THE APPLICATION OF METEOROLOGY TO FOREST FIRE PROTECTION

by

J. G. Wright and H. W. Beall

Technical Communication No. 4
Imperial Forestry Bureau

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FOREWORD

This is the third in our series of reprints of early forest fire research publications. Many of these have been out of print for years and thus not readily available to workers in forest fire control. The Institute has undertaken a program of reprinting these as part of a continuing service to disseminate fire research information.

The original publication "The Application of Meteorology to Forest Fire Protection" was Technical Communication No. 4 of the Imperial Forestry Bureau. Permission to reprint was kindly granted by Sir Thomas Scrivenor, Secretary, Commonwealth Agricultural Bureaux, Farnham Royal, Bucks., England.

To the extensive list of references included in the original publication we have added a bibliography of Canadian forest fire research literature covering the period 1945 to 1967. This updates some of the earlier Canadian references.

Biographic notes on the authors of "The Application of Meteorology to Forest Fire Protection" will be found in the forewords of Information Report FF-X-5 and FF-X-8, available from the Institute.

D. E. Williams
Director

I. INTRODUCTION

The systematic study of the influence of weather upon forest fires is of comparatively recent origin. While forestry has inherited from European sources a considerable volume of literature on silviculture, wood technology, forest pathology and forest entomology, there is no comparable literature on the subject of "forest pyrology", to use an expressive term coined by Gisborne (1939) of the United States Forest Service, who has been one of the most prolific writers on this subject. This lack of interest in the subject of forest fires on the part of European foresters indicates that losses from this cause do not loom as large in the national economies of the countries concerned as they do in North America and Australia, to take two outstanding examples. There are several reasons for this, one being that in Europe normal rainfall during the summer season is comparatively more plentiful and frequent, so that there are relatively fewer days on which fires can spread.

In Europe, forest fires are not as a rule as damaging as those which occur for example in Canada. In Russia the size of the average fire in the period 1931-35 was 235 acres [cf. Serebrennikov and Matreninski (1940)]. In Finland the average in 1920 was about 68 acres [cf. Saari (1923)]. In Great Britain the average is only 3 acres [cf. Great Britain (1937)]. In Canada, the average fire exceeds 400 acres in extent. As will be seen later, serious forest-fire losses in regions of normally ample summer rainfall are confined to abnormal years or periods when there is a rainfall deficiency. In many regions on the North American continent the normal summer rainfall is insufficient to prevent forest fires, and it is only in abnormal years that there are small fire losses.

Other factors that tend to reduce fire losses in Europe are better forest management and closer utilization of forest products, resulting in less flammable debris being left in the woods to provide fuel for forest fires, and the fire consciousness of the public arising from long recognition of the importance of forests to the national life.

In the United States the first national statistics on the occurrence of forest fires were compiled in 1880 as part of the tenth census [cf. Palmer (1917)]. Even as late as 1902 there was apparently no real official recognition of the necessity for an "all-out" effort to combat forest fires, since the following appears in a Forest Reserve Manual issued in that year [cf. Nelson (1940)]:

> "While the government is willing and anxious to prevent and fight forest fires, and is willing to go to considerable expense therefor, it is unreasonable to suppose that an unlimited amount of money is to be devoted to this effort. Experience has proven conclusively that in most cases a reasonable effort is all that is justified, and that a fire which cannot be controlled by 20 to 40 men will run away from 100 or more men, since heat and smoke in such cases make a direct fight impossible. Unusual expenditures will not be tolerated. They are unnecessary, wasteful and even mischievous."

In Canada, forest-fire statistics on a national basis were not available before 1918, although some of the older provinces gathered fire statistics much earlier. The earliest known record in Canada of any governmental plan for forest-fire protection appears in a report of Aubrey White (1886) to the Commissioner of Crown Lands of Ontario. White called attention to the great destruction of the forest wealth of the province by forest fires and submitted for consideration a plan to exercise government supervision over the public domain in order to prevent, as far as possible, the starting of fires, and to control and extinguish fires before they assumed dangerous proportions. He recommended the establishment of a fire ranger service at an estimated cost of $5,000 per year and outlined the duties of the rangers. What is of interest to this study is White's early recognition of the principal factors controlling fire behaviour. He says, "I have not thought it necessary to describe minutely the various modes of combatting bush fires as the necessary steps depend largely upon the extent of the fire, the state of the weather and the nature and localities of the timber."

According to Gisborne (1928, 1942a) it was not until 1907 that the results of studies of forest fires began to appear in print with any frequency. In the United States, the creation of a large number of national forests from 1904-07 and the assumption by government of responsibility for the preservation and protection of great areas of forest land, focused the national attention upon the fire problem, which previously had been only a matter of local interest. These early studies dealt mainly with the causes of fires, the amount of damage, methods of preventing fires from starting and the best methods of putting them out.

The first analysis of the effect of weather upon forest fires was made by E.A. Beals (1914) of the U.S. Weather Bureau. Beals recognized the possibility of using weather forecasts as a basis in preparing for periods of great fire danger. It was largely owing to his efforts that the first fire-weather warning service was instituted in the Pacific North-West in 1914.

The first quantitative experiments to determine why fires burn more fiercely at certain times, and what controls their behaviour, were begun in 1915 by S.B. Show (1919) of the United States Forest Service in California. From 1919 onwards the literature becomes increasingly plentiful.

Most of the early investigators tried to identify single weather factors, the measurement of which would serve as an indicator of fire danger. Some observers, however, early recognized that the problem was not quite so simple and that much exhaustive research had still to be carried out. Among these may be mentioned H.R. Weidman of the Priest River Forest Experiment Station in Idaho, and J. Patterson of the Canadian Meteorological Service.

In 1923 Weidman wrote as follows: "While relative humidity is important it is not the only factor which must be considered. The duff moisture content resulting from various amounts of rain; the rate of drying after various amounts of rain; the effect of duration of rainfall; the effect of forest canopy upon the amount of rain reaching the ground; the effect of temperature, relative humidity and wind velocity upon the drying of duff; the moisture contents attained by various fuels under all possible combinations of temperature and relative humidity; these are factors to be studied."

In 1925 Patterson stated: "There is another question that should be investigated in order to know more completely the conditions that govern the fire risk and that is the critical value of the moisture content, the point where the material takes fire instantly without further drying, and also the rate at which the moisture is given out or taken up as the humidity changes. Some substances follow the changes of humidity very closely and as soon as the humidity has fallen below a certain value, the critical point is reached; others again, have a lag and it may be an hour or two before the substance has dried sufficiently to reach the critical point. . . . These are problems that should be studied for the different fire zones, because the substances in each zone may behave differently, and it is only when these facts are accurately known that the best and most efficient use can be made of the weather service."

In the past twenty years most of the questions propounded above, and a great many more, have been studied. This paper is an attempt to review the principal discoveries made by a great many investigators. Only those phases of the fire problem which are likely to be of interest to both foresters and meteorologists have been covered, and if some important contributions have been overlooked, the writers tender their apologies to the authors. Nearly all of the literature available for reference has been published in North America. The contributions by Wright and Beall are based on work begun in 1929 at the Petawawa Forest Experiment Station of the Dominion Forest Service at Chalk River, Ontario, and in later years extended to Quebec, New Brunswick and the Prairie Provinces.

II. FACTORS AFFECTING FOREST FLAMMABILITY

Fuel Moisture and Flammability

The laws which govern the combustion of the fuels in a forest fire are essentially the same as those which apply in any ordinary fire [cf. Wright (1935)]. There must be a sufficient quantity of fuel physically arranged in a manner conducive to combustion, the moisture content of the critical fuel must be low enough to permit combustion, and there must be an ignition agent capable of supplying sufficient heat at a high enough temperature to ignite the fuel. In a given fuel type, moisture content is usually the variable which determines whether or not a fire will burn. The moisture content of the litter of dead material on the forest floor (which constitutes the critical fuel in most forest types) is in turn largely dependent upon weather factors.

In 1915 Show (1919) found that in California forest litter composed of Pine needles, twigs, particles of bark, dead weeds and grass would not burn when its moisture content was above 8 per cent. His determination of moisture content appears to have been based on air-dry weight at normal temperature and relative humidity, a condition under which the samples would probably contain 8 per cent or more residual moisture so that the limit of flammability probably occurred at about 16 per cent based on oven-dry weight. Show found that the fuels absorbed moisture from the air at night, beginning about 5:00 p.m., and began to lose it again about 6:00 a.m. the following morning. The relative humidity reached its minimum about 3:00 p.m. and its maximum about 4:00 a.m. This indicates an equilibrium time lag of about 2 hours, which agrees with the findings of later investigators.

About 1923, Gisborne (1928), at the Priest River Forest Experiment Station in Idaho, defined six zones of flammability for Western White Pine (Pinus monticola) duff based upon moisture content:

Flammability	Duff moisture content per cent	Ignition agent effective
Nil	Over 25	None
Very low	19-25	Large slash fires
Low	14-18	Camp fires
Medium	11-13	
High	8-10	Dropped matches
Extreme	0-7	

He found that finely-divided fuels came quickly into equilibrium with the prevailing relative humidity but that heavier branch wood and logs required weeks to dry thoroughly from a wet condition.

Stickel (1931) in the Adirondacks defined zones of flammability for eastern mixed wood forests based on moisture content of forest duff:

Flammability	Moisture content surface duff per cent	Effective fire brands
Generally safe	30 or more	None
Very low	23 to 29	Camp fires
Low	17 to 22	Matches
Medium	11 to 16	Pipe heels
High	6 to 10	Locomotive sparks
Extreme	Under 6	Cigarettes

Wright (1932) defined flammability zones for the Pine forests of eastern Canada:

Flammability	Moisture content of top-layer duff per cent	
	Mixed Red and White Pine, and mixed Jack, Red and White Pine	Pure Red Pine
Nil	24 and over	35 and over
Low	19 to 23	24 to 34
Moderate	15 to 18	17 to 23
High	11 to 14	11 to 16
Extreme	10 and under	10 and under

Red Pine = *Pinus resinosa*; White Pine = P. *strobus*; Jack Pine = *banksiana*

While fuel moisture content is generally the best indicator of how a fire is likely to behave, it is important not to lose sight of other factors that influence combustion. There must be a sufficient quantity of fuel physically so arranged as to be conducive to combustion. If the fuel is scanty or discontinuous fire may not spread, regardless of the moisture content; hardwood litter may become so compacted after leaf canopy development as greatly to retard the spread of fire; at certain seasons, dead grass or other seasonal vegetation may contain sufficient green shoots to prevent the fire spreading. These factors make it necessary to study each fuel type independently in order to determine the variables which control the fire hazard.

Weather Factors

Rainfall.

Rainfall is the principal source of moisture in forest-fire fuels. As early as 1920 Larsen and Delavan (1922) of the Priest River (Idaho) Forest Experiment Station made an analysis of the reports of over 12,000 fires which had, during the previous decade, burned over 15 per cent of the national forest area in Idaho and Montana. They found that in eastern Montana, where the annual precipitation was 14.22 inches, fire losses were only a small fraction of those which occurred in Idaho where the annual precipitation was 30.37 inches. This anomaly was explained by the fact that Idaho had only 1.40 inches of rainfall per month in July and August, while eastern Montana had nearly 3.0 inches in each of these summer months. The analysis showed that 2.0 inches of rain per month was the minimum necessary to prevent the development of serious fires. It was also found that the amount of winter precipitation had little, if any, effect upon fires in the following summer. In a later article Larsen (1935) suggests that the normal length of the fire season can be found by noting the length of the intercept of the 2-inch precipitation line on a graph of normal rainfall by months.

Gisborne (1928) largely confirmed Larsen's findings, stating that as a general rule about 2.0 inches of rain per month are necessary to keep down fire danger, the amount varying with the duration of the rainfall and the drying conditions between storms. Rains of 0.6 inch or more, evenly distributed trhough 48 hours, are necessary to saturate forest duff. Rains of 0.2 inch or more in 24 hours are generally sufficient to end danger temporarily. The effects of a downpour are often less beneficial than the effects of a smaller volume of rain well distributed over a longer period.

Mitchell (1926, 1929) at the Lake States Forest Experiment Station analyzed the occurrence of fires in relation to rainfall, for ten-day periods, by seasons, and found that the amount of rainfall required to keep fires from spreading was greatest in summer, somewhat less in the spring and least in the autumn. In general, he found that 0.2 inch of rain would prevent fires from spreading for a day or so.

At the Petawawa Forest Experiment Station it has been found that a minimum of 2.0 inches of rainfall per month, evenly distributed, is necessary to prevent fires from spreading in the Pine types.

The amount of moisture absorbed from a given rain depends upon the kind of fuel, its moisture content before the rain, the nature of the site, the amount of rain, and its duration [cf. Wright (1932)]. The degree of forest canopy and the nature of the duff, which depends upon the species as well as the exposure, also affect the influence of a given amount of rain [cf. Wright (1935)]. More than 0.5 inch of rain are required to end the spring fire hazard in tolerant hardwood forests after the leaf canopy is 50 per cent developed [cf. Wright and Beall (1940)], and in mixed wood forests the hardwood leaves must be fully developed before 0.5 inch of rain will have this effect. Empirical curves have been prepared showing the wetting effect upon Pine duff of rains of varying amount and duration [cf. Wright (1932)].

Saari (1923) in Finland found a coefficient of correlation of 0.46 to exist between the annual number of fires and rainfall during the summer months (June-August). An examination of Saari's data reveals that the normal summer rainfall is about 2.6 inches per month and that large fire losses were confined to the years when the summer rainfall averaged less than 2.0 inches per month. In Great Britain (1937), with a normally high monthly rainfall, the number of fires varies inversely with the amount of rainfall, the majority of fires being confined to abnormally dry summers. In the forests of Northern Russia, where the normal rainfall in spring and early summer is less than 2 inches a month, only 9,000 hectares were affected by fire in the abnormally wet year of 1935, compared with 520,000 hectares in the abnormally dry year of 1932 [cf. Serebrennikov and Matreninski (1940)]. Newfoundland has a normal summer rainfall in excess of 3.5 inches per month, but destructive fires developed there during periods of abnormal drought in 1935 [cf. Shaw (1936)] and again in 1943. The conclusion may therefore be drawn that regions having a normal summer rainfall of less than 2 inches per month may expect bad fire seasons as a normal occurrence, with relief only in an abnormally wet year. Other regions with normal rainfall above 2 inches per month must be on guard against abnormal drought periods, when heavy damage may occur.

In 1925 Munger prepared rainfall probability graphs by 10-day periods for western Oregon and Washington and his method of computing rainfall probability was followed later in other regions.

A reference to the amount of rain intercepted by forest canopy may be of interest. Horton (1919) gives interception values for different tree species. The percentage of rainfall reaching the ground is small in the earlier stages of a rain and increases until the tree surfaces become saturated, after which the loss is confined to evaporation from the tree surfaces. The average loss ranges from 70 per cent in very light showers to about 24 per cent in long heavy rains. Mitchell (1929) sets the average loss at about 20 per cent but points out that the effect of this loss upon the fire hazard is more than compensated by the slower rate of drying under forest canopy. Beall (1934a) found that the average loss in softwoods was about 40 per cent and in hardwoods about 20 per cent. He also found that the presence or absence of foliage on hardwood trees does not materially affect the percentage of rainfall reaching the ground, except possibly in the case of very light rains.

In forest rainfall studies it is sometimes necessary to measure rain on exposed, windy slopes. Hayes (1944a) points out that conventional rain-gauges may, under these conditions, give highly erroneous results. He describes a more reliable pit-type rain-gauge in which the orifice is flush with the ground and cut to the same slope as the ground.

Temperature.

Air temperature has, of course, an important influence on the capacity of the air to hold moisture [cf. Wright (1935)]. For instance, one cubic foot of air at a temperature of 60°F. will hold 5.745 grains of water vapour at saturation (100 per cent relative humidity), but at 90°F. it will hold 14.700 grains. If air at 60°F. and 50 per cent relative humidity (2.872 grains per cu.ft.) is heated to 90°F., the relative humidity will be reduced to 19 per cent (2.872/14.790), a dangerously low level in so far as forest fires are concerned.

Furthermore, the rate of evaporation is roughly proportional to the depression of the wet bulb of a psychrometer. At 60°F. and 50 per cent relative humidity the depression of the wet bulb is about 10 degrees. At 90°F. and 19 per cent relative humidity the depression is about 27 degrees. The rate of transfer of moisture from wet fuels to air should therefore be nearly three times as rapid in the latter case as in the former.

In spite of this, investigators have found rather poor correlation to exist between temperature and the occurrence of fires, although it is admitted that fires are seldom associated with temperatures below 50°F. Larsen and Delavan (1922, 1925) found that the fire season began when the mean temperature rose above the 50°F. line and ended when it dropped below that line in the autumn. Saari (1923) found a coefficient of correlation between mean summer temperature and number of fires of 0.31, and Stickel (1931) also found a relatively low correlation. Mitchell (1929) found that temperature had little effect upon fire hazard except in its influence upon relative humidity. Gisborne (1928) defined zones of temperature to which he attached different degrees of duff flammability but did not recommend their use except in conjunction with known duff moisture contents, rate of drying, and wind velocities.

Temperature	Flammability
55°F. or less	Generally safe
56°-70°F.	Slightly dangerous
71°-85°F.	Dangerous
Over 85°F.	Extremely dangerous

Gisborne (1941) also shows that at ground-level under forest canopy the temperature begins to drop (and the relative humidity to rise) after 3:00 p.m. so that by that time the peak of the day's hazard is over, although in the open the peak may persist for another two hours or longer.

Relative Humidity.

As previously explained, relative humidity is the percentage of moisture present in the air in comparison with the amount of moisture the air would hold if saturated at the prevailing temperature. Relative humidity is also given by the ratio of maximum vapour pressure at dew-point temperature to maximum vapour pressure at prevailing air temperature.

About 1919, Hoffman and Osborne (1923a,b) stressed the importance of measurements of relative humidity as an index of fire behaviour. They stated that high fire hazard is always a result of low relative humidity. Strong winds, steep slopes and intense heat from burning materials are important factors which naturally increase the rate of spread *after* the material has reached a certain degree of flammability, but *regardless* of these factors, any fire will soon die down to, and remain in, the smouldering stage, or go out, if the relative humidity of the air becomes high.[1] From studies at the Wind River (Washington)

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[1] It was found later that this last claim was somewhat over-optimistic.

Forest Experiment Station and from observations made at large fires, Hoffman and Osborne drew the following conclusions as to fire behaviour:

Relative humidity per cent	Fire behaviour
Above 60	No spread
50-60	Spread slowly in favourable material
40-50	Begin to pick up
30-40	Gain headway and may spread rapidly
Below 30	May go beyond control
Below 25	Crown fires develop

Show and Kotok (1925) in California endeavoured to separate statistically the effects of wind velocity and relative humidity upon fires. They concluded that each of these factors had an important effect upon the size of fires and that relative humidity alone could not be used as an index to fire behaviour. They pointed out that the issue had been confused in the past because high winds are frequently associated with low relative humidity.

Saari (1923) in Finland found the coefficient of correlation between average summer relative humidity and number of fires to be only 0.36, and later Stickel (1931) and Jemison (1935) found poor correlation between relative humidity and duff moisture content.

Gisborne (1928) and Wright (1932) produced curves showing the equilibrium moisture contents of a number of fuels under various conditions of temperature and relative humidity. Both showed that even 100 per cent relative humidity will not induce more than about 40 per cent moisture content in the duff and that this is quickly lost when the relative humidity drops. Relative humidity is important in determining the ultimate dryness of fuels, and high humidity may induce relief from hazard for short periods if it persists [cf. Gisborne (1928)]. It is necessary to know the kind of fuel, its present moisture content, its exposure, the rate of evaporation, the temperature and the wind velocity, in order to interpret relative humidity in terms of flammability. Bearing these facts in mind, Gisborne gives the following general rule for using relative humidity as a guide to flammability.

Relative humidity per cent	Flammability
Over 70	Generally safe
46-70	Slightly dangerous
26-45	Dangerous
25 and under	Extremely dangerous

Simpson (1930) showed a time lag in equilibrium between relative humidity and the moisture content of certain fuels:

Fuel	Lag in hours
Fern..	1
Outside 1/8 in. of Douglas Fir "snags"	1-1/4
Douglas Fir duff	1-1/2
Decayed wood	2-1/4

Wright (1932, 1935) found a time lag of about 2 hours for the common finely-divided fuels in which fires will start.

Vapour Pressure.

Vapour pressure, unlike relative humidity, is a measure of the absolute weight of aqueous vapour in the air, and is therefore less subject to rapid local variations due to temperature changes.

Munns (1921) in studying the relation between vapour pressure and forest fires that had occurred in California during the previous decade, found that fire occurrence varied inversely with vapour pressure. He states that when the vapour pressure increased rapidly to 0.380 in. local thunderstorms occurred in the mountains, and when it rose above 0.420 in. rain accompanied the storms. Dangerous dry lightning storms occurred with vapour pressures between 0.380 in. and 0.420 in. He was of the opinion that vapour-pressure records offered great possibilities for fire-weather forecasting. McCarthy (1923) supported this view. Stickel (1928) in Massachusetts found that vapour pressures below 0.300 in. were generally dangerous. Gisborne (1928) in Idaho, however, found little correlation between vapour pressure and duff moisture content but admitted its value in predicting rain.

Wind.

The influence of wind on the fire problem has always been obvious, but quantitative measurements of its effects have been difficult to obtain because of other associated and obscuring factors frequently present. Wind accelerates the rate of drying by carrying away the layer of air in contact with the fuel before it tends to become saturated [cf. Wright (1935)]. When a fire has started the wind fans the flames, drives the heat against adjacent fuels, greatly increases the rate of spread, and may produce uncontrollable "crown" fires in the forest canopy. Wind may transport burning embers and start "spot" fires ahead of the main fire, thus rendering fire control more difficult. Wind direction and velocity are of prime importance in planning fire control action, and assist the forecaster to predict the degree of hazard that may be anticipated.

About 1917 Show (1919) attempted, by the use of experimental fires, to determine the effect of wind in increasing the rate of fire spread. He found that convection currents induced by the fire itself complicated the issue and tended to increase the effect of wind velocity. He expressed a general rule to the effect that "rate of spread as governed by wind velocity may be stated to vary as the square of the wind's velocity". It should be noted that rate of spread was measured in terms of perimeter increase. Wright (1932) cites three instances which suggest that the rate of lineal advance of large fires varies as the square of the wind's velocity. He also found that, on the average, fire advances three to four times as fast with the wind as against it. Some recent, and as yet unpublished, investigations by Wright are based on the reports of 19 large fires in rapid-spread types at Prince Albert National Park (Saskatchewan) and Riding Mountain National Park (Manitoba). Studies made in conjunction with fire-hazard weather stations in operation in these parks since 1939 supply further evidence that, on the average, the rate of lineal advance of fire with the wind varies with the square of the wind's velocity.

Gisborne (1927a), in the study of a large fire, found that rate of spread was influenced chiefly by wind direction and velocity, secondly by small changes in relative humidity, and least by small changes in temperature. Wallace (1936) states that in Australia wind shows little correlation with current fire hazard but has great significance when considered with rate of spread. Wind direction, owing to its close association with movements of the weather systems, provides some indication of future hazard.

Beall (1934b) gives comparable values for wind velocity above the tree tops and at 4 feet above ground level in a Pine forest, and Fons (1940) in California has determined the wind velocity at different heights above ground in grassland, Ponderosa Pine forest, and brush. The wind velocity is greatly decreased in the forest canopy and is not a constant percentage of the velocity above the crowns. This is illustrated by the following table for three different wind-velocity classes in Ponderosa Pine[1]:

Height ft.	Wind velocity at specified heights above ground Miles per hour		
142	5.8	10.7	15.9
90	5.5	8.9	12.5
69	2.8	3.9	-
40	1.1	1.4	1.7
30	1.0	1.3	1.6
20	1.1	1.2	1.6
10	1.2	1.4	2.1
5.5	1.3	1.7	2.2
2.5	1.5	2.0	2.4

From weather stations established at five levels on a 156-foot steel tower erected in Western White Pine forest Gisborne (1941) determined the distribution of the different weather values in a vertical cross-section of the forest at different times of the day and by months. A wind of 15 miles per hour at the 156-foot level produces a velocity of only 1.5 miles per hour at 2 feet above the forest floor.

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[1] Even-aged stand with average height of 70 ft., average density of 850 trees per acre, average d.b.h. of 7.5 in., and average distance between canopy and ground of 10 ft.

The above findings emphasize the importance of knowing the level at which wind velocity is measured. In this review of the literature the writers have been impressed with the wide variety of levels at which anemometers are placed. At all stations operated by the Dominion Forest Service, the standard level for wind measurements is 15 feet above the tree crowns.

An interesting study has been made by Curry and Fons (1938) of the rate of spread of 160 experimental fires in Ponderosa Pine needles with burning periods of up to 22 minutes. Wind velocity was measured at 2-1/2 feet above ground and seldom exceeded 3.5 miles per hour, even when wind velocity in the open exceeded 30 miles per hour. Analysis of the data indicated that the influence of both moisture content and wind velocity is linear. With low wind velocities the maximum rate of increase of the fire perimeter, as controlled by the moisture content, was soon reached, but with higher wind velocities more time was required to reach a constant rate. The effect of slope on rate of spread was found to be curvilinear. Empirical formulae were derived as a basis for estimating the rate of increase of perimeter per hour under varying conditions of wind velocity, fuel moisture and ground slope at any time interval up to 22 minutes. The findings apply to a fire in Ponderosa Pine needles under canopy sheltered from the true wind velocity, and there is no assurance that the relation found would hold good for a fire fully established and exposed to wind, as in an exposed site or where fire has opened up the stand. They no doubt represent what happens in the early stages of a fire under the conditions of the experiment.

Insolation and Solar Radiation.

All investigators agree that exposure of fuels to the sun greatly hastens their rate of drying. The rate of evaporation is strongly influenced by the temperature of the evaporating medium. Unpublished studies by Wright indicate that the evaporation of a Livingston white-bulb atmometer is highly correlated with solar radiation. Duff temperatures as high as 148°F. have been observed in the open when the shade temperature was between 80°-90°F. The fuels on clear-cut forest areas therefore dry out much more rapidly and reach a high degree of flammability much earlier than do similar fuels under the shade of forest canopy. North slopes which receive the sun's rays at a more oblique angle dry out much more slowly than those with a southerly exposure [cf. McCarthy (1927)].

Gast and Stickel (1929) measured the influence of solar radiation on duff moisture content. Under direct sunlight the rate of evaporation increased, and, because of the higher temperatures induced, a lower duff moisture equilibrium value may be reached than under shade. Radiation intensity is of course affected by the hour angle of the sun, its declination, the latitude, slope of the ground, degree of cloudiness, and the density of forest canopy. The amount of insolation, therefore, determines the length of the fire day. Beall (1934b) found that seasonal variations in the accuracy of an uncorrected index of fire hazard, computed from the weather factors, followed very closely a curve of the possible hours of sunlight. The sunshine curve was used as the basis for correcting these seasonal inaccuracies.

Evaporation.

In his early studies in California, Show (1919) recorded the daily rate of evaporation with a Weather Bureau evaporation pan, and concluded that evaporation was the chief factor in reducing the moisture content of forest litter after rain. Munns (1921) concluded that since evaporation depends principally upon temperature, relative humidity and wind, it should represent the integration of their combined effects in an easily measurable form. In order to measure this factor Bates (1923) devised an inner cell wick evaporimeter which functioned well in freezing weather but presented some difficulty in maintaining calibration. Larsen and Delavan (1922) used a Livingston porous cup atmometer and found that when evaporation from this instrument exceeded 25 cc. per day dangerous fire conditions soon developed. They state that when evaporation from a free water surface exceeds five times the precipitation, dangerous conditions will follow.

Show and Kotok (1925) discovered that the days with highest evaporation rate do not always correspond to the days of greatest fire hazard. Stickel (1931) felt that some of the disappointing results from evaporation records may have arisen from the use of unreliable instruments. He found that hourly measurements with a Livingston atmometer showed the closest correlation with duff moisture content of any of the weather factors evaluated.

Wright (1932), using Livingston atmometers, found that evaporation, when correlated with the moisture content of Pine duff at the beginning of the day and the loss during the day, provided a reliable index of the rate of drying after rain. Later it was discovered that the rate of evaporation of moisture from duff was most nearly proportional to evaporation from a free water surface, and a simple pan type of evaporimeter was developed [cf. Wright (1935)]; this has been improved and is now quite satisfactory. An unpublished article on this instrument shows that the readings in cubic centimeters can be converted into Livingston units of evaporation by the equation $y = 2.37 + 0.427x$, with a probable error of $\pm$ 1.6 Livingston units. Readings from the instrument have been correlated with data from a ground evaporation tank 6 ft. x 6 ft., the Piche evaporimeter, and with lake evaporation. It is used regularly at a large number of forest weather stations to furnish data for the daily computation of fire hazard [cf. Wright and Beall (1940)].

Thunder Storms.

Lightning is the only weather phenomenon which is the direct cause of forest fires. The proportion of fires started by lightning varies greatly in different regions and is usually highest in mountainous areas. The distribution of lightning fires in Canada is as follows:

Proportion of forest fires caused by lightning (average 1933-42)

Region	Per cent	Region	Per cent
Nova Scotia ..	0	Manitoba ..	9
New Brunswick ..	12	Saskatchewan ..	6
Quebec	5	Alberta	4
Ontario	4	British Columbia	35
		All Canada ..	18

The following concise explanation of the causes of thunderstorms is quoted from W.R. Stevens (1934) of the U.S. Weather Bureau:

"The thunderstorm is the result of vigorous vertical convection of humid air under conditions of air instability which may be brought about by strong surface heating; by over-running of one layer of air by another at considerably lower temperature; by under-running and uplift of a saturated layer of air by a denser layer; and by forced ascent of humid air masses up mountain slopes.

"There are two main classes of thunderstorms; (a) the heat storm and (b) the cyclonic storm, based upon the cause of the instability producing them.

"Conditions favourable to heat storms occur when the pressure is nearly uniform and slightly below normal over a wide area. When this situation prevails the winds are light and the surface air becomes strongly heated resulting in vigorous vertical convection currents and cumulo-nimbus clouds, provided the decrease of temperature with altitude (lapse rate) exceeds the dry adiabatic rate of 1°C. per 100 metres, and sufficient water vapour is present to produce rain-drops in the rising air. Genesis of such storms is favoured by drafts up mountain slopes. Such storms are likely to form after 2 or 3 days of unusually warm weather when the lower air has become so heated that convection extends to high altitudes.

"Cyclonic thunderstorms may occur in the south-east quadrant of a cyclone, in which case the high lapse rate necessary for rapid convection results from the different directions of the lower and upper air currents. The surface air in the south-east quadrant flows from warmer regions, while the currents aloft which flow more nearly from the west are often sufficiently colder to induce the convection necessary to produce thunderstorms. They also occur along the 'cold front' of a cyclone. Warm tropical winds are associated with the eastern portion of a cyclone, while cold polar winds prevail over the western portion. The boundary between the cold air and the warm air, usually well marked, is known as the 'cold front'. The cold air advances in the form of a wedge, friction at the ground surface retarding the advance of the lower air while the upper air advances unimpeded. This results in a wedge of cold air, with its point some distance above the ground, overhanging the warm air below. So are produced conditions favourable to vertical convection."

Plummer (1912) has pointed out that trees with their spreading branches and root systems provide ideal conductors for the lightning discharge from cloud to earth. Susceptibility to lightning strike is increased if a tree is taller or on higher ground than its neighbours, is isolated, deeply rooted, or is wet. The tree itself, or the humus at its base, or both, may ignite. There are zones of marked hazard from lightning owing to soil variation, mineral deposits and altitude. Palmer (1917) presents data on the percentages of lightning fires in California forests, and states that 0.25 inch of rainfall with a storm will render the spread of fire unlikely.

Show and Kotok (1923) found that most of the lightning fires in California were confined to June, July and August, and their seasonal distribution followed closely the course of the mean temperature from month to month. The number of fires set per storm ranged from a few up to 350, and well-defined zones of lightning-fire occurrence were recognized. Lightning fires are difficult to control because they may occur in groups, may not be discovered for some time (depending on the amount of rain) and are often in areas difficult of access.

From analysis of nearly 15,000 lightning reports from 200 forest-lookout stations in the Northern Rocky Mountain region of the United States, Gisborne (1926, 1931) concluded that thunderstorms occurred in waves mainly in July and August. With fire-starting storms rain lasted, on the average, from 8.7 minutes before to 30.8 minutes after the lightning stroke. With storms from which no fires resulted the average rain lasted from 14.6 minutes before to 44.0 minutes after the lightning. Certain years showed a higher percentage of lightning bolts striking the ground than others. Sixty per cent of the storms were safe and 40 per cent started fires. In the former category 76 per cent of the flashes were confined to the clouds, but in fire-starting storms only 56 per cent of the flashes were so confined. Sixty-two per cent of all storms moved towards the north and northeast. Referring to the fact that several different kinds of lightning have been found to occur, Gisborne (1942b) suggests that the long-duration white flash is the most dangerous type, while the extremely short red type is probably only rarely a fire starter.

G.W. Alexander (1927) of the U.S. Weather Bureau at Seattle classified lightning storms under four types according to the pressure distribution causing them. Such storms are most frequent in the zones of highest summer temperature with marked convectional activity and up-mountain winds. Given suitable pressure distribution, the storms follow the movement of high temperature from west to east at an interval of 12 to 36 hours after temperature maxima.

Morris (1934a,b) reported that lightning causes an average of 750 fires a year in Washington and Oregon. Three storm regions are defined. "General" storms caused an average of 35 fires per storm day and a maximum of 215. "Local" storms caused only one fire per storm day. Sixty-six per cent of all lightning fires were caused by "general" storms. Forty per cent of the flashes from these storms were from cloud to cloud. Lightning started fires in the following fuels in order of increasing incidence:

(1) Needles and duff on the ground
(2) Live trees
(3) Dead standing trees.

There was no difference between high and low altitudes in the number of ligntning fires per acre when the storm frequency was the same and suitable fuels existed at the high altitude.

Stevens (1934) analyzed the barometric and vapour pressure conditions associated with the thunderstorms studied by Morris, and suggested certain conclusions as an aid in forecasting thunderstorms in that region.

From a study of lightning fires in Maine, Fobes (1944) concluded that in the Spruce-Fir-hardwood forests of northern New England lightning did not present a serious fire problem.

Influence of Altitude on Weather Factors.

In a study of weather records from lookout stations in Idaho, Larsen (1922) found that maximum temperatures were higher by 10° to 17°F. and minimum temperatures lower by about 4°F. at valley stations than at higher mountain stations. The average daily wind velocity at mountain stations was about three times that shown at the valley stations. There was little difference between day and night wind velocities at the high stations, but in the valley the air was often still at night. Relative humidity was lower at night and higher during the day at mountain stations than in the valley. These facts explain why night fires burn better at high than at low elevations.

From observations made over a period of five years, Hayes (1941) recognized three altitudinal zones with different characteristics:

(1) A low zone with the greatest daily temperature range.
(2) A thermal belt lying between 700 and 1,700 feet above the valley floor, with the highest night temperature, the smallest temperature range, and the highest mean temperature.
(3) A high zone with small temperature range and cooler than the thermal belt.

Inversions of relative humidity and fuel moisture content naturally arise from these nocturnal inversions in temperature, and night fires burn more readily in the thermal belt.

In the mountainous regions of Northern Idaho, Hayes (1944b) found that single daily measurements to determine average fire behaviour in the area as a whole should be made at a valley-bottom station at noon or at 5 p.m., or at a 5,500-foot south-slope station at 2 p.m.

Other Factors That May Affect Forest Flammability

Chemical Composition of Fuels.

It has occurred to various investigators that the changing fire behaviour of certain fuels at different seasons might depend upon changes in oil or resin content. Wright (1932) found that dry needles of Red Pine had a slightly higher calorific value than those of White Pine, but it is doubtful if this slight difference alone accounted for the higher flammability of Red Pine duff. Richards (1940) in Idaho collected at 10-day intervals samples of certain seasonal vegetation which had been found to burn more readily at some seasons than others. These samples were analyzed as to moisture content, calorific value, resins and oils. His conclusion was that moisture content was the dominant factor influencing fire behaviour, although certain plants showed greater tenacity than others in retaining both their free and chemically-combined moisture.

Sub-Litter Moisture.

Gisborne (1928) found no indication that sub-litter or soil moisture affected the moisture content of surface duff to any appreciable extent. Wright (1935) found that even saturation of sandy soil did not raise the moisture content of the surface litter more than one or two per cent. Both these investigators admitted, of course, that damp soil was a great aid to fire suppression and retarded ground fires.

However, Hayes (1941), in his studies of the effect of altitude on fire danger, found that soil moisture affected duff moisture content in all locations at night, but only on north slopes and under forest canopy during the heat of the day. Exposure to sun and wind was found to be the most important factor influencing the drying of duff.

Dew.

Contrary to popular belief, fuels under forest canopy do not become wet from dew [cf. Wright (1935)]. The temperature of the duff at night is practically always higher than that of the air immediately above it, and under such conditions there can be no condensation unless a fog is present. In open spaces, where there is no forest canopy, dew formation does, of course, occur.

III. VISIBILITY RANGE

Atmospheric conditions affecting visibility assume great importance to fire protection authorities when they hamper the detection of forest fires. Poor visibility has been responsible for many fires reaching costly proportions because they were not discovered by the forest lookouts soon enough to permit control action to be taken in their early stages. This condition may arise from haze in the atmosphere induced by moisture conditions, by smoke particles from distant fires, or by both. When this haze increases to such an extent that a forest lookout cannot discern smoke columns from fires starting in his normal area of coverage, it becomes necessary to man additional lookout points or have ground or aeroplane patrols covering the area made invisible from the primary lookout. Daily records of visibility distances are therefore of the first importance to the fire control officer.

In Canada, visual range is usually estimated by reference to known points. Middleton (1941) of the Meteorological Service of Canada has outlined the general theory of visibility in meteorology. In the United States there has been considerable investigation of the specific problem of smoke-column visibility and various haze-meters have been designed to measure conditions of visibility from lookout stations.

The Byram haze-meter was developed at the Pacific North-West Forest Experiment Station [cf. McArdle (1935)]. From his studies Byram (1936) drew certain conclusions. Small smoke columns can be seen from farther when the observer is looking into a low sun than when he has the sun at his back. The opposite is the case in looking at trees, houses and similar objects. Smoke columns can be seen from farther on cloudy days than on clear days, the difference being much greater against light backgrounds than against dark ones. Opaque objects such as trees cannot be seen from as far on cloudy days as on clear days. The safe visibility distance of a smoke column in shadow seen against a low sun is zero. Small changes in size of the smoke column do not cause appreciable changes in its visibility distance.

In tests with 200 experimental fires in Ponderosa Pine needles, Buck (1938) studied the factors influencing the lapse in time from the start of fire to its discovery. These were (a) atmospheric obscurity, (b) the background against which the smoke is seen, (c) the distance from the lookout to the fire, (d) the relative position of the sun with respect to the observer, (e) the behaviour of the fire and the amount of smoke. An object is visible because of its contrast with the background, either in colour or brightness. Smoke seen against the green background of the forest is always brighter than its background, but there is usually little contrast in smoke seen against the sky. The average discovery time for fires 7 miles distant (with green background) was 9 minutes. At 25 miles the time was 13.5 minutes. The relation is curvilinear. When the sun is behind the observer the discovery time is longer.

In a highly theoretical article, Bruce (1941) analyzes the optical factors influencing smoke column visibility. The analysis indicates that the maximum distance at which a smoke column is visible is inversely proportional to the amount of haze in the atmosphere. From an analysis of over 450 tests with standard smoke candles, Bruce (1944) produced diagrams showing lookout coverage under varying conditions of haziness, background, and angle between sun, observer and smoke. In the northern hemisphere, smoke visibility is poorest over the quadrant N.W. to N.E. More intensive distribution of lookout points is required in country where light-coloured or mottled backgrounds predominate, than where the forest cover is uniformly dark.

IV. MEASUREMENT OF FOREST-FIRE DANGER

Index of Flammability

It has been shown that the moisture content of the forest fuels largely determines how readily a fire will start. Since it is not possible to measure daily the moisture content of all the fuels in a forest area, it is necessary to select some critical fuel, the moisture content of which can be easily measured and used as an index of probable fire behaviour, or to devise some form of index based upon the weather factors to accomplish the same end. A variety of methods has been suggested to provide such an index.

About 1916, E.H. Finlayson of the Dominion Forest Service (Canada) attached certain negative values to rainfall and positive values to temperature, sunshine, wind, and relative humidity, and plotted from day to day a graph of the results as they departed from what was considered a neutral or safe line [cf. Wright (1935)]. The test of accuracy for the provisional values given to each weather factor was to be whether or not the curves returned to the neutral line in periods when there was no fire danger. The method was followed for several years in Alberta but the work appears to have lapsed owing to change of personnel.

Larsen and Delevan (1922) suggested that standard samples of duff from the forest floor be weighed in different localities simultaneously, so that the relative flammability of the forests in each locality could be indicated. This method was followed in later years by Nichols (1928-31) in Quebec, who used wire trays containing the full layer duff, which were inserted in the areas of forest floor from which the sections of duff had been removed. The method was tested for a number of years at Petawawa [cf. Wright (1932)], but was abandoned for two reasons: (a) The full layer duff with heavy humus content and high moisture capacity did not respond reliably to changes in surface fuel flammability; (b) the contents of the trays were subject to rapid progressive decomposition losses which were difficult to assess, and which introduced serious errors.

In 1923 the Priest River (Idaho) Forest Experiment Station introduced the duff hygrometer for measuring the moisture content of forest duff [cf. Gisborne (1928), and Weidman (1923)]. This consisted of a perforated metal tube containing a strip of rattan which expanded or contracted with changes in the moisture content of the duff in which the tube was placed, and actuated a pointer on a dial graduated in moisture content. It attained wide use for some years until it was superseded by the wood cylinder method developed at the same station [cf. Gisborne (1933)].

There have been many modifications of the wood cylinder method introduced in various regions, but the principle involved is to expose one or more prepared sticks, usually about half an inch in diameter and of known oven-dry weight, in a standard manner. The moisture content of the sticks can be determined at any time by weighing them on a special scale graduated in moisture content [cf. Byram (1940b)]. In some regions sticks of different diameters are used to indicate the probable moisture content of branch wood of comparable size [cf. Gisborne (1936), and Wallace (1936)]. In some cases square sticks are used, in others flat sticks or slats [cf. Jemison (1942)], but usually they are in the form of cylinders. Several varieties of wood are used in the manufacture of the sticks. Matthews (1935, 1940) and Morris (1940a) compared the behaviour of sticks of various shapes, sizes and kinds of wood, subjected to various methods of exposure, and found differences in results with woods of different species or densities. There was no important difference between round and square sticks of the same area cross-section, but flat sticks showed important differences in behaviour. The type of ground surface made little difference when the sticks were exposed at a height of 9 to 15 in. above it.

It is recognized that there is a progressive loss of weight in the sticks from weathering during the summer. This will introduce an error in calculations unless allowance is made for it, and scales have recently been devised which have an adjustment to make the necessary correction [cf. Byram (1940b)]. Moisture indicator sticks in one form or another are now used throughout the United States, in Australia (cf. Wallace (1936), and Wallace and Gloe (1938)] and in British Columbia.

Sickel (1931, 1934) in New York developed alignment charts to compute the degree of hazard from daily records of relative humidity, air temperature and hours since last rain. The method makes no allowance for the amount of rain.

Thompson (1927) of the U.S. Geographical Survey suggested the measurement of stream flow as an indicator of fire hazard. The flow of both small and large streams was measured at the Petawawa Forest Experiment Station for a number of years. The results indicate that, while the effect of rainfall is apparent, the variations in flow from day to day do not provide any practicable fire hazard data.

Loveridge (1935) of the U.S. Forest Service suggested the use of cumulative surpluses or deficiencies from the average of precipitation over extended periods in gauging the probable degree of fire danger on a country-wide basis, for administrative purposes. Shank (1935) recommended the use of cumulative excesses and deficiencies of relative humidity to measure fire danger and compare costs of fire suppression in different years and regions.

The Dominion Forest Service (Canada) since 1929 has experimented with the various moisture indicator sticks described above, as well as a wide variety of other hygroscopic materials, including chemicals, in an effort to discover an ideal fuel moisture indicator. Certain chemicals show promising results since they can be readily standardized and are not subject to deterioration during the summer. However, this Service still computes the daily index of fire hazard from certain weather factors by means of specially prepared tables [cf. Wright and Beall (1940)]. The factors used are the amount and duration of rainfall, rate of evaporation, relative humidity, wind velocity and time of the year, together with a correction for cumulative drought. The index obtained is not an index of flammability only, as in the case of a direct measure of fuel moisture. It might more properly be described as a "burning index" since it takes into account the effect on fire behaviour of wind velocity, state of seasonal vegetation, and prolonged drought. The method has been in use for several years with good results throughout Quebec, New Brunswick and the western Canadian National Parks. It lends itself readily to the translation of weather forecasts into terms of fire hazard.

In recent years attention has been directed in Europe to the measurement of forest flammability. Angstrom (1942) has developed in Sweden an index for this purpose, based on relative humidity and temperature. It is understood that a system of forest-fire hazard measurement has also been introduced in Russia, but details of the method are not yet available. The importance of meteorological factors in this connection is well recognized, and forest services in Russia are regularly supplied with reports on weather conditions by the State meteorological stations [cf. Serebrennikov and Matreninski (1940)].

Rate of Spread of Fire and Its Resistance to Control

A knowledge of the probable rate of spread of fire is essential to the forest officer for the effective planning of fire control, strategy, and tactics. He must also know the probable rate at which fire fighters can build fire line. Since both rate of spread and rate of fire-line construction vary with the forest type and ground conditions, it is necessary to prepare a fuel-type map of the region, on which the boundaries of the various fuel types are shown and classified as to average rate of spread and resistance to control.

Much work in this field, based on individual fire reports, has been done in the United States. Fortunately, owing to the foresight of Coert Du Bois in California [cf. Abell (1940)], as early as 1914 the fire report form of the United States Forest Service was designed to collect the necessary information on rate of spread, and many thousands of reports in all fire types and regions are thus available for analysis. Abell (1940) presents the results of an analysis of 9,500 such reports. The average rate of perimeter increase varied from 2 chains to 50 chains per hour, depending on the fuel type. Jemison and Keetch (1942) published results of similar studies on seven national forests in the eastern United States. Fourteen fuel types were listed and the average rate of perimeter increase and rate of fire-line construction per man-hour shown for each.

In 1939 in Canada the Dominion Forest Service and certain provinces revised their report forms so as to collect data essential to fire control planning. Useful information is already being obtained from these reports.

Integration of Fire Danger

The "Forestry Terminology" of the Society of American Foresters (1944) defines fire danger as: "The resultant of both constant and variable factors which determines whether fires will start, spread and do damage, and determines as well the difficulty of control. . . . Constant factors are those which are relatively unchanging, e.g., normal risk of ignition, topography, all fuels, and exposure to prevailing wind. Variable factors are variable from day to day, season to season, and year to year, e.g., all weather elements, fuel moisture content, and variable risks of ignition."

Briefly, therefore, fire danger is the sum total of factors which determine whether fires will start, spread and do damage. It will be noted that a measure or index of flammability is only one of the factors to be considered in estimating fire danger.

Gisborne (1936) developed a meter to integrate the effects on fire danger of fuel moisture, season of the year, relative humidity, wind velocity, visibility distance, lightning, and land-clearing fires into seven classes of fire danger, and he specified the administrative steps recommended to be taken for each danger class. The success of Gisborne's meter led to the development of similar fire-danger rating methods in other regions.

In California, a meter was devised to integrate (a) an ignition index of man-caused fires, (b) a lightning index, (c) a rate of spread index, and (d) an index of man-power requirements. The meter integrates these factors into seven classes of fire danger and specifies the organization requirements for each class [cf. Curry, Gray and Funk (1940)].

In the eastern United States, Jemison (1942) describes a meter which integrates (a) season of the year, (b) amount of last rain, (c) number of days since last rain, (d) condition of vegetation, (e) fuel moisture content, and (f) wind velocity, into five classes of fire danger and shows organization plans for a sample forest for each class of fire danger.

A comparison of the various types of forest-fire danger meters in use in the United States is made by Jemison (1944).

Beall (1939) prepared fire-danger tables for the timber limits of a private company in New Brunswick. He pointed out that the fire-hazard index [cf. Wright and Beall (1940)] does not take into account such variable factors influencing fire-control as: the pprevalence of fire-starting agencies, the values to be protected, the speed with which fires may be attacked, fire detection coverage, etc., since these can only be known for a specific area. The fire danger tables were prepared with these factors in mind, due weight being given to each. The tables give sixteen units of fire danger, show the probability of fires in each unit, and the administrative changes necessary as the fire danger increases.

V. WEATHER FORECASTING

It has been shown how intimately the various weather factors affect the problem of forest fire protection and how steps have been taken to evaluate their influence. A true picture of the fire situation at a given moment is of great value, but foreknowledge of how the picture is likely to appear in a few hours or days can be still more valuable, since it permits of intelligent planning to meet the changing situation. It is here that the meteorologist can render valuable aid with his science of weather forecasting.

The need for specialized weather forecasts was brought to the attention of the U.S. Weather Bureau in 1912 as a result of disastrous fires on the Pacific Coast, which had been aggravated by desiccating east winds from the interior desert [cf. Calvert (1925), and Pierce (1938)]. A fire-weather warning service was put into operation in 1914. Weather stations were established in the forests in co-operation with the Forest Service, and forecasters studied the topography to assist them in making localized forecasts of wind velocity and direction. In 1924 two meteorologists were assigned specially to this work, and a few years later special appropriations made possible the extension of the service to other regions. Facilities were provided for local short-range forecasts at the scene of fires by means of mobile units equipped with radio and weather instruments [cf. Gray (1929)]. Fire-weather forecasts are now available over most of the United States. A central office in each region sends out regular forecasts covering local conditions.

In Canada, the first move towards specialized forecasting for fire protection began about 1925 when the Meteorological Service was asked to provide forecasts of dangerous winds, temperatures, and relative humidities to certain forest regions. Since that time the Service has always been ready to co-operate with forest officers in setting up weather stations and, upon request, to supply them with weather maps and daily telegraphic forecasts, usually for 24-48 hours ahead, of wind, temperature, relative humidity, rain, and thunderstorms. These forecasts, while perhaps not so extremely localized as those of the fire-weather warning service in the United States, have been of great value to forest officers.

To be of value, weather forecasts must be for a long enough time ahead to enable the forest officer to arrange or amend his plans accordingly. In the past, many forest protection units have been unable to receive forecasts in time because of poor communication systems. With the extending use of radio this handicap will tend to disappear. For the benefit of officers who were unable to receive official forecasts, Beall (1940) prepared a short treatise on amateur forecasting in the forest. In cases where it was possible to obtain weather maps not more than one or two days old very good results were obtained with these instructions. He also showed how to translate weather forecasts into terms of fire hazard, so that the forest officer could estimate the probable degree of hazard to be expected.

A guide to amateur weather and fire-hazard forecasting in Western Australia is given by Wallace and Gloe (1938). This method is based primarily on wind direction, studied in conjunction with the latest available weather maps.

Most forest officers hope that the day may come when meteorologists will be able to predict the weather a long way ahead. Naturally it would be of great value to know with certainty that the following month or year would be wet and no danger from fire would arise. Much useful work could be planned and carried out in the safe periods. On the other hand, a knowledge that bad fire conditions can be expected would enable the organization to make special plans to meet the emergency.

Larsen and Delavan (1922) endeavoured to determine if there were cycles in fire weather, but found that precipitation records alone did not assist them much since a great deal depends upon even short periods of summer drought in what might otherwise be a wet year. They did, however, find evidence of long-period fluctuations in fire hazard. Gray (1934) of the U.S. Weather Bureau also found evidence of long-period sequences in weather and forest fires. For presenting his data he used a system of accumulated departures from the normal or average which is well adapted for showing secular sequences or trends. On the basis of his curves he suggested probable weather trends up to the year 2050. Wright (1940) endeavoured to correlate the acreage burned with sunspot numbers and showed the probable effect of the sunspot cycle in the next few years. Bumstead (1943) found some tendency for lightning fire incidence to be correlated with the sunspot cycle.

Unfortunately there are many pitfalls for those who attempt to devise from past experiences a telescope with which to peer into the future and, except for their own amusement, foresters would do well to leave the development of long-range weather prediction to the meteorologists. Recent years have seen marked advances in the science of meteorology and no doubt the accuracy and time range of weather forecasts will increase.

The objectives of meteorology in forest fire protection may be briefly summed up as follows:

1. To provide localized weather forecasts to suit the needs of particular forest regions. This may involve considerable study of local conditions, particularly in mountainous regions.
2. Forecasts should be for 24 and 48 hours ahead and as much longer as possible, and should cover rainfall, wind, temperature, relative humidity, thunderstorms and visibility.
3. The study of the possibility of long-range forecasting should not be overlooked.
4. The continued co-operation between foresters and meteorologists is essential to the development of improved forest fire protection.

VI. PRACTICAL APPLICATIONS FOR FOREST-FIRE RESEARCH IN CANADA

Forest Weather Stations

It has been shown that an index of fire behaviour, in some form or another, is an essential part of any system for rating forest-fire danger. In many of the National Parks and other forest areas of Canada, fire behaviour is determined by means of the Wright system of fire-hazard measurement [cf. Wright and Beall (1940)]. The forest weather stations required for the application of this system normally include a rain-gauge, a Wright evaporimeter, a wet- and dry-bulb hygrometer housed in a ventilated shelter, and an anemometer. The last-named instrument, although very desirable for making wind observations, may be dispensed with if necessary, the wind velocity being estimated visually with the aid of a wind scale specially prepared for forest use [cf. Wright and Beall (1940)].

Sites for forest weather stations must be selected with care to avoid screening by trees, buildings and other objects. Over-exposure to the elements, although less common, may be encountered on isolated hill-tops. A network of weather stations should be installed in such a manner that a record is obtained of local variations in weather over the area concerned. The intensity of coverage required varies greatly according to topography and other factors. Rainfall, in particular, is often subject to wide variation over short distances, especially in mountainous country. Where a sufficiently intensive deployment of complete weather stations is impracticable, rain-gauges alone may be installed at certain points, the readings being used to apply local corrections to the hazard index computed at the nearest weather station.

Mid-afternoon values of wind velocity and relative humidity are obtained from readings made at about 2:30 p.m. and 4:30 p.m., local mean time. The rain-gauge is read at 8 a.m. and 6 p.m. and the evaporimeter at 6 p.m. only, at which time the hazard index for the day is calculated by means of the fire-hazard tables [cf. Wright and Beall (1940)]. Since it is not usually feasible to work out the hazard index for each individual fuel type in the region, an index which is representative of one of the faster-drying fuel types is commonly used. For certain administrative units, "administration" hazard index tables have been prepared, based on an average of the various fuel types weighted according to their area. When factors other than fire hazard are also taken into account, an administration danger index can be applied [cf. Beall (1939)].

According to local arrangements, the hazard index may be calculated directly by the weather observer, or the weather readings may be telephoned to a central office at which the index for all stations in the area is computed. Where facilities exist, a forecast of the next day's hazard index is also made. The weather observations are frequently taken by forest rangers or their families, or by lookouts or other members of the protection staff where suitable sites exist. Valuable co-operation has also been obtained from farmers and other local residents.

Fire Prevention Measures

Forest-fire risk (that is, the prevalence of fire-starting agencies) and fire hazard together constitute two principal elements of forest-fire danger. Man-made sources of fire can be controlled to some extent through public co-operation and by the enforcement of suitable legislation. A knowledge of the existing fire hazard thus enables the forest officer to exercise some compensating control over fire risk, so that periods of maximum fire danger may be reduced or even avoided.

Public co-operation may be fostered by means of notice boards displayed at suitable points, showing the prevailing degree of fire hazard. Press and radio bulletins and warnings issued to woods operators and other workers in forest lands, may also be employed to advantage. In many parts of Canada, legislation exists whereby permission to set camp-fires to use certain types of machinery, or to travel in forested areas may be curtailed or suspended, if the fire-hazard situation is sufficiently serious.

Settlers' land-clearing fires constitute a major source of risk in certain areas. Ideally, such fires should be set during periods in which the debris to be cleared is dry enough to ensure a clean burn, while the flammability of the surrounding forest is low. It is obvious that a reliable index of fire behaviour in the fuel types concerned will be of great assistance to the forest officer responsible for issuing settlers' fire permits, and for supervising the actual burning operations.

Organization of Fire-Protection Forces

The fire hazard (or, preferably, fire danger) index may be used to great advantage in the allocation of duties within the forest protection service. During relatively safe periods, fire-fighting equipment may be dismantled for repair and inspection; some lookouts and patrols may be released to obtain supplies or to clear trails and telephone lines; work parties may be sent to the less accessible parts of the area for such duties as road or building construction, since the possibility of their being required on short notice for fire-fighting operations is remote.

As the index rises, additional lookouts and patrols may be instituted, and equipment and supplies brought to a state of readiness. Work crews may be concentrated in areas where they will be immediately available if fire occurs. In periods of severe danger, key personnel or entire crews may be kept on stand-by duty during non-working hours and on holidays, and arrangements made to replace positions vacated by fire calls.

The extra cost introduced by some of these precautionary measures should properly be regarded as a fire-insurance investment. The prompt detection and suppression of a single fire in its early stages may save, in merchantable timber values alone, an amount much greater than the additional cost of such precautions for a whole fire season. Moreover, payroll expenditures represent increased purchasing power to the community instead of the destruction of a capital asset.

When a fire does occur, a knowledge of the prevailing and predicted hazard is of much assistance in deciding how many men and what equipment to dispatch with the suppression crew. The information will be of still greater value if a fuel-type map of the area is available, which, together with the hazard index, shows the probable rate of spread of the fire and its resistance to control. Other maps may be provided to show the travel-time required to reach the fire; the location of roads, trails, water routes and telephone lines; the position of tool caches or camps in the vicinity, and the closest water supply for pump operation [cf. Beall (1939)].

At the fire-line itself, circumstances will arise in which a knowledge of prevailing hazard and weather conditions, together with anticipated changes, will be useful to the officer directing fire-fighting operations. Decisions as to whether an attempt should be made to hold a fire on an existing front or to adopt a new position, whether to use direct attack or resort to backfiring, and other questions, may be largely guided by predicted changes in fuel flammability and in the strength and direction of the wind.

In conclusion it should be pointed out that fire-control planning in Canada is still in its infancy. Many practical applications of forest-fire research remain to be fully exploited. Among the possible developments of the future may be mentioned the use of fire-danger records and other fire statistics for assessing fire-control efficiency in different years and in different regions, and the employment of fire-danger ratings as a basis for the evaluation of insurance risks.

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ADDENDUM

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