of these eight occurred in the 1820's when an unknown method was used to compute average temperature. Therefore, 1894 does fit the concept of extremely hot and dry conditions preceding a serious fire situation. In contrast to the 1894 events are the Cloquet prefire conditions where most of the 1918 summer was cool and the temperature during the month preceding the fire was 6.5° F. below the expected.

Computing average temperatures is, of course, only one way of examining the effects of temperature. If the nights were unusually cold and the days unusually hot during these prefire periods, the average temperature might be the same as it would be during periods having only small amplitudes in the diurnal range. Therefore, average temperatures may not accurately reflect daytime drying conditions under high maximum temperatures. The deviation of the maximum temperatures from normal shows the 1894 hot-dry situation to be even more intense than did the deviation of the average temperature (fig. 5). However, this does not appear to be true for the other fires.

We also evaluated temperature by computing the number of days in each month that the daily maximum temperature reached or exceeded 90° F. during the prefire period (table 3). Temperatures in 1894 again stand out as unique. The Hinckley region recorded four to five times the number of hot days that it normally has, and southeastern Minnesota recorded temperatures above 90° F. on half the days in July. Therefore, regardless of the method used to analyze temperature, 1894 stands out as an abnormally hot season.

However, the number of days recording temperatures of 90° F. or higher was less than normal before the Cloquet and Michigan Thumb fires. Therefore, this aspect of temperature did not appear to have had an effect on prefire developments. The Baudette region experienced three times the expected number of days of high maximum temperature before its fire, but almost all of these days occurred during the latter half of June, more than 3 months before the fire began. *Looking at long-term prefire temperature data, we can conclude that abnormally high temperatures are not a necessary prerequisite to large fires.*

When we examine temperatures within 10 days of the fire, however, a somewhat different pattern emerges (table 4). Only the 1871 daily temperatures follow much the same trends shown for longer periods preceding the fires. In 1881 temperatures were 7° above normal for the 10 days preceding the fire, and in 1894 they were 10° above normal. In 1910 temperatures were 12° above normal, and in 1918 they were slightly above normal. It would appear, consequently, that if there is a conflagration reaction to temperature, *it is often a short-term response.*

Table 3. — Average monthly temperature and number of days temperature was 90°F. or above

Year	Station	Average monthly temperature departure during months of drought preceding fire	Average temperature departure during month preceding fire	Number of days temperature was 90° F. or above[1]										Ratio O:E
				June		July		Aug.		Sept.		Oct.		
				O	E	O	E	O	E	O	E	O	E	
		°F.	°F.											
1871	Lansing	+1.1	-1.6	--	--	--	--	--	--	--	--	--	--	--
	Chicago	-1.1	-4.0	--	--	--	--	--	--	--	--	--	--	--
	Madison	- .9	-2.0	--	--	--	--	--	--	--	--	--	--	--
	Milwaukee	-1.0	-4.3	--	--	--	--	--	--	--	--	--	--	--
1881	Port Huron	-1.1	+2.1	0	3	3	6	7	3	2	2	--	--	12:14
1894	Collegeville	+4.9	+3.0	10	2	16	3	7	2	3	1	--	--	36:8
	Cambridge	+2.1	± .0	7	1	15	2	6	2	2	1	--	--	30:6
1910	Baudette	+ .6	+ .2	9	1	3	2	0	1	0	0	0	0	12:4
1918	Cloquet	- .5	-6.5	0	1	1	1	1	1	0	0	0	0	2:3

[1] O = occurred; E = expected.

Table 4. — Temperature 10 days before the fire [1]
(In degrees F.)

Year	Station	September		October								10-day average
		29	30	1	2	3	4	5	6	7	8	
1871	Grand Rapids	55	67	72	69	69	63	73	54	62	76	66
	Grand Rapids normal	69	69	68	68	68	67	67	66	66	65	68
	Lansing	61	69	65	78	69	67	70	80	54	62	68
	Lansing normal	67	67	67	66	66	66	65	65	64	64	66
	Thunder Bay	56	62	62	60	60	56	52	49	54	56	57
	Alpena normal	62	62	62	61	61	61	60	60	59	59	61
	Chicago	64	78	76	76	84	70	76	52	70	85	73
	Chicago normal	72	71	71	70	70	70	69	69	69	68	70
	Sturgeon Bay	61	64	62	64	70	58	52	51	60	63	61
	Manitowoc	64	62	67	70	75	60	53	50	65	65	63
	Green Bay normal	72	71	71	70	70	70	69	69	69	68	70
		August					September					
		27	28	29	30	31	1	2	3	4	5	
1881	Port Huron	86	80	90	94	94	79	74	82	85	95	86
	Detroit normal	80	79	79	79	79	78	78	78	78	77	79
		August									Sept.	
		23	24	25	26	27	28	29	30	31	1	
1894	Cambridge	90	82	84	89	85	88	72	77	83	94	85
	Collegeville	92	82	89	94	89	86	78	81	79	95	87
	St. Cloud normal	79	78	78	77	77	77	77	76	76	75	77
		September			October							
		28	29	30	1	2	3	4	5	6	7	
1910	Baudette (Roseau)	74	72	77	70	71	64	71	59	68	76	70
	International Falls normal	60	60	59	59	58	58	58	57	57	56	58
		October										
		3	4	5	6	7	8	9	10	11	12	
1918	Cloquet	60	58	58	53	50	67	70	72	69	75	63
	Duluth	60	53	57	48	49	67	69	73	52	76	60
	Duluth normal	59	59	59	58	58	57	57	57	56	56	58

1/The 1871 temperatures were taken at 2:00 p.m. EST. All other data are maximum temperatures, including normals.

Potential Evapotranspiration and Water Balance

Up to this point weather variables have been discussed as separate entities, whereas in nature they interact. Therefore, with both precipitation and temperature data tabulated, we now can more fully describe their importance by looking at the soil-water balance.

There are a number of methods available for computing time distributions of soil-water balance. The advantages and disadvantages of the various methods have been discussed by Zahner (1956), Palmer (1965), and Chang (1968). For this study the Thornthwaite method was chosen because we have the computational information needed. This method requires (1) mean air temperature and total precipitation, (2) the necessary conversion and computational tables, and (3) information on the water-holding capacity of the depth of soil for which the balance is to be computed. We have the mean monthly temperature and precipitation data, the necessary conversion and computational tables are provided in Thornthwaite and Mather (1955, 1957), and information on types of soil in the fire regions was extracted from a Wisconsin Agricultural Experiment Station soils classification bulletin (1960). Values for available water-storage capacity and wilting coefficients of forest soils are given in Smith and Ruhe (1955) and Blake *et al.* (1960).

There are disadvantages in the Thornthwaite method. Bias may develop because of neglect of solar radiation, relative humidity, and wind, because they all affect the evapotranspiration term. However, if one uses time periods of sufficient length (2 weeks or longer), average percent absolute error is no higher than 10 to 15 percent (Palmer 1965). Another problem appears when snow or heavy rain enters into the calculations, because these types of precipitation often result in runoff. The method, however, assumes that all precipitation enters the ground and that there is no runoff until the soil is at saturation. Therefore, regardless of the previous year's moisture situation, our calculations produced fully saturated soils after snowmelt each spring. But because we are examining late-summer fires, this bias is eliminated by the time we reach the main period of concern.

Soil-water calculations were made for 3-foot soil depths, the upper rooting depth of bromegrass. When the wilting point of this type of vegetation has been exceeded, large amounts of fine fuel become cured, setting the stage for later serious fire situations. Computations were based on the supposition that all the soils in the fire regions have a 6-inch water-holding capacity and that the vegetation wilting stage is reached when the water amount decreases to below 1.8 inches. Because of the transitional changes and complexities of soil types throughout any region, these are, of course, average figures.

Drought profiles based on the soil-water calculations are shown for one station from each fire year (fig. 6). The upper curve is based on monthly normal temperature and precipitation and depicts the usual seasonal variation of the soil's water supply. While Michigan's vegetation is usually near the wilting stage in September, it is unusual for east-central Minnesota's vegetation to be subjected to extreme drying.

The water-holding capacity of the soil in Minnesota has also been examined by Blake *et al.* (1960) using Penman's (1948) evaluation methods on a daily basis. Blake found that the expected number of drought days is much lower in east-central Minnesota than in the rest of the State. It is about half the number of days expected in the Baudette region. This is almost the same ratio shown between these stations in figure 6. At the low value of the Baudette normal curve there is a departure of about 3.5 inches from field capacity levels. At Cloquet the normal departure from field capacity is less than 2 inches.

The departures from the normal moisture conditions and length of time in wilt again point out the problem of drought definition (fig. 6). The graphs indicate that Baudette was below the defined wilting stage for over 2½ months. The period was about 2 months at the Michigan and Wisconsin stations in 1871, and at the Cloquet station in 1918. The shortest wilt stage was recorded for the 1881 and 1894 fire seasons — 1⅓ months. On the other hand, if we look at the prefire departures from normal water-holding amounts, then the 1894 drought was much more severe than any of the others, with a water departure of over 3 inches from the expected. The Lansing 1871 departures are the least spectacular, the greatest prefire departure from expected being only 1⅓ inches. The reason for this apparent conflict is again obvious: Wilt is a more normal condition at some places than it is at others.

Sunshine Duration

As stated earlier, the neglect of certain meteorological variables might cause erroneous results when computing the soil-water balance. For instance, increased solar radiation contributes to increased evapotranspiration. However, it is impossible to use solar radiation directly in this analysis, for it is measured at relatively few stations and these records are short-term. In contrast, the less important but more easily measured variable, duration of sunshine, has been recorded at many stations, with some records extending back to the 1890's. Baker and Haines (1969) have shown that

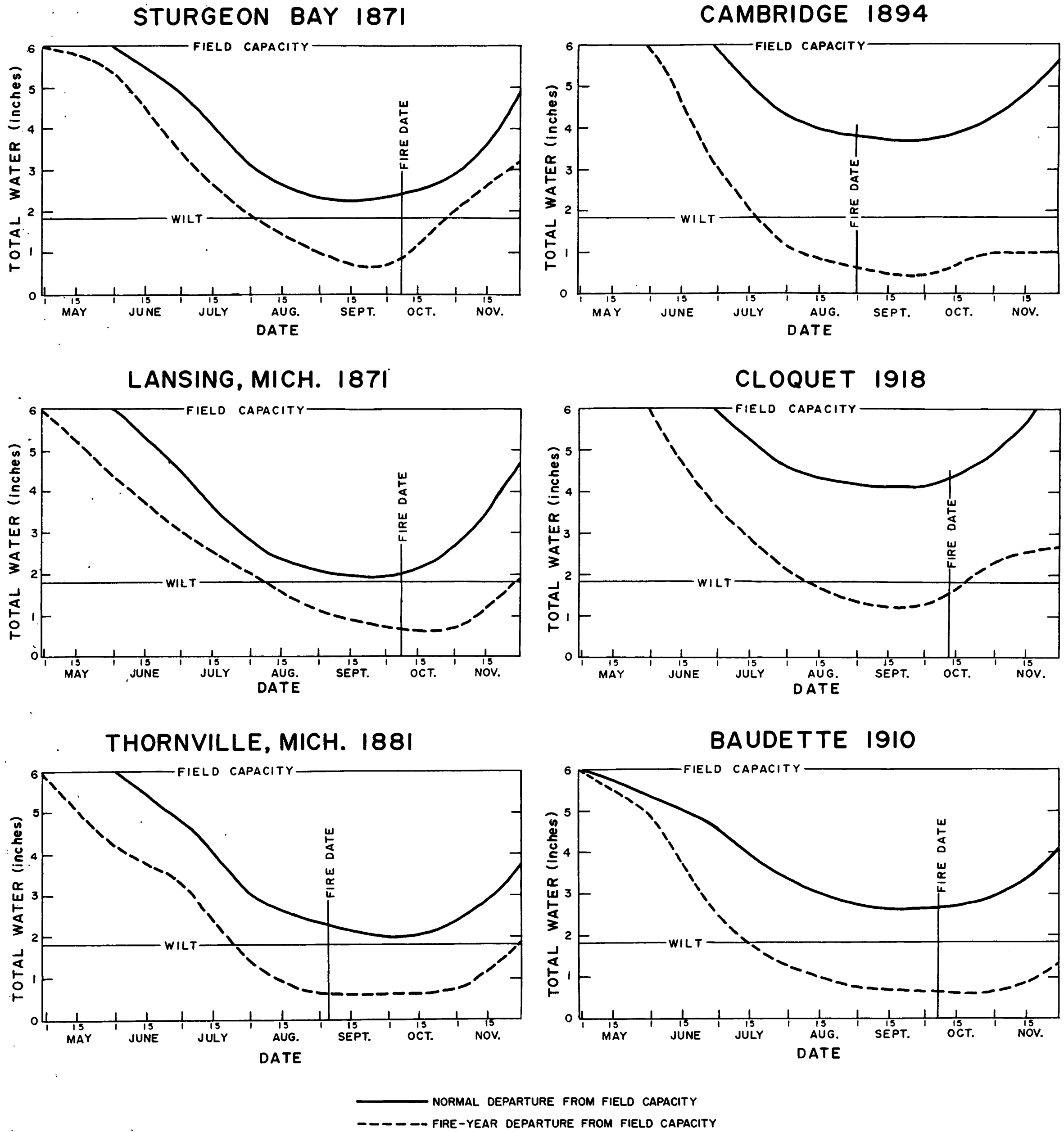

FIGURE 6. — Agricultural drought profile during the seasons of the Peshtigo, 1871 Michigan, 1881 Michigan Thumb, Hinckley, Cloquet, and Baudette fires. Data were computed for a 3-foot soil depth, assuming a 6-inch water-holding field capacity and a 1.8-inch wilt threshold value.

a high correlation exists between the two terms; therefore, available sunshine duration records taken during the fire years are presented in lieu of solar radiation tabulations (table 5).

The information recorded at observation sites during 1894, 1910, and 1918 shows that well-above-normal sunshine prevailed during the early portion of these seasons. Except during May 1918, every monthly average through July exceeded the expected percentage. There was a small minus departure in August 1894 preceding the Hinckley fire, but a plus departure in the month preceding the 1918 Cloquet disaster. However, an added factor may have entered into the Hinckley record. The

Table 5. — Departure from expected sunshine duration

(In percent)

Year	Station	March	April	May	June	July	Aug.	Sept.	Oct.
1894	Collegeville	--	--	+1	+16	1/+22	-4	-1	--
1910	Collegeville	--	--	+17	+16	+11	±0	+9	+11
	Devils Lake (N. Dak.)	+15	+11	+8	+17	+9	-7	-1	+7
1918	Duluth	+9	+13	-9	+13	+4	+7	+9	-9

1/ Only 10 days of record available in July. Supporting data indicate the value is probably closer to +10 to 15 percent.

sunshine instrument depends upon a certain intensity of solar radiation for activation. The Sunrise City, Minnesota, U.S. Weather Bureau observer states on his August 1894 form, "Most of the month has been clear and very smoky so one could look at the sun without smoked glass." Perhaps, then, smoke caused diminished sunshine at Collegeville in that month.

Evidence is somewhat contradictory during August and September preceding the Baudette fire. The Devils Lake, North Dakota, record shows percentages below the expected, while Collegeville shows percentages at or above the expected. However, the percentage of Clear Sky Charts (U.S. Weather Bureau 1910) for these 2 months places Baudette in the same regional pattern as Devils Lake; consequently, the Devils Lake record is probably more representative. The overall pattern that emerges from our somewhat scanty sunshine percentage data indicates above-normal solar radition through spring and summer, but a tendency toward near-normal reception during the month before the fire. Thus, above-normal sunshine duration during the prefire periods substantiates our previous drought estimates.

Relative Humidity

Relative humidity is, of course, most critical immediately before and during the fire, but it may also have a long-term effect on coarse fuels. Therefore, the departures of average monthly relative humidity from expected, especially the month-to-month trends, are significant (table 6).

Table 6. — Departure from expected monthly relative humidity

(In percent)

Year	Station	Local time of observation	March	April	May	June	July	Aug.	Sept.	Oct.
1871	Ann Arbor	2:00 p.m.	-6	-2	+4	+11	+7	+7	+5	-2
	Chicago	1:00 p.m.	+11	+8	+15	+10	+11	+10	-9	-18
	Madison	1:00 p.m.	-1	-7	-3	-6	-8	-2	-16	-22
1881	Thornville	2:00 p.m.	+15	+1	+1	+9	+3	-3	+2	--
1894	Duluth	7:00 p.m.	--	+17	+3	-8	-13	-5	-12	--
	Collegeville	7 a.m., 7 p.m.1/	--	--	--	±0	-10	-3	-10	--
1910	Devils Lake	7 a.m., 7 p.m.1/	-11	-9	-6	-16	-13	-6	+3	-4
	Duluth	7:00 p.m.	-10	+1	-10	-18	-13	-4	-4	-6
1918	Duluth	12:00 noon	-8	-6	+7	-6	-1	±0	-11	-7

1/ Mean of two observations.

The average monthly relative humidity was below the expected throughout much of the 1894, 1910, and 1918 fire seasons. We have seen that monthly temperature was not abnormally high in 1910 and 1918 prefire periods, but diminished atmospheric moisture seems to have contributed to the explosive fire situation.

Long-term humidity effects apparently had no bearing on the 1881 Michigan Thumb fire but most certainly did in the Wisconsin-Illinois outbreaks of 1871. Although the Ann Arbor 1871 records show nothing of significance, the Madison and Chicago observations are interesting. The fact that Chicago recorded above-average and Madison below-average humidity from March to August seems to indicate something unusual in one of the records. Large plus departures at Chicago may be at least partly the result of inappropriate normals. However, the interesting facet of the data is the lowered relative humidity departures from August to October at both stations. At Chicago there was a drop of 28 percent in the departure from expected between August and October, and at Madison a 20-percent drop — a phenomenal drying of the air covering this region. This is, of course, reflected in the actual humidities recorded at these stations in the days preceding the fires (table 7).

Humidity was extremely low preceding the Wisconsin 1871 fire, with Chicago recording 1:00 p.m. humidities in the 20's or 30's for 6 of the 10 days before the fire, and Milwaukee and Madison recording humidities of 13 percent within a week of the outbreak. Afternoon humidities for other years are also included in table 7 for comparison.

Table 7. — Relative humidity 10 days before the fire

(In percent)

Year	Station	September		October							
		29	30	1	2	3	4	5	6	7	8
1871	Chicago[1/]	74	38	27	27	44	49	36	44	27	24
	Madison[1/]	18	26	18	26	13	32	37	22	21	24
	Milwaukee[1/]	79	54	27	33	13	64	56	49	34	28
	Ann Arbor[1/]	40	31	42	48	45	60	43	38	47	40
		August					September				
		27	28	29	30	31	1	2	3	4	5
1881	Thornville[1/]	56	40	36	36	40	73	62	55	55	32
		October									
		3	4	5	6	7	8	9	10	11	12
1918	Duluth[2/]	36	94	100	74	90	33	26	24	84	31

[1/] Observations at 2:00 p.m. EST.
[2/] Observations at 1:00 p.m. EST.

Nonweather Factors

The extreme behavior exhibited by all the fires studied appears to have been largely due to unusual weather conditions; however, nonweather factors also contributed to the situations. It is important to note that all of the fires occurred during the period when the forest land in the Midwest was being actively logged and converted to agricultural land. As a result, settlers were dispersed throughout the countryside and large areas of logging residue were common. The extent to which the slash accumulation contributed to the behavior of the fires is unknown; however, the Hinckley and Peshtigo fires burned large logged-over areas (Wilkinson 1895, Brown 1894, Wells 1968). On the other hand, the Cloquet fire burned an area where little, if any, active logging was being carried out (Richardson 1919).

Bailey (1882) stated that one of the principal causes of the Michigan Thumb fire of 1881 was the large acreages of dead timber left standing from former fires and the large areas of windfalls and slashings.

Fire behavior is largely determined by interactions of fuel, weather, and topography (Davis 1959). However, behavior of these mass conflagrations was greatly influenced by one additional factor — ignition. In all the fires studied, it is well documented that there were many ignition points when extreme fire behavior began. Robinson (1872) wrote, "For weeks preceding the Peshtigo fire, fires were sweeping through the countryside," while Bailey (1882) stated that in the days of early August 1881, fires were burning everywhere and no attempts were made to control them. According to Wilkinson (1895), fires were burning in the Hinckley area as early as July. Fisher (1918) and Richardson (1919) both state that for several days before the Cloquet fire there had been numerous brush and peat bog fires burning. The map of the Cloquet fire (fig. 1) clearly shows that the fire originated from several points and large areas were burned as a result.

Synoptic Patterns

The series of events leading to these great fires might be compared to the steps involved in firing a weapon. A large amount of fuel was usually available before the fire; this would be analogous to a rifle shell. A unique series of climatic events prevailed during much of the fire season — *the shell is loaded into the rifle chamber*. Smaller fires were burning in the forests and bogs — *the hammer is pulled back*. A favorable synoptic weather pattern developed over the region — *the trigger is pulled and the bullet is on its way*.

This study is primarily concerned with climatic events leading to great fires rather than with the analysis of the synoptic map features on the day of the fire. Therefore, this section will only touch on the important points of this last phase. Those interested in synoptic details may wish to read Beals (1914) for a discussion of pressure features that shows how they might have contributed to the high winds occurring with the 1881 and 1894 disasters. Richardson (1919) examined the 1918 Cloquet fire with the same objective in mind. Briefly, both authors concluded that the strong winds were fire-produced. For example, Richardson believes that during the Cloquet fire, synoptic features ". . . favored wind velocities not much in excess of 30-mile rates." Yet during the fire, Duluth registered maximum velocities of 65 m.p.h. and, according to Richardson winds were ". . . blowing at a rate of 80 to 90 miles adjoining the fire fronts from 2 to 6 miles or more distant from . . . (Duluth)."

Both Beal and Richardson were handicapped in their synoptic examinations by two factors. Frontal theory had not been developed at that time nor did the Weather Bureau take upper air soundings. Upper air patterns occurring during these events will never be known; however, a U.S. Air Force, Navy, and Weather Bureau team (1899-1955) has prepared a Historic Weather Map series and reanalyzed daily observations. This added information for 1918 shows that a frontal system passed over Minnesota on the 11th of October. By the morning of the 12th — the day of the fire — the cold front was well to the east, over eastern Michigan, with the 1,000-millibar, low-pressure system north of the Canadian border, near 90° W. longitude. A westerly flow pattern prevailed over Minnesota and Wisconsin, but the pressure gradient was not excessive. These added surface features help to substantiate Richardson's conclusion that large-scale pressure patterns did not cause the extremely high winds, but rather that ". . . the major force of the gale . . . was fire created."

Synoptic information is available through other sources describing the fires occurring after 1880; however, no good information is available for the 1871 fires. This was an especially interesting year because it saw the largest fire problem ever known triggered by an early October synoptic system. The Peshtigo, Chicago, and Lower Michigan fires resulted from it. Consequently, we will present the weather map features for this period.

A week of October 1871 weather observations were plotted on standard charts and analyzed. The analysis showed that a low-moisture, high-pressure cell moved through the Midwest on Thursday the 5th and Friday the 6th. By Saturday morning the northern sector of the double-celled 1,024-millibar high was centered over Ohio. The potential fire region was in the northwest quadrant of this high and coming under the influence of a complex low then over Montana and Wyoming.

As the first Chicago fire began late Saturday evening, this low had dropped southeastward and was causing a south-to-westerly flow pattern eastward to Lake Michigan. Winds were still relatively light at this time, with the highest in northern Illinois and Lower Michigan, 12 to 14 m.p.h. By Sunday morning this deepening low dominated weather over much of the Western Plains, and, in conjunction with the slow-moving high (1,032 millibars) centered over Virginia and North Carolina, it created an increased pressure gradient.

By Sunday afternoon a frontal system extending from a wave lay over central Minnesota (fig. 7), over northern Wisconsin, and continued into another low positioned east of lower Hudson Bay. Low-level, dry air was moving northeastward into the fire region, and high winds developed from Kansas through Michigan. At 2:00 p.m. EST Sunday, October 8, Milwaukee reported 32, Chicago 22, and Grand Rapids 23 m.p.h. The same conditions continued that evening, with the Peshtigo fire well underway and the Great Chicago fire just beginning, as south to southwest winds of 25 m.p.h. were blowing along both sides of Lake Michigan.

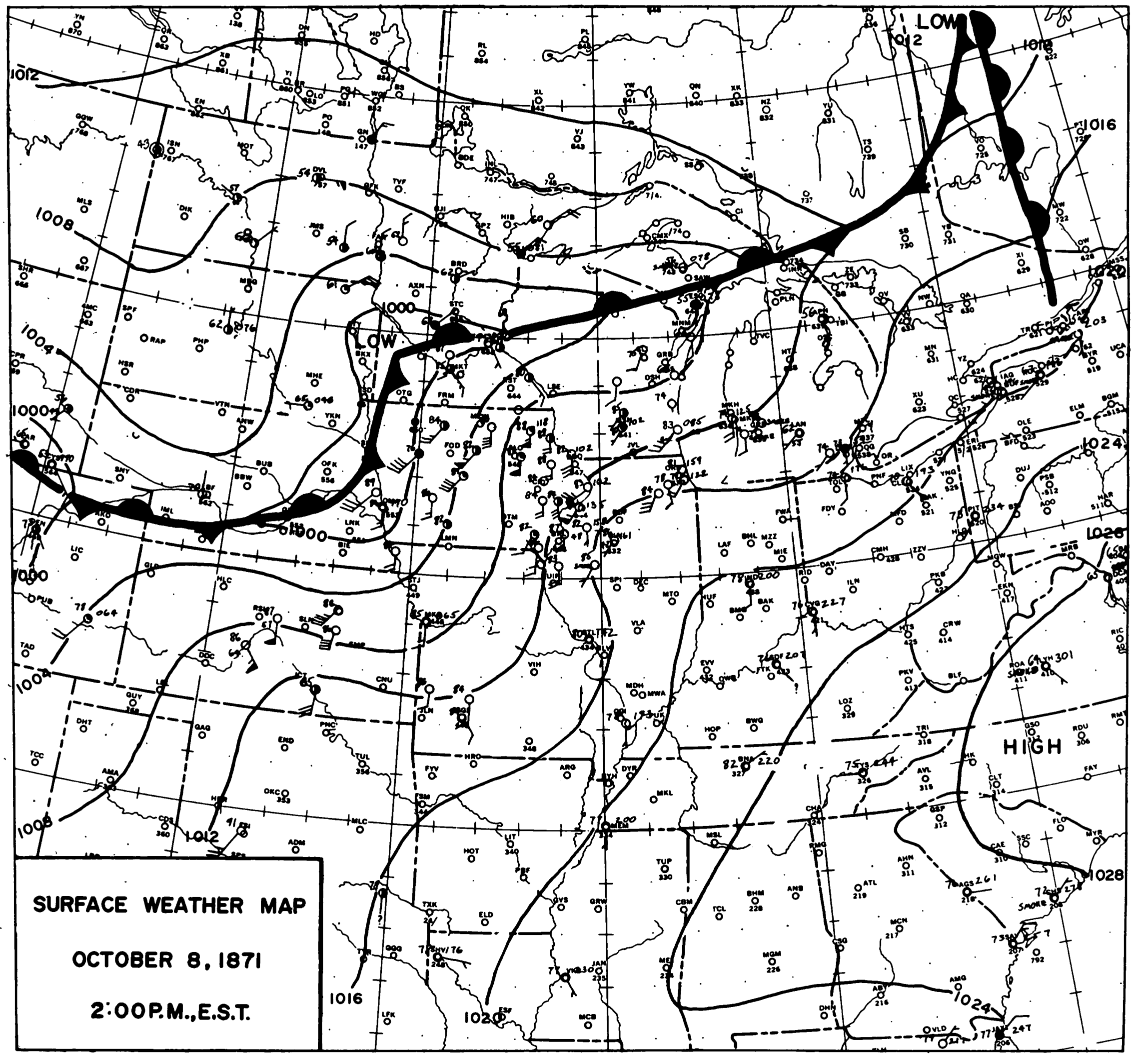

FIGURE 7. — Surface weather map at the time of the Chicago, Michigan, and Peshtigo fires, October 8, 1871, 2:00 p.m. EST. Isolines are drawn for 4-millibar intervals. Open station circles indicate mostly clear skies; half-filled circles represent partly cloudy skies; and filled circles, cloudy skies. Wind barbs conform to the Daily Weather Map code. Note the strong isotach field centered in Iowa, southeast Wisconsin, and northern Illinois.

Monday morning, October 9, the low had moved to southwestern Minnesota and winds of 14 to 16 m.p.h. prevailed in northeast Wisconsin and Lower Michigan. That evening the low was centered over northern Wisconsin. Winds of 20 to 26 m.p.h. were still reported in portions of the fire region.

By Tuesday morning, the 10th, the low was centered over the northern Great Lakes and by evening the associated cold front was pushing through extreme eastern Michigan. At 7:00 a.m. the Thunder Bay observer reported southerly winds of 25 m.p.h. and ". . . smoke so dense and heavy from the fires in the woods on the mainland . . . that the house had to be lighted up the same as night. Could not see to read any newspapers . . . the chickens went to their roosts, a most dismal sight. . . . At noon a heavy blast of wind from the SW continued all the rest of the day." Average winds of 45 m.p.h. were reported before and after the cold front passed over this island station.

Fire-day weather. — Weather conditions during the early afternoon on the day of each fire are tabulated in table 8. In addition, the National Fire Danger Rating Indexes (Nelson 1964) have been computed by using this data and are included in the table. These indexes are widely used in present-day fire-control operations as predictors of potential fire activity.

Table 8. — Weather conditions on the day of the fire [1]

Fire location	Weather station	Temperature	Relative humidity	Wind	National Fire Danger Rating: Buildup Index	Timber Spread Index	Fine Fuel Spread Index
		°F.	Percent	M.p.h.			
Peshtigo, Wis.	Sturgeon Bay	63	--	12	--	--	--
	Madison	80	24	12	101	51	57
	Embarrass	75	--	12	--	--	--
	Milwaukee	83	28	32	90	99	100
Chicago, Ill.	Chicago	85	24	22	80	74	87
Lower Michigan	Lansing (Oct. 9)	78	37	12	60	40	51
	Thunder Bay (Oct. 10)	57	--	45	--	--	--
	Grand Rapids (Oct. 9)	75	--	25	--	--	--
Michigan Thumb	Thornville (Aug. 31)	99	40	34	80	93	100
	Port Huron (Aug. 31)	94	--	2/25	--	79	94
Hinckley, Minn.	Sandy Lake	90	--	3/20	198	84	87
	Cambridge	94	--	3/20	74	74	87
	Collegeville	95	28	3/20	87	69	82
Baudette, Minn.	Duluth	70	34	4/22	51	60	74
	Roseau	76	--	--	51	--	--
Cloquet, Minn.	Cloquet	75	--	--	66	86	100
	Duluth	76	31	5/65	63	86	100

1/The 1871 temperatures were taken at 2:00 p.m. EST. All others are maximum temperatures. Unless noted, all relative humidity and wind velocity values were recorded during the early afternoon.

2/Beals (1914).

3/Maximum value recorded at St. Paul.

4/Maximum value observed for date.

5/Maximum wind for the day, but believed to be extremely strong because of the proximity of the large fire.

SUMMARY AND CONCLUSIONS

The most striking factor in the climatic conditions preceding these seven historic fires in the north-central region is the decreased precipitation over a 3- to 8-month period. In four cases, at least one weather station in the area recorded the lowest precipitation total ever observed. In another case it was the second lowest of record. Precipitation amount was a consistently good climatic indicator; precipitation frequency, on the other hand, varied from fire to fire and provided little additional information.

The data indicate that abnormally hot weather for the season is not a prerequisite to large fires in the north-central region. Although records show above-normal temperatures at some time during the fire year in all instances, most of the departures occurred early in the year. If we restrict temperature analysis to just the prolonged season of dry weather, then only the Hinckley disaster can be truly classed as hot and dry. Four fires actually had below-normal temperatures during the dry period. If we consider maximum temperature departure, again only 1894 recorded well-above-normal temperatures. Examining the frequency of hot days during the season also gave little additional information on temperature.

Short-term temperature fluctuations, however, do appear to be highly significant. Some weather stations recorded normal or even below-normal temperatures on a seasonal basis, but well-above-normal temperatures during the 10 days before the fire.

When we combine temperature and precipitation and use them to analyze agricultural drought, we find that vegetation was below wilt stage for from 1⅓ to 2½ months preceding the conflagrations. These conditions contributed to the serious fire problem by increasing the amount of available fuel.

Solar radiation, as revealed in the percentage of possible sunshine records, was generally above normal during spring and summer of the fire years. This, of course, substantiates our contention that drought was severe.

Lowered relative humidity in most cases also appears to have contributed to the drought conditions. The Michigan data of both 1871 and 1881 show near- or above-normal humidity during the prefire seasons, but all other fire years had below- to well-below-normal relative humidity for most of the season or the month preceding the fire. The Hinckley fire was preceded by the most extreme climatic conditions of any of the cases studied.

Over the past 50 years many of the once-burned forests have been regenerated and protected from fire. Moreover, residue from logging, thinning, and pruning in many of these forests provides an ample source of fuel for conflagrations. Arnold (1968), for example, believes that the Michigan forests today "provide a ready source of large amounts of fuel," and therefore Michigan has the basic ingredient needed for mass fires.

There is no reason why the unusual climatic conditions could not recur in the future; i.e., (1) below-normal precipitation for 3 to 8 months, (2) low vegetation in drought or wilting stage for 1⅓ to 2½ months, (3) long-term below-normal humidity, (4) above-average sunshine duration. In addition, the daily weather patterns that preceded these fires were not unique.

Present ignition potential is much more difficult to assess. All the fires studied burned extremely large areas in short periods of time. Today's large fires that commonly originate from one ignition point never approach the size of these historic fires. As examples, the 1967 Sundance fire of Idaho burned more than 50,000 acres (Anderson 1968), Montana's Sleeping Child fire of 1961 burned 33,000 acres, and Maine's Centerville fire of 1966 burned 12,000 acres. The major source of ignition — people — is greater than it was 50 years ago. However, public awareness of the importance of fire prevention and constant fire control efforts by State and Federal agencies have dampened the threat of major conflagrations. But until man learns how to fireproof the forest or modify the weather, he must remain constantly alert to the threat of new fire disasters, and continue to intensify forest fire prevention and control activities.

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ABOUT THE FOREST SERVICE . . .

As our Nation grows, people expect and need more from their forests — more wood; more water, fish, and wildlife; more recreation and natural beauty; more special forest products and forage. The Forest Service of the U.S. Department of Agriculture helps to fulfill these expectations and needs through three major activities:

- Conducting forest and range research at over 75 locations ranging from Puerto Rico to Alaska to Hawaii.
- Participating with all State forestry agencies in cooperative programs to protect, improve, and wisely use our Country's 395 million acres of State, local, and private forest lands.
- Managing and protecting the 187-million acre National Forest System.

The Forest Service does this by encouraging use of the new knowledge that research scientists develop; by setting an example in managing, under sustained yield, the National Forests and Grasslands for multiple use purposes; and by cooperating with all States and with private citizens in their efforts to achieve better management, protection, and use of forest resources.

Traditionally, Forest Service people have been active members of the communities and towns in which they live and work. They strive to secure for all, continuous benefits from the Country's forest resources.

For more than 60 years, the Forest Service has been serving the Nation as a leading natural resource conservation agency.