WORLD METEOROLOGICAL ORGANIZATION

TECHNICAL NOTE No. 41

CLIMATIC ASPECTS OF THE POSSIBLE ESTABLISHMENT OF THE JAPANESE BEETLE IN EUROPE

(Report prepared by Mr. P. Austin BOURKE,
president of the Commission for Agricultural Meteorology)

TECHNICAL NOTE No. 42

FORECASTING FOR FOREST FIRE SERVICES

(Report of a working group of the Commission for Agricultural Meteorology
prepared by J.A. TURNER, chairman - J.W. LILLYWHITE - Z. PIESLAK)

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FORECASTING FOR FOREST FIRE SERVICES

J. A. Turner - J.W. Lillywhite and Z. Pieslak

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FOREWORD

The Commission for Agricultural Meteorology of the World Meteorological Organization, at its second session in Warsaw in the autumn of 1958, in accordance with Resolution 8 (CAgM-II), set up a working group to study the problem of providing forecasts for forest fire services. The terms of reference provided to the group were as follows :

"To draft a report, suitable for publication as a WMO Technical Note, on the methods being used in preparing special forecasts for forest fire services."

The group was composed of Dr. Z. Pieslak (Poland), J.W. Lillywhite (Australia), and J.A. Turner (Canada), chairman.

The work of the group has been entirely by correspondence, except for a two-day meeting between Mr. Lillywhite and the chairman late in 1959.

In the above resolution it was noted that while special forecasts for forest fire services were being issued in a few countries, little had so far been published on the methods used.

The present Technical Note is the outcome of the work of the group and is intended to provide meteorologists who may be unfamiliar with the special problems involved, with a summary of these problems, and some of the ways in which they are currently being solved.

The material in this Technical Note is based on information available to the members of the group through personal experience, communication with other workers in this field and through replies to the questionnaire circulated to Members of WMO. This information varies considerably in detail; the following paragraphs must necessarily reflect these differences. While it has been the intention that sufficient information be provided in this Note to indicate the way in which the problems are being met in the countries in question, the chairman of the group strongly urges that where further details are required the author of a particular original paper or the organization using a particular system be contacted directly.

I am glad to have this opportunity of expressing to Mr. Turner and to the other members of the working group the appreciation of the World Meteorological Organization for the time and effort they have devoted to the preparation of this valuable report.

(D.A. Davies)
Secretary-General

FORECASTING FOR FOREST FIRE SERVICES

Summary

The occurrence of accidental fires in forest, brush or grassland can provide a serious threat to life and property in any area of the world where the occurrence of adequate supplies of potential fuel coincides with the occasional or frequent occurrence of sufficiently extended periods of dry weather.

In many countries organizations have been developed at the state or the community level for the purpose of protection against fire. According to an official publication of the Forestry Division of the Food and Agriculture Organization, the development of special fire danger forecasts is desirable wherever such a fire control organization exists or is contemplated.

Such specialized forecast services have been or are being developed in many countries, and it is the purpose of this Note to outline what is being done to provide such services and to provide a background of the work that has been done on the relationships between weather and fire behaviour.

Specialized service for the use of fire control organizations may take the form of generalized forecasts of the degree of fire danger to be expected, in order that routine duties of forestry staff may be planned to fit in with the appropriate stage of "readiness". Special forecasts may also be provided in the form of specific advice on a suitably small scale so that individual fires may be fought with maximum efficiency.

Even in areas where there is no centralized fire control agency it may be the responsibility of the meteorological service or institute to keep the public informed of the degree of fire danger whenever it reaches a significant level.

There are three ways in which weather may exert a significant effect on accidental fires. First, it may exert a cumulative effect by controlling the distribution of moisture content in the dead vegetation which is the principal fuel. Secondly, it may be a direct cause of fire in the form of lightning, provided the moisture content in at least one class of fuel is sufficiently low to maintain combustion. Finally, the weather may control the progress of existing fires primarily through the effects of wind and moisture, but also, in the case of large fires through instability and wind shear.

Existing methods of providing special forecast services in the interests of protection against fire usually include some estimate of the degree of inflammability or of fire danger. A number of meteorological organizations have developed simple indices of inflammability based on one or more current weather elements or on some cumulative function of past weather. Where organized forest protection agencies exist, more complex indices of fire danger have been developed which usually incorporate some measured value of fuel moisture and an indication of the physical state of the potential fuels.

The problem of obtaining representative observations is met in many countries by setting up supplementary networks of special fire weather stations. In other areas the normal network of synoptic and climatic stations provides adequate coverage. Special techniques have been developed for the measurement of the moisture content in certain critical fuels.

The general undeveloped state of forested land in some countries results in special problems in communication, particularly with respect to the collection of observations and the distribution of forecasts.

The value of a specialized fire weather forecast service becomes greatest when there is an effective liaison between the forecast office and the fire control organization. In some areas this is achieved by locating radio equipped mobile forecast units staffed by fire weather forecasters at the scene of large fires.

PREVISIONS POUR LA LUTTE CONTRE LES INCENDIES DE FORETS

Résumé

Les incendies qui éclatent accidentellement dans les forêts, la brousse ou les paturages peuvent constituer une grave menace pour la vie et les biens dans n'importe quelle partie du monde où l'existence de réserves potentielles de matières inflammables coïncide avec l'apparition, occasionnelle ou fréquente, de périodes assez longues de sécheresse.

Dans de nombreux pays, on a mis sur pied - à l'échelon de l'Etat ou de la communauté- des organismes chargés de la protection contre le feu. Selon une publication officielle de la Division des forêts de l'Organisation des Nations Unies pour l'alimentation et l'agriculture, il est souhaitable d'établir des prévisions spéciales de danger d'incendie partout où existe (ou est envisagé) un tel organisme de lutte contre l'incendie.

De nombreux pays ont créé des services spéciaux de prévision de ce genre ou sont en train de le faire; la présente Note technique a pour but d'indiquer ce qui est fait actuellement dans ce domaine et d'exposer les travaux qui ont déjà été effectués sur les relations entre la météorologie et la pyrologie.

L'assistance spéciale fournie aux organismes de protection contre le feu peut prendre la forme de prévisions générales concernant le "degré de danger d'incendie" qui permettront au personnel forestier d'élaborer son programme de travaux quotidiens de manière à être prêt à intervenir au moment voulu. Le service compétent peut également émettre des prévisions spéciales portant sur une zone plus restreinte qui permettront de combattre le plus efficacement possible les foyers d'incendie.

Même dans les régions où il n'y a pas de service centralisé de lutte contre le feu, le service ou l'institut météorologique peut être chargé d'informer le public de l'imminence et de l'ampleur du danger d'incendie chaque fois que ce danger atteint un degré assez élevé.

Les conditions météorologiques peuvent exercer de trois manières une influence décisive sur les incendies accidentels : 1° Elles peuvent avoir des effets cumulatifs en déterminant la répartition de l'humidité dans la végétation morte, qui constitue la principale matière combustible. 2° Elles peuvent être la cause directe de l'incendie, par exemple sous la forme de la foudre, lorsque le degré d'humidité d'au moins un des éléments combustibles est suffisamment faible pour entretenir la combustion. 3° Enfin, les conditions météorologiques peuvent exercer une influence sur l'extension des foyers d'incendie, sous l'action surtout du vent et de l'humidité, mais aussi, lorsqu'il s'agit d'incendies très étendus, sous l'effet de l'instabilité et du cisaillement du vent.

Les prévisions spéciales destinées à la lutte contre le feu sont fondées habituellement sur une évaluation du degré d'inflammabilité ou du danger d'incendie. Plusieurs administrations météorologiques ont établi des indices d'inflammabilité simples basés sur des conditions météorologiques plus ou moins récentes ou sur une fonction cumulative du temps passé. Là où il existe un service organisé de protection des forêts, des indices plus complexes ont été mis au point; ils tiennent compte en général du degré d'humidité, de la nature et du degré de maturité des combustibles forestiers.

De nombreux pays obtiennent des observations représentatives en établissant des réseaux supplémentaires de stations météorologiques spécialisées dans la protection contre le feu. Dans d'autres régions, le réseau ordinaire de stations synoptiques et climatiques recueille les données d'observation adéquates. Des méthodes spéciales ont été mises au point pour mesurer la teneur en eau de certains combustibles critiques.

Dans certains pays, l'état général de sous-développement des régions forestières pose des problèmes de communications particuliers, notamment en ce qui concerne le rassemblement des données d'observation et la diffusion des prévisions.

L'utilité d'un service spécialisé de prévisions météorologiques est la plus grande là où il existe une liaison efficace entre le service de prévision et le service de protection contre le feu. Dans certaines régions, cette liaison est assurée par l'envoi, dans les zones menacées par de grands incendies, d'équipes mobiles spécialisées de prévisionnistes disposant d'installations radio.

ПРОГНОЗЫ ДЛЯ СЛУЖБЫ ПО БОРЬБЕ С ЛЕСНЫМИ ПОЖАРАМИ

Краткое изложение

Возникновение случайных пожаров в лесу, в кустарниках и в траве может представлять серьезную угрозу жизни и собственности в любом районе земного шара, где наличие соответствующих запасов потенциального топлива совпадает с наличием нерегулярных или часто повторяющихся, достаточно длительных периодов сухой погоды.

Во многих странах были созданы организации либо на государственном, либо на частном уровне в целях борьбы с пожарами. В соответствии с официальной публикацией Лесного Отдела Продовольственной и Сельскохозяйственной Организации в тех местах, где уже существуют или создаются организации по борьбе с пожарами, желательно развивать службу специальных прогнозов по возникновению опасности лесных пожаров.

Такие специализированные службы прогнозов были уже созданы или создаются в настоящее время во многих странах, поэтому, целью настоящей заметки является сделать обзор тому, что делается в области создания таких служб и какая работа была проведена по установлению взаимосвязи между условиями погоды и пожарами.

Специализированная служба, предназначенная для использования противопожарными организациями, может сводиться к обеспечению обобщенными прогнозами о степени ожидаемой опасности возникновения пожара с тем, чтобы люди, занятые в лесном хозяйстве могли планировать свою работу таким образом, чтобы в определенные периоды быть в "состоянии готовности". Специальные прогнозы могут также даваться в форме отдельных консультаций небольшого масштаба с тем, чтобы борьба с отдельными пожарами могла проводиться с максимальной эффективностью.

Даже в тех районах, где отсутствует централизованное учреждение по борьбе с пожарами, эта работа может входить в сферу деятельности метеорологической службы или института в целях предоставления информации населению о степени возможности возникновения лесных пожаров, в периоды, когда она достигает максимального уровня.

Имеются три вида, когда погода может иметь существенное влияние на возникновение пожаров. Во первых, она может иметь совокупный эффект, посредством регулирования распределения влажности среди мертво-сухой растительности, которая является основным горючим. Во вторых, она может быть непосредственной причиной возникновения пожара от молнии, при условии, что содержание влажности в горючем, по крайней мере одного вида, достаточно низкое, чтобы поддерживать горение. И, наконец, погода может влиять на усиление начавшихся пожаров в основном через ветер и влажность; однако, в случае больших пожаров существенное влияние может также быть оказано в связи с неустойчивостью атмосферы и изменениях ветра.

Существующие методы специального прогностического обслуживания в интересах противопожарной защиты включают обычно некоторый учет степени воспламеняемости или опасности пожара. Целый ряд метеорологических организаций разработал простые индексы воспламеняемости, основанные на одном или нескольких элементах текущей погоды или на некоторых совокупных функциях прошедшей погоды. В тех местах, где существуют организованные службы, разработаны более сложные индексы опасности пожаров, которые обычно включают в себя определенные значения горючей влажности, а также указание на физическое состояние потенциального горючего.

Проблема получения репрезентативных наблюдений во многих странах решается посредством установления дополнительной сети специальных метеорологических станций пожарной охраны. В других районах обычная сеть синоптических и климатологических станций обеспечивает необходимую густоту. Была разработана специальная техника по измерению содержания влаги в определенных критических горючих материалах.

Состояние недостаточного общего развития лесных хозяйств в некоторых странах создает специальные проблемы связи, в особенности, по отношению сбора наблюдений и распространения прогнозов.

Значение специализированной противопожарной прогностической службы приобретает большее значение там, где существует хорошая связь между прогностическим центром и противопожарной организацией. В некоторых районах это достигается посредством размещения подвижных прогностических единиц с радиооборудованием. Эти единицы укомилектованы прогнозистами, специализировавшимися на составлении прогнозов по борьбе с пожарами в местах больших пожаров.

PREVISIONES PARA LOS SERVICIOS FORESTALES CONTRA INCENDIOS

Resumen

Los incendios accidentales de bosques, monte bajo o praderas pueden constituir una seria amenaza para la vida y los bienes de cualquier zona del mundo donde la existencia de posibles materias combustibles coincida con períodos suficientemente largos de sequía que pueden ser ocasionales o frecuentes.

En muchos países se han establecido organizaciones dependientes del Estado o de los municipios para la protección contra el fuego. Según una publicación oficial de la División de Bosques de la Organización para la Alimentación y la Agricultura, conviene organizar servicios especiales de previsión del peligro de incendio siempre que exista una organización de lucha contra el fuego o que se piense en su creación.

Esos servicios especiales de previsión existen o están siendo organizados en muchos países y la presente Nota se propone esbozar lo realizado para proporcionar dichos servicios, y facilitar los antecedentes del trabajo realizado sobre la relación existente entre la meteorología y los incendios.

El servicio especializado para las organizaciones encargadas de luchar contra el fuego puede adoptar la forma de previsiones generalizadas del grado de peligro de incendio que cabe esperar, a fin de que los trabajos normales del personal forestal puedan organizarse de tal modo que se tenga el grado de preparación necesaria. También se pueden hacer predicciones especiales en forma de avisos concretos en una escala pequeña adecuada de tal modo que cada incendio pueda ser combatido con la mayor eficacia.

Incluso en aquellos sitios donde no exista un organismo central de lucha contra el fuego, el servicio o instituto meteorológico se puede encargar de informar al público del grado que alcanza el peligro de incendio a partir de un determinado nivel.

El tiempo reinante puede ejercer de tres formas su influencia sobre los incendios accidentales. En primer lugar, puede ejercer un efecto cumulativo sobre el control de la distribución del contenido de humedad de la vegetación muerta, que constituye el alimento principal de los incendios. En segundo lugar, puede ser causa directa de un incendio, en forma de rayo, siempre que el contenido de humedad de uno por lo menos de los posibles combustibles sea suficientemente bajo para que perdure la combustión. El tiempo puede, finalmente, influir en el desarrollo de los incendios ya declarados, en primer lugar, a través de los efectos del viento y de la humedad, y, en el caso de los grandes incendios, por medio de la inestabilidad del tiempo y de los cambios de viento.

Los métodos existentes en la actualidad para facilitar servicios especiales de previsión a fin de obtener una protección contra el fuego suelen comprender cierta valoración del grado de inflamabilidad o peligro de incendio. Algunas organizaciones meteorológicas han elaborado índices sencillos de inflamabilidad basados en uno o varios de los elementos meteorológicos corrientes o en cierta función cumulativa del tiempo que ha hecho anteriormente. Donde existen organismos encargados de la protección de los bosques, se han elaborado índices de peligro de incendio más complejos, en los que suele figurar cierto valor medido de la humedad de los posibles combustibles y una indicación del estado físico de los mismos.

El problema de cómo efectuar observaciones que sean representativas se resuelve en muchos países estableciendo redes suplementarias de estaciones meteorológicas especiales contra incendios. En otras zonas, proporciona una cobertura suficiente la red normal de estaciones sinópticas y climáticas. Se han elaborado técnicas especiales para medir el contenido de humedad de algunos posibles combustibles.

En algunos países, las regiones de bosques suelen estar poco desarrolladas y esto plantea problemas particulares de comunicaciones, especialmente en lo que se refiere a la reunión de datos de observación y a la difusión de las predicciones.

La utilidad de un servicio especializado de previsión meteorológica es tanto mayor cuando existe un enlace eficaz entre el servicio de previsión y el servicio contra incendios. En algunas regiones ese enlace queda asegurado por el envío a las zonas amenazadas por grandes incendios de equipos móviles especializados de previsionistas, que disponen de instalaciones de radio.

FORECASTING FOR FOREST FIRE SERVICES

1. INTRODUCTION

1.1 The problem

The occurrence of accidental fires in forest, brush or grassland is a significant problem in many countries under conditions ranging from tropical to sub-Arctic. Such fires may result in important economic losses of potential timber values, in reduction of watershed and recreational values, and in the loss of life and personal property.

Uniform fire statistics are not available on a world-wide basis, or often not even on a country-wide basis. However, a few examples may serve to illustrate the magnitude of the problem. In the U.S.A. it has been estimated that an average of 85,000 fires cause a loss of approximately eighty million dollars annually in timber values alone, while secondary losses bring this estimate up to two and one-half times that figure. In Canada, where one person in fifteen is estimated to be dependent on the forest industry of the country, approximately 4.5 million acres were burned in 1958. In France, an average of just under 27,000 hectares a year is reported for the period 1953-1956. Similar figures might be quoted for other areas.

On the more spectacular side, it is possible to refer to the great fire of October 1871 in the states of Michigan and Wisconsin, which burned some 3.8 million acres and was responsible for the loss of more than fifteen hundred lives (Davis 1959). In south-eastern Australia a group of fires in January 1939 caused the loss of seventy-one lives (Foley 1947). A forest fire occurring in Siberia in 1915 (Nesterov 1939) was reported to cover ten million hectares.

Such accidental fires may occur under appropriate conditions on any land area capable of supporting reasonably continuous growth of vegetation, thus excluding only polar regions, desert areas, and elevations above the timber line. In some areas, such as the south-eastern U.S.A., the danger of fire may be present throughout the greater part of every year, while in other locations conditions may only rarely be favourable for the spread of fire. The most common situation is the occurrence of fire danger, normally limited to a particular season, or seasons, and occurring in various degrees of severity almost every year.

In any particular area, the variations that do occur in the intensity of fire danger are almost entirely dependent on the weather. Wherever there are organized forest fire protection agencies, it follows that there is a demand for forecasts of the degree of fire danger. To quote from a recent official publication of the Food and Agriculture Organization on Forest Fire Control (1953) " ...... the development of fire danger forecasts ...... merits adoption wherever a fire control organization exists, or is contemplated".

Landsberg and Jacobs (Compendium of Meteorology, 1951) place fire weather in the most complicated of their classifications of applied climatic problems, namely "Multiple point or areal problem - Complex time relation - Multiple climatic element".

This Technical Note is an attempt to summarize what has been done in a number of areas of the world to provide adequate forecasts of fire danger in terms of past, present and forecast weather conditions. It is not intended to be a complete operational manual but is intended to be a guide to the meteorologist who may be unfamiliar with the problems of forestry or forest fires, but who is faced with the problem of organizing a programme of meteorological service to assist such organized forest protection agencies.

1.2 Basic principles of combustion

Fires occurring under natural conditions are subject to the same natural laws of combustion as any other type of fire, even though the conditions under which they burn are seldom simple or uniform. In the dead vegetation that makes up the bulk of the forest fuels, ignition does not normally take place until the temperature of the fuel is raised to the neighbourhood of 280°C. Complete combustion of dry wood yields approximately 4,500 calories per gramme, thus providing the heat necessary to raise the temperature of adjacent fuels to the ignition temperature.

It is a relatively simple matter to calculate the amount of heat necessary to raise the temperature of wood of a known moisture content to the ignition point. Vowinckel (1958) and Hawley (1926) have done this on the assumption that the associated water is heated to the boiling point, evaporated at that temperature and the resulting water vapour heated to the ignition temperature of the wood. Table I below indicates the heat required per gramme of dry weight for several initial values of temperature and moisture content. Hawley has suggested that, under natural conditions approximately 10 grammes of air are required for complete combustion of each gramme of wood. The effect of heating this amount of air up to ignition temperature is also indicated in Table 1.

Table 1

Heat required to raise 1 gramme of wood and associated moisture to ignition temperature,

(a) neglecting air;
(b) with 10 grammes of air.

Moisture content (% of dry weight)	Initial temperature					
	10°C		20°C		30°C	
	(a)	(b)	(a)	(b)	(a)	(b)
0	89	737	86	710	83	683
10	161	809	156	781	152	753
20	233	880	227	851	222	822
30	305	952	298	922	292	892

Neglecting the air a difference of 1 per cent in moisture content has the same effect as a change of 15°C in the opposite sense. However, when the heat required by the air is considered, a change of 1 per cent in moisture content has the same effect as a change of $2\frac{1}{2}$°C in the opposite sense.

A more rigorous treatment by Byram et al (1952) indicates that the process of freeing the adsorbed water from its bond with the wood is more complex than the above arguments would indicate. However, the resulting calculations give values which are not significantly different from those shown above.

Comparison of these values with the figure of 4,500 calories per gramme released by combustion would indicate that there should be more than sufficient heat to maintain combustion under almost any condition of moisture. However, the process is in fact dependent on the proportion of the heat of combustion which is available to heat the adjacent fuels. One factor affecting the efficiency of the reaction is the speed with which the moisture can be driven out of adjacent fuels, which is proportional to the ratio of surface area to volume of the fuel under consideration. Thus finely divided fuels can maintain combustion at higher moisture content than coarser fuels.

Another factor which affects the combustion process is the efficiency of the heat transfer to adjacent fuels. This heat transfer takes place by conduction, convection, and radiation, although conduction is relatively unimportant. The efficiency of the process is normally assisted by horizontal air movements (wind) which deflect the flames and heated vertical air currents to bring them into closer contact with the adjacent fuels. In similar fashion the efficiency of the transfer process is increased on the uphill side of the fire because the adjacent fuel is closer to the flame and to the vertical convection currents.

The effect of moisture content operates in another way that is not indicated in Table I. The amount of oxygen which can exist in the space surrounding the fuels undergoing heating may be reduced by the partial pressure of the water vapour released from the fuel. At normal temperatures the effect is negligible, but at temperatures above the boiling point of water, where saturation vapour pressure exceeds atmospheric pressure, it is theoretically possible for oxygen to be completely excluded if the amount of moisture released is large. Increased circulation of air can increase the dissipation of this excess moisture and provide oxygen by diffusion. Wind plays an important part here while the fire is small, but with larger fires the convective currents are normally adequate to diffuse this excess moisture.

In summary, the factors which determine whether any fire will go out, smoulder, or burn with increasing intensity, are :

(i) the quantity of heat required to raise the temperature of the fuel to the ignition point;

(ii) the efficiency with which the heat of combustion is transferred to adjacent fuels; and

(iii) the rate at which oxygen is available for combustion.

The influence of the weather in controlling these factors is discussed in section 2.

1.3 Definition of specialized terms

There are a number of terms that have acquired special meanings to individuals working in the field of forest protection, particularly in the English-speaking countries. A selection of these terms is defined in this section. Most of the definitions are based on material in the "Glossary of terms used in fire control" (1956) and in the "British Commonwealth forest terminology", Part 1, (1953) although there may be minor differences in wording.

BLOW-UP - A sudden increase in fire intensity, or rate of spread. This may be accompanied by violent convection and may have other characteristics of an atmospheric storm.

BUILD-UP - An expression for the cumulative effect on fire behaviour of weather conditions over some extended period of time operating through the loss of moisture from progressively deeper layers of fuel.

CROWN FIRE - A fire which travels in the tops of, or which burns all or a large part of the upper branches and foliage of trees, often more or less independently of the fire at ground level.

CURING - The change of state of grass and leafy vegetation from a live green condition to a dry dead condition. (The term is normally applied only to the lesser vegetation and not to changes in deciduous trees.)

DUFF - The partly decomposed organic material of the forest floor beneath the litter of freshly fallen twigs, needles and leaves.

FIRE DANGER - A general term expressing the degree of inflammability of fuels, the probable rate of spread and difficulty of control. The sum of both constant and variable factors.

FIRE DANGER RATING - A general term for any system of integrating selected fire danger factors into one or more qualitative or quantitative indices of current protection needs.

FIRE HAZARD - (a) A measure of that part of the fire danger which depends only on the kind, arrangement, amount and moisture content of the forest fuels.

(b) Fuels constituting a threat, either of special suppression difficulties if ignited, or of probable ignition because of their location.

FIRE RISK - The relative chance or probability of fire starting determined by the presence or absence of fire setting agents.

FUEL MOISTURE CONTENT - The quantity of moisture in a fuel, usually expressed as a percentage of the weight when thoroughly dried at 100°C.

FUEL MOISTURE INDICATOR STICKS - A specially prepared stick, or set of sticks of known dry weight, continuously exposed to the weather under standard conditions, and periodically weighed to determine changes in moisture content as an indication of the moisture change in forest fuels.

FUEL TYPE - An identifiable association of fuel elements of distinctive species, form, size, arrangement or other characteristics that will cause a predictable rate of fire spread or difficulty of control under specified weather conditions.

INFLAMMABILITY - The relative ease with which fuels ignite and burn regardless of their quantity. (In U.S. usage the term "Flammability" is preferred.)

PRESCRIBED BURNING - The planned use of fire to achieve definite objectives in silviculture, wild-life management, grazing, hazard reduction etc., under conditions which will permit confinement of the fire to a predetermined area.

SLASH - Debris left after logging, pruning, thinning, or brush cutting. It may include logs, chunks, bark, branches, stumps, and broken understory trees or brush.

SNAG - A standing dead tree or part of a dead tree from which at least the leaves and smaller branches have fallen.

SPOTTING - The behaviour of a fire producing sparks or embers that are carried by the wind and start new fires beyond the zone of direct ignition by the main fire.

STRATEGIC AREA - A defined region in which fires could cause extensive damage to grass, timber, or property, and danger to livestock and people, and where there is an organized fire protection organization. (Australian usage)

2. FIRE WEATHER RELATIONSHIPS

2.1 Weather factors influencing fire behaviour

As described in section 1.2, weather sets the stage for forest fires primarily through the control of the moisture content of the forest fuels. The control is exerted mainly by precipitation and dew, which increase the fuel moisture content, and by low atmospheric vapour pressure combined with wind, which reduce the moisture content of fuels. The effect of these meteorological elements is dependent on the amount, types, physical disposition and exposure of fuels in forests and bush country. Such fuels consist primarily of dead organic matter (chiefly cellulose and lignin) in associated sizes, arrangements and exposures.

2.1.1 Extended period influences

The fire season or fire danger period begins when the fuel moisture content decreases below the stage at which the fuel becomes potentially combustible. The onset of the danger season is the result of long-range pre-season influences which may extend backwards for many months. For example, in the case of vegetation which has an annual cycle of growth, the abundance of growth and the rate of curing of such vegetation to the stage at which it becomes a significant fire hazard, is governed by rainfall, temperature and evaporation (Robin 1957). The occurrence of killing frost is significant in deciduous forests for determining the onset of the autumn (fall) danger period.

In some areas the amount of snowfall during the winter may have an effect on the compaction of the previous season's vegetative growth.

In attempting to forecast both the onset and the potential severity of a fire danger period, the meteorologist should take account of the seasonal anomalies of the meteorological parameters of rainfall (and snowfall) and temperature and, if correlations are available, of their effects on the rate of growth and curing of vegetation.

2.1.2 Pre-ignition influences

Once vegetation and forest litter have reached the stage where they become potential fuels, the controlling factor in fire behaviour is the moisture content of the fuels as it is influenced by atmospheric moisture.

The woody materials that make up the greater part of forest fuels have the ability to take up and retain water in two ways -

(i) Such materials may contain an amount of moisture up to approximately one-third of the dry weight of the material as "bound water" which has been adsorbed on the interior surface of the material.

(ii) Any moisture in excess of this amount, called the "fibre saturation point", is held as free water. Free water is only acquired by woody materials in the presence of liquid moisture, usually in the form of rain or ground water, but occasionally as condensation from cloud or fog, or, under favourable exposures, as dew.

The loss of free water by forest fuels is closely related to evaporation, although capillary processes may limit the rate of loss where the moisture is deep-seated. Thus, in the initial stages of drying, the process is purely a surface effect and depends on the wind speed, fuel temperature and atmospheric vapour pressure.

Once the fuels have dried to the "fibre saturation point" where no further free water is available, the process becomes a reversible one as adsorption or desorption of bound water takes place in response to changes in the relative humidity and temperature of the environment.

For any given value of atmospheric moisture and temperature there is a corresponding moisture content of forest fuels at equilibrium with that environment. This value is known as the equilibrium moisture content. Because the atmospheric conditions are constantly changing, the moisture content of any particular fuel is also fluctuating, but with a time lag which depends on the size and exposure of the fuel as well as the wind speed, which controls the moisture gradient in the immediate vicinity of the fuel surface.

At one extreme, the very fine, well-exposed fuels such as uncompacted cured grasses or dead bracken may respond almost immediately to changes in relative humidity and temperature. On the other hand, large logs or compacted material may take a whole season to dry out. It follows therefore that there is no unique value of fuel moisture at any given time, but rather a whole spectrum of values which reflect the particular sequence of past weather conditions. In practice, therefore, although it is possible to determine the equilibrium moisture content from atmospheric conditions, this state is rarely, if ever, reached in the normal course of events although it will be approached most closely by the very fine fuels.

Any attempts to relate changes in moisture content of fully exposed fuels to values of ambient temperatures and relative humidity must take into account the effects of solar and terrestrial radiation. Byram (1940, 1948) and Byram and Jemison (1943) have investigated some of the apparent paradoxes in the behaviour of fuel moisture content under the influence of incoming (solar and sky) and outgoing (terrestrial) radiation but the problem is quite complex.

The meteorologist's interest in the distribution of moisture content of forest fuels is not primarily because of any utility as a forecasting tool but rather to assist him in interpreting past weather in terms of forest inflammability. Forest fire protection agencies however, regard this as a matter of prime importance, and have developed a number of methods for taking routine observations of the moisture content of significant fuels or for estimating the moisture content from meteorological parameters.

These methods which are described in greater detail in sections 2.3.1 and 3.1 are in general of three kinds -

(1) The routine weighing of standardized indicators in the form of rods or slats of a known dry weight immediately after exposure under natural conditions (see "Fuel moisture indicator sticks" under "Definitions" in section 1.3). The principal drawbacks to this practice appear to be the difficulty in standardizing the material and the progressive losses resulting from weathering, but the procedure is widely used in the United States as well as in parts of Canada, South Africa, New Zealand and Australia.

(2) The insertion of a hygrometer, suitably calibrated in terms of moisture content, into accumulations of forest litter. This instrument, known as a "duff hygrometer" is not widely used at present because of the difficulty of calibration.

(3) The derivation of an index of moisture content of one or more significant fuel types from a combination of purely meteorological parameters, past and present. Such indices have been developed in a number of countries including Canada (Beall 1950), Australia (Cromer 1946), U.S.S.R. (Nesterov), Sweden (Angström 1942) and Finland (Franssila 1958).

Normally the fuels chosen for measurement or estimation of their moisture content are those in which fires normally start, but for fire control purposes it is also useful to estimate the moisture content of fuels which have a much slower response, such as (1) large logs which contribute much of the heat in a going fire, or possibly (2) large volumes of compacted fuel under a relatively dense canopy of green timber.

The derived indices of moisture content of slow-drying fuels are commonly called "drought" or "build-up" indices. Many of the danger rating tables in use, e.g., those developed by the Canadian Forestry Branch, are based on the number of days since a soaking rain, while others employ derived estimates of the moisture content of larger logs lying on the ground, e.g., the British Columbia Forest Service build-up index which is related to the behaviour of logs of 3 to 4 inch diameter (Turner 1957), while the California build-up index is based on logs of 6 inch diameter (Jensen and Schroeder 1958). The possibility of using water table measurements for this purpose is currently being investigated in the Canadian Forestry Branch (Williams 1954). A number of other rating systems make use of techniques of averaging the fast-drying moisture contents over some past period of time without explicitly relating the index so derived to any particular physical quantity. The seasonal variation in moisture content of living material also appears to be a significant factor, particularly in the foliage of evergreens which have a high percentage of volatile materials.

2.1.3 Natural ignition (lightning)

2.1.3.1 The forecasting problems

The only meteorological element which can directly cause a fire is lightning, but because its effectiveness as a fire setting agency is dependent also on the moisture content of the critical fuels, the importance of lightning in causing fires has been either overlooked or underestimated until recent years. Bennett (1958) has summarized the problem for North America. It should be noted also that the period of maximum lightning fire frequency rarely coincides with the season of maximum thunderstorm incidence. Consequently, past records and even some present records of fires caused by lightning are incomplete. The forecaster is thus faced with a dual problem, firstly that of forecasting the occurrence of cloud-to-ground lightning discharges and secondly that of determining and forecasting the critical moisture content of the fuels. Gisborne (1931) found from an analysis of five years of data in Rocky Mountain forests that the duration of rainfall associated with the thunderstorm was the principal factor in determining whether or not fires were set. On the other hand, recent research suggests that moisture may not be the sole determining factor and Malan (1959) suggests that a single stroke of lightning may tend to be explosive rather than incendiary, whereas it may require a continuous current or succession of discharges to cause ignition. The meteorological factors which distinguish these types of lightning are as yet unknown.

Two facts to be noted particularly in connexion with lightning as a fire setting agency are the intensity of the heat sources (estimated to be as high as 30,000°C) and the fact that the forest litter under the dense canopy provided by certain types of trees often remains unwetted by the brief accompanying showers. It is possible in these circumstances for a fire started by lightning to smoulder in a limited area for as long as two or three weeks until conditions become favourable for the general fuel in its vicinity to carry fire. In such situations the significant fuels are very probably the slow drying or heavy fuels involved in the build-up indices. It is important to recognize this tendency for lightning fires to smoulder unobserved for many days until drying reduces the fuel moisture content below the critical value with a subsequent outbreak of fires.

An important phenomenon associated with lightning is the "thunderstorm down-draught". This will be most significant in the case of dry fuels where fires can begin to run almost immediately on ignition, or in the case of fires which are already burning in the area affected by the storm.

2.1.3.2 Thunderstorm types

The type of thunderstorm is also important in determining the potential fire setting efficiency of the lightning. Research in the western U.S.A. and Canada suggests that local heat thunderstorms, general frontal storms, and high-level thunderstorms associated with upper-level cold "lows" all have significantly different fire setting potentials. However, although it is generally assumed by foresters that a distinction must be made in this regard between "dry" lightning storms and those accompanied by substantial rainfall, investigation has shown that only 6 to 10 per cent of all lightning storms can be truly called "dry" and that these storms have effectively the same relative fire setting potential as those associated with rain (Gisborne 1931).

2.1.3.3 Favoured altitudinal zones

It does not necessarily follow therefore that the regions of the world where thunderstorms occur most frequently are the most susceptible to the ignition of forest fires by lightning. This question of most favoured zones for lightning fires has attracted the attention of foresters in many countries, notably in the north-western States of the U.S.A.

Solutions are essentially empirical and research is hampered by the incompleteness of records of past fires, already referred to. Morris (1934), in a detailed analysis of a large number of lightning storms in Washington and Oregon States, was unable to find any localities which could be designated as "lightning storm breeding areas". On the other hand, he did find that on 73 per cent of days when thunderstorms were general over a large area, lightning storms began simultaneously. Gray (1932) investigated the problem of a favoured altitudinal zone for the occurrence of lightning storms in California. For this region he suggested that such a zone occurred at 3,000 feet, and that the most favoured altitude decreased as the latitude increased.

Barrows (1951) suggests 5,000-6,000 feet west of the continental divide in Idaho and Montana and 3,000-4,000 feet east of the divide.

Gray's investigations led him to the empirical conclusion that the altitude at which lightning fires were most likely to start was approximately 2,500 feet below the base of the storm cloud.

2.1.3.4 Favoured fuels for lightning strikes

Again inadequate records have led to a diversity of ideas on the types of fuel most frequently struck. Barrows states that in 34 per cent of all fires in the northern Rocky Mountains a standing dead tree or snag was the first material ignited.

Morris states that needles and duff came first with live trees and "snags" second.

It is most likely that in areas where old burns have left large numbers of dead standing trees these are the prime targets, whereas where green timber is plentiful, particularly in coniferous stands, the significant fuel is the accumulation of duff or litter at the base of the trees.

Details are difficult to obtain for tropical forests, probably for one or more of the following reasons -

(a) There is no systematized meteorological service for the forecasting of forest fires in many tropical countries.

(b) There is no forest protection service as fires are of little account.

(c) Lightning storms are confined to the wet season when fires, if ignited, do not spread.

2.1.3.5 Lightning suppression

No discussion of the lightning problem would be complete without a reference to the sincere wish on the part of foresters everywhere that potential lightning storms may somehow be modified to reduce the annual toll they take of the world's forests.

Although the immediate prospects of such a goal are still in doubt, the fundamental knowledge of the physics of lightning storms being obtained by co-operative projects such as "Skyfire" (Barrows 1960) cannot help but place the forecasting and detection of lightning fires on a much firmer foundation than heretofore.

2.1.4 Post-ignition influences of weather on fire behaviour

It has long been recognized that there are fundamental differences in the behaviour of forest fires between the small fires of low intensity and those of disastrous high intensity. Many investigators, notably Byram (1954) and Colson (1956), have shown that the distinction is not merely one of degree of intensity, but a basic difference between an essentially two-dimensional entity and a three-dimensional structure. According to Byram, once the critical stage of "three dimensions" is reached, a fire begins to "create its own weather" and takes on the characteristics of an atmospheric storm, with a rate of energy production of sufficient magnitude to become significant as an atmospheric disturbance of a micro or even meso scale.

The distinction between the two basic types of fire behaviour is fundamental to a discussion of the post-ignition influences of weather on fires.

2.1.4.1 Influence on low-intensity fires

The principal meteorological factors influencing the rate of spread of fires in the early stages are relative humidity, wind speed and atmospheric stability.

Relative humidity, by virtue of its control of the moisture content of surrounding fuels, is the prime weather factor in the initial establishment period of a fire, the duration of which is claimed to vary from approximately 3 minutes in fine fuels with low moisture content to as much as 14 minutes or more in heavier fuels with high moisture content. The direct significance of relative humidity, according to Fahnestock (1953) decreases with increase in the concentration of available fuels.

A secondary and almost insignificant effect of relative humidity is in directly controlling the partial pressure of the oxygen available for combustion (Bryan 1947). This effect is quite independent of fuel moisture.

After the initial establishment of the fire, it reaches a temperature sufficient to pre-heat the fuel and thus reduce its moisture content. At this stage, wind speed becomes the controlling weather factor in the spread of the fire, operating in two ways - first by controlling the rate of oxygen supply and second by helping to carry the heat to adjacent fuels, pre-drying them in advance of the fire. Wright (1943) and others have developed a widely accepted rule of thumb that the rate of lineal advance of a fire on level ground is proportional to the square of the wind speed. Wind-tunnel experiments by Fons (1946) indicate a forward spread proportional to some smaller power of the wind speed.

Atmospheric stability also influences fire behaviour, particularly in the early stages. An unstable lapse rate and a negative vertical wind shear assist convection to considerable levels over the site of a fire, accelerating the inflow of air and so increasing the rate of combustion.

Other meteorological factors which influence low-intensity fires are temperature and cloudiness, but these are only indirectly effective through their association with relative humidity and stability and hence with fuel moisture.

2.1.4.2 Influence on high-intensity fires

By far the greater percentage of forest fires never develop beyond the low intensity stage discussed above. Their behaviour is normally quite predictable in terms of changes in atmospheric and fuel moisture and surface wind, provided the distribution and composition of available fuels are known.

A small proportion of these fires may suddenly, and often unexpectedly, develop storm characteristics and become "blow-up" fires, known also in some countries as "explosive" and "crown" fires (Australia). These fires account for the greatest part of the total acreage burned and offer the most serious threat to human life. Arnold and Buck (1954) stress the interaction of meteorological factors, fuel concentrations and topography in providing suitable conditions for these sudden changes in fire behaviour.

Byram (1954) lists four necessary conditions for the development of such fire behaviour, based on case histories of a number of such fires and a consideration of the energy balance between the fire and the atmosphere -

(1) A plentiful supply of dry fuel;

(2) An unstable, or recently unstable atmosphere;

(3) Winds in excess of 18 mph at or just above the fire; and

(4) A marked decrease of wind with height for the first several thousand feet.

These conditions are necessary to permit the development of a persistent convective column above the fire which adds the significant third dimension to it. Such a convective column provides a forced draught for the fire and contributes to its spread by carrying in the updraught large burning embers which may be dropped several miles in advance of the fire front, to start new fires outside any guards that may have been constructed, and on occasion, trapping fire-fighting personnel.

Of the four conditions listed by Byram, stability in the lowest layers of the atmosphere appears to have the greatest effect on the behaviour of larger fires. The occurrence of superadiabatic lapse rates may result in the formation of small whirlwinds in the fire area and occasionally whirlwinds develop tornadic violence, capable of uprooting large trees. Graham (1955, 1957) and Whittingham (1959) have investigated cases of fire whirlwinds in the U.S.A. and Australia respectively.

While forecasting the occurrence of shallow layers of strong wind near the surface is a problem requiring particular consideration, if fire fighting authorities are to be given adequate warning of potential blow-up conditions, Byram (1954) and Whittingham (1959) have also demonstrated the necessity for directing attention to the forecasting of upper-level winds.

Schaefer (1957) in a study of a number of "blow-up" fires, suggests that a necessary condition is the presence of a trough in the jet stream overhead.

2.1.4.3 Wind and slope

Finally, in a discussion of the post-ignition influence of wind, reference must be made to the occasional anomalous behaviour of the winds in a fire area in relation to the slope of the terrain.

Fires normally spread most rapidly upslope under the influence of convection. Under normal conditions, upslope winds occur during the hottest part of the afternoon when fuel moisture is at its lowest value, while downslope winds are associated with higher moisture content just before daybreak. The net result is a general tendency for fires to burn rather rapidly uphill in the afternoon with little activity overnight, other factors being equal. This tendency is recognized and expected by well-informed fire fighters.

However, there have been numerous instances when fires have burned strongly downslope during the hottest part of the day. Krumm (1959) has studied a number of these cases and finds three separate developments which can force fires to burn strongly downhill :

(1) The passage of a dry cold front.

(2) Large-scale subsidence.

(3) Downdraughts associated with thunderstorms.

The association between the development of mountain wave formations (Alaka 1958) and downslope winds in the lee of major ridges indicates that such conditions may be expected with :

(a) extreme stability in the lower layers with less stability aloft;

(b) wind direction constant with height and within 30° from a direction normal to the direction of the ridge;

(c) winds increasing with height and generally exceeding a value of 8 - 13 metres per second at the level of the summit of the ridge.

2.2 Methods of fire weather investigation

The investigation of the complex relationships between weather and forest fires can only produce results which will be useful to forecasters and foresters alike if the investigators keep in mind the necessity for reducing to a minimum the subjectivity inevitably bound up in any method of approach to the problem. The aim of objectivity in establishing relationships between forest fires and meteorological parameters should apply equally to theoretical and to empirical methods.

Five techniques of fire weather investigation are outlined here but it should be understood that many of the most fruitful researches have been those which combined several of these methods.

2.2.1 The statistical-climatic approach

The objective of this method is to seek to isolate the meteorological parameters associated with the ignition and spread of forest fires from statistical study of the occurrence of fires and to correlate values of the significant weather elements with fire danger activity. For example, in a particular region associations may be found between the statistics of fire behaviour and mean values of relative humidity, sunshine, maximum temperature etc.

Studies of this type have been undertaken in most countries which have a forest fire problem. The method is well exemplified by Larsen (1925) in a study for the States of Idaho and Montana, Geiger (1948) for Germany and more recently by Krueger (1959) for Georgia (U.S.A.).

Larsen, for example, determined that :

(1) approximately 2.00 inches of rain per month is necessary to prevent damaging fires;

(2) the normal length of the fire season can be determined by the length of the period during which the monthly rainfall is below that figure;

(3) a threshold mean daily temperature of 50°F is necessary for fire occurrence.

2.2.2 Synoptic typing

In this method fire danger factors, fire occurrence and fire behaviour are related directly to recognizable features of the synoptic chart. The advantage of this technique is that it can be used for forecasting fire danger and even fire behaviour.

Meteorologists in most countries have used synoptic typing in other fields of meteorological investigation, as well as in fire weather relationships. In recent years punched cards and skewer cards have facilitated the use of this method of analogues. Workers in this field include Schroeder (1950), Turner (1953, 1955), Douglas (1957), Robin and Wilson (1958), and many fire weather forecasters in the western U.S.A.

2.2.3 Observation of the behaviour of fires

By co-operation with Forest Fire Protection Authorities meteorologists often have the opportunity to carry out instrumental and visual observations in the vicinity of forest fires to establish the micro-meteorological conditions associated with fires. The same results are obtainable from standardized test fires and controlled "burns" arranged by forestry and other interests, sometimes for the purpose of disposing of trash and forest litter out of season under conditions which will not be conducive to the fires getting out of control. It is of course a necessary step in any investigation to relate the behaviour of small test fires to the behaviour of large fires wherever possible.

The danger rating tables of the Canada Forestry Branch were derived from observations made of standardized test fires (MacLeod 1948). Examples of other investigations of this nature are given by Ångström (1942), Fons (1946), Vowinckel (1959) and Whittingham (1958).

2.2.4 The case history method

This method involves the accumulation of all recorded and remembered details of the occurrence and behaviour of fires and is probably the only way of acquiring a full knowledge of the larger catastrophic fires. It is a technique rather than a method of fire weather investigation and can be applied equally to large forest fires, prescribed burns and test fires.

Such case history studies have been widely used, e.g., by Byram (1954), Small (1957) and others in the U.S.A., and by a number of investigators in Australia, e.g., Foley (1947), Robin (1958) and Whittingham (1959).

In Australia the case history record of each major fire or fire danger period is classified into two groups, the first being maintained continuously until the fire is extinguished and the second consisting of miscellaneous data filed as they become available.

Group 1 consists of :

(a) brief-size extracts of :

(i) surface synoptic charts for 6-hourly intervals;

(ii) 700- and 500 mb-charts including thickness, streamline and isotherm analyses;

(b) radiosonde and upper-wind soundings within a 500 mile radius of the fire outbreak;

(c) relevant daily bulletins and rain maps;

(d) detailed observations from nearby synoptic stations;

(e) complete record of all observations received from all sources outside the routine network;

(f) teletype copies of all special fire weather reports;

(g) fuel state reports in fire areas;

(h) copies of all computed fire danger indices in the fire area; and

(j) copies of all warnings, operational forecasts and special advices issued for the fire area.

Group 2 consists of :

(a) fire logs, including notes of fire behaviour, special phenomena (such as whirlwinds, fire storms, etc.) and the type, condition and amount of fuel in the fire area;

(b) relevant newspaper cuttings;

(c) copies of all autographic records, e.g., anemographs, when available near the site of the fire.

2.2.5 Theoretical investigations

The four methods of investigation into the fire weather relationship outlined above are all to a certain extent empirical. Any study on this subject necessitates also a careful analysis of the physical factors involved, quite apart from the fact that opportunities for experiment on observation of the behaviour of the significant "blow-up" fires are very infrequent.

A good example of a completely theoretical approach to the problem of the ignition and spread of forest fires is given by Byram (1959) in a consideration of the energy balance in an atmospheric combustion model. In a combined empirical theoretical study Whittingham (1958) has leaned heavily on theory to determine favourable conditions for successful prescribed burns of unwanted forest species.

2.3 Fire weather observations

In many areas the needs of forest protection cannot be met by the normal synoptic network, nor by the existing climatological organization. This deficiency may be overcome by the establishment of a supplementary network of special fire-weather stations operated only during the normal fire season.

Such a supplementary network of special stations serves two main purposes. First it provides meteorological information for the use of the forecaster in areas not normally represented by the existing synoptic network. Such a network provides in addition information which is representative of forested sites rather than from urban areas. The second function of fire weather stations is the provision of the non-meteorological information necessary for calculations of fire danger. This information is primarily for the use of protection personnel, who are particularly concerned with local variations in the factors that affect fire danger.

The degree of participation by the meteorological organizations in the establishment of such a supplementary network varies considerably from one area to another. Although such supplementary stations exist in many areas, details are not generally available. However, a brief outline of the situation in three areas where the problem is acute should serve to illustrate what is being done.

In Australia, the Bureau of Meteorology is responsible for organizing a supplementary network of telegraphic rainfall reporting stations as required to give an adequate picture of the rainfall pattern in any strategic area. In addition the Divisional Office Forecasting and Warning Sections are responsible for organizing a network of stations to provide the forecaster with reports of the state of the fuel and other significant meteorological information, such as atmospheric moisture and wind changes, during periods of high fire danger.

In the U.S.A. the Fire Weather Service of the U.S. Weather Bureau plays a major part in the establishment of the network of fire weather stations. Provision of equipment and supervision of the observations is generally the function of the Weather Bureau, which also looks after the collection and processing of the information. The actual operation of such fire weather stations is a function of government and of private forestry organizations who require the information in order that they may be continuously aware of local variations in fire danger.

In Canada, the establishment and operation of such fire weather networks is considered to be the responsibility of the forest protection agencies, rather than of the Meteorological Branch, although there is very close co-operation between the regional offices and the various forestry organizations in setting up such stations. Any information obtained at these stations is available to the forecaster as required.

A highly organized network exists in the province of Quebec, where the establishment and operation of such stations has been undertaken by the provincial Bureau of Meteorology which operates under the Department of Lands and Forests. (This network of stations is also organized to provide specialized information in the field of hydrology and of winter sports.) Details of observation methods are contained in Villeneuve (1948, 1949).

It is not within the scope of this report to go into details with regard to special fire weather observations. This information is available in such publications as Jemison, Lindenmuth and Keetch (1949), MacQueen and Turner (1953), and Hardy _et al_ (1955), to mention only a few. Discussions here will be limited to those observations which may generally be unfamiliar to meteorologists, namely, direct observations of fuel state.

2.3.1 Observations of fuel state

The two fuel states which are most significant in the estimation of fire danger are the stage of the seasonal development of growth and curing, and the moisture content of dead woody material.

Variations in seasonal development are significant for various reasons. In deciduous forests the time of flushing of the leaves is significant for the shade provided to the litter beneath, while the time of leaf fall is important for the provision of fresh hazardous fuel, and loss of shade. In observing this factor it is necessary to be sure that observations are made on a representative forest area rather than one which is responding to some climatic anomaly.

Wherever grass is a significant fuel, the stage of seasonal development is of utmost importance, overshadowing all other factors. Observations of this particular factor may be limited to a simple statement of "green" or "cured", or may include estimates of the "percentage cured" or the "percentage green" as in the California Fire Danger Rating System or the Canadian Forestry Branch Tables.

In the hardwood types of the eastern U.S.A., the condition of "lesser" vegetation is indicated (Keetch 1954). The term "green" is used from the time when associated grasses, weeds and shrubs are one-half to three-quarters grown, until they are killed by the fall frosts. The spring transition period extends from the time green growth begins until the grasses and weeds are about three-quarters grown. The fall transition period begins about the time the first fall frost cures the annual vegetation and persists until the leaves are generally dropping from the deciduous trees. In mountainous areas it may be difficult to obtain a representative estimate of the state of the fuel; in this case it is best to rate the whole area by the most hazardous condition observed.

In lower latitudes and "summer dry" climates, the curing or drying of lesser vegetation may be controlled by drought rather than by frost. This is the case in Australia, where Robin (1957) has attempted to eliminate the need for observing this factor, by estimating it in terms of the balance between rainfall and evaporation.

Routine observations of fuel moisture on an operational basis generally employ sets of standardized wooden sticks following a method which is said to have been originated by McArdle of the U.S. Forest Service, and later used extensively by the late H. T. Gisborne in Montana and Idaho.

On the North American continent, fuel moisture indicator sticks for operational use are of two general types. In the west these consist of four 1/2 inch dowels spaced 1/4 inch apart on two 3/16 inch wooden pins. These dowels are made of carefully selected wood of uniform density and free from defects. Ponderosa pine is used in the U.S.A. (Hardy 1953) while Douglas fir sticks are used in British Columbia. These sticks are carefully oven-dried and cut to 100.0 grammes oven-dry weight. The final step involves reconditioning and testing to eliminate those sets of sticks which behave abnormally. The manufacture and distribution of the fuel moisture indicator sticks are the responsibility of the appropriate forest service. In the eastern part of the U.S.A. the indicator sticks consist of three flat basswood slats of known oven-dry weight, 18 inches long, 2 3/8 inches wide and 1/8 inch thick.

Methods of exposure vary with the danger rating system in use, but the intention is to simulate the exposure of the more critical fuels in some standardized manner. According to Fons and Countryman (1950) the type of litter underlying the sticks appears to have no significant effect although other investigators insist on some standard type of underlying surface.

For research purposes, the Canadian Forestry Branch employs flat trays approximately 24 inches by 16 inches by 2 inches containing pine-match splints of 400 gm oven-dry weight. The trays consist of a galvanized wire frame 24 inches by 16 inches by 2 inches covered by a synthetic fabric mesh. The unit is set into the representative litter and weighed by means of an accurate spring balance, and from the known tare weight of the tray the moisture content is calculated.

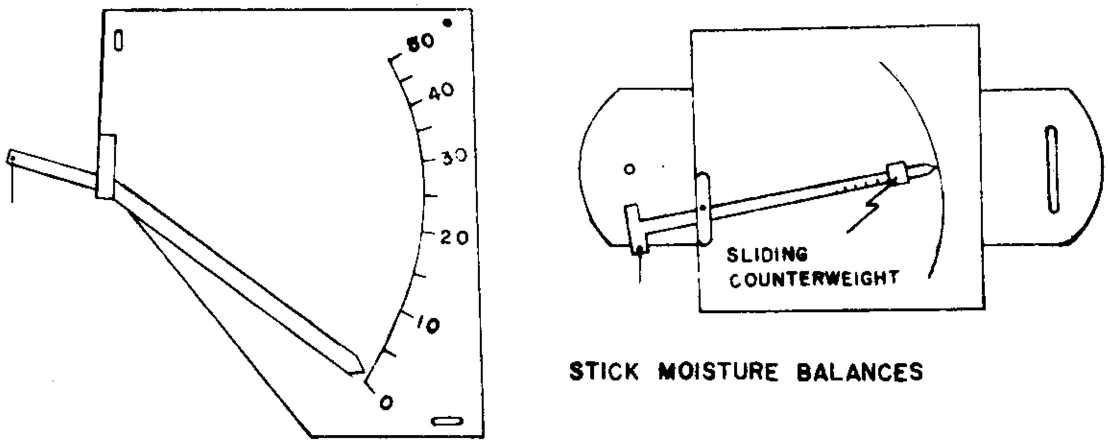
In some regions of Australia fuel moisture is measured by sets of 1/2 inch cylinders of plantation grown <u>pinus radiata</u> cut to 50 grammes oven-dry weight. (A density of

30 - 33 lb per cubic foot at 12 per cent moisture content is specified.) These sticks are exposed 10 inches above ground level, and may be fully exposed or may be 5 inches below six thicknesses of gauze "flywire" mesh.

In South Africa (Vowinckel 1960) fuel moisture is indicated by pinus patula sticks of a specified density measuring 0.4 x 0.4 x 30.0 cm in sets of 8. These sticks are exposed under average forest conditions, one set on top of the litter and one at the bottom.

Although routine weighing of fuel moisture sticks can be accomplished by any portable balance of suitable sensitivity, there are two types which have been specifically designed to give direct readings of moisture content.

These are illustrated diagrammatically below :



STICK MOISTURE BALANCES

Figure 1

The simple "bent arm" balance is used where the sticks are cut to a fixed oven-dry weight. Levelling of the balance is accomplished by rotating the plate on its mounting until the pointer reads zero moisture content with a 100 grammes check weight on the balance.

The type of balance in the right-hand diagram of Figure 1 is used where sticks are cut to fixed dimensions, with the oven-dry weight varying slightly from set to set. The small sliding counterweight is moved along the pointer arm which is calibrated in terms of oven-dry weight.

2.3.2 Spatial variations in fire weather elements

As in most branches of applied meteorology, the variations in observed weather elements over small distances are often as important as the large-scale weather conditions in the control of fire behaviour and, on occasion, may be more so. Although the general subject of small-scale meteorology has been admirably covered by Geiger (1950) and others, there has been sufficient work of this type done specifically concerned with problems of fire behaviour to justify a brief account in this Note.

The problem is centred around what Geiger calls the "Range of validity" of standard meteorological observations. In the first place, it is important to know to what extent the information available from standard meteorological stations is representative of conditions where forest fires occur, and under what conditions additional measurements should be made for the purpose of estimating fire danger. In the second place, it is necessary to determine the minimum amount of detail that can be included in a forecast to enable the user to make a reasonable estimate of expected conditions at the particular location in which he is interested.

With relatively flat terrain it is usually assumed that the normal synoptic network provides adequate information regarding the current state of fire danger and, in many countries, satisfactory estimates are based entirely on such information. However, even in the absence of pronounced topographic features there will be some bias in using information from urban centres to represent conditions in nearby wooded areas. This can be determined by field research and appropriate adjustments made if they are found to be necessary. Another problem that must be recognized is the variation in rainfall over short distances, particularly under the showery conditions often associated with periods of fire danger.

As the topographic features become more pronounced, the problem of obtaining a complete picture of the state of fire danger is solved in two ways :

(i) by the development of a supplementary fire weather network usually reporting once or twice daily;

(ii) by extending the "Range of validity" of existing stations through the use of short-term investigations.

Where slopes are moderate and valleys reasonably wide, it is a relatively simple matter to relate conditions on the slopes to those measured under level conditions either in the valley bottom, or on the plateau. Here the problem is largely one of differences in the intensity of solar radiation which can become particularly significant at higher latitudes. Byram and Jemison (1943) give an excellent discussion of this effect.

Where the topography is such that large differences in altitude occur over short distances the problem is further complicated by variations in airflow and by inversion effects. Morris (1940) has made a statistical analysis of the number of stations required to give representative measurements for administrative units averaging approximately 300,000 acres in the mountainous regions of Washington and Oregon where the range in elevation is of the order of 9,000 feet. According to his criteria, between 4 and 11 stations are desirable for each of these administrative units. Jemison, Lindenmuth and Keetch (1949) suggest 1 to 2 stations per 300,000 acres for the mountainous country of the eastern U.S.A.

A number of studies have been undertaken to relate fire danger conditions on various slopes to those observed in the valley bottom or at the mountain top. One of the more complete studies of this type was undertaken by Hayes (1941) in the Priest River Experimental Forest in northern Idaho during the years 1935 - 1938.

Pairs of stations were located along either side of a forested ridge running from west to east out of the Priest River Valley from the valley bottom at 2,300 feet up to the 5,500 foot level. A number of charts are presented, summarizing up to four years of measurements by recording instruments, of most of the factors involved in fire danger estimates. The following tables, giving variations in moisture content of the half-inch indicator sticks and of the duff as measured by a hygrometer calibrated in terms of duff moisture, have been derived from these charts.

Although rainfall increased with elevation, Hayes found no indication that the difference in amount of rain significantly affected the length of time that fuel moisture remained above the level of inflammability. Differences in exposure to drying influences after rain were found to be more significant.

The most striking effect found in the above study was the occurrence of a "thermal zone" of relatively high night-time temperatures and low relative humidities coinciding with the top of a pronounced inversion. This inversion condition was found to be typical, occurring more often than 90 per cent of the time. Detailed measurements during one month indicated that the top of the inversion was usually found between the 3,100 and 3,400 foot levels, or 800 to 1,100 feet above the valley bottom.

The occurrence of similar typical inversion conditions has been studied in southern Alberta (MacLeod 1948). The importance of inversion conditions has been recognized for many years in the west coast areas of North America, where it has become the policy to locate fire weather stations at elevations within the "thermal zone" whenever possible.

Table 2.

Half-inch stick Moisture - Median August day 1935-8

Altitude (feet)	Aspect	Hour of Day 22	24	02	04	06	08	10	12	14	16	18	20
2300	level	8	10	11	12	13	12	10	8	6	6	6	7
2700	south	8	9	10	10	11	10	8	7	7	6	7	8
	north	10	11	11	12	13	13	11	9	8	8	9	10
3800	south	7	7	8	8	8	8	7	6	6	6	6	7
	north	8	8	8	9	9	9	8	8	7	7	7	8
5500	south	9	9	10	10	10	10	9	8	8	8	8	8
	north	10	10	10	11	11	10	10	9	9	9	9	9

Duff Moisture Content Median August day, 1936-8

Altitude (feet)	Aspect	Hour of Day 22	24	02	04	06	08	10	12	14	16	18	20
2300	level	14	16	20	22	24	22	10	6	5	6	8	10
2700	south	11	12	14	16	16	18	8	4	4	5	7	9
	north	14	16	18	20	22	24	20	10	8	8	10	12
3800	south	9	11	12	13	14	14	6	4	4	5	6	8
	north	14	15	16	16	17	16	16	8	8	8	11	12
5500	south	11	12	14	15	16	16	6	4	4	4	7	9
	north	12	14	16	17	18	18	9	6	6	6	8	10

By determining the amount of correction to any given danger rating to obtain the rating at some other type of exposure or at some other time of day, the "range of validity" of the station is extended. Hayes (1942), MacLeod (1948) and Fahnestock (1951) have done this for the particular rating systems they were using.

Relationships between conditions at two stations with different exposures and at different elevations are seldom simple, particularly in coastal areas, and attempts to extend the range of validity of any station can often be improved by taking into account the fact that these relationships may be different for different synoptic situations. Results of a study of this type for stations in the vicinity of a mountain top lookout in western Oregon have been reported by Berg and Lowry (1959). The Canadian Forestry Branch has been engaged in studies of this type for several years along the eastern slopes of the Rocky Mountains in south-western Alberta.

Local variations in wind are particularly important in connexion with special forecasts for controlled burning or in forecasts for large wild fires. North American studies particularly designed to discover the nature of some of these variations have been reported by Cramer (1957), Countryman and Colson (1958), and Schroeder and Countryman (1960). In many cases cross-sectional diagrams of potential temperature have been used with good results in mountainous country to account for some of the anomalous winds that have been observed (Cramer 1960).

It is necessary to mention here that many of the observations which have gone into the development of a number of fire danger systems do not conform to the usual meteorological standards, which are not always suited to the problem. For example, wind speeds have been measured at various levels down to two feet from the ground, and at locations ranging from fully exposed to densely forested. The period of time over which wind speeds are averaged varies considerably from system to system. As a result, appropriate adjustments must be determined and applied when standard observations are used.

Although rainfall observations are generally taken at exposed locations, it is often necessary to take into account the fact that light showers of short duration may not have any appreciable effect on forest litter under a dense forest canopy.

The temperature and relative humidities affecting logging "slash" and other potential fuels which are fully exposed to solar radiation, and themselves able to radiate freely, are much more extreme than those measured under standard shelter conditions. Byram and Jemison (1943) found the following relationship between fuel temperature and standard air temperature in terms of surface wind velocity and intensity of radiation, as measured in their synthetic weather chamber :

$$T_f - T_a = \frac{I}{0.015V + 0.026}$$ where

T_f is the surface temperature of oak litter in degrees F,

T_a is the air temperature in degrees F,

I is the intensity of radiation in calories per square centimetre per minute and

V is the wind velocity at the surface in miles per hour.

It is stressed that the constants which were obtained empirically for this particular type of litter could vary considerably from one fuel type to another, depending on the rate of heat flow through the litter.

By combining this equation with an approximate formula relating the above temperature difference to the ratio of surface relative humidity to the standard shelter value, namely :

$$H_f / H_a = e^{-0.033 (T_f - T_a)}$$

a convenient nomographic chart was developed for determining the proportional reduction in relative humidity at the surface of the litter, in terms of intensity of solar radiation and surface wind speed (Figure 2).

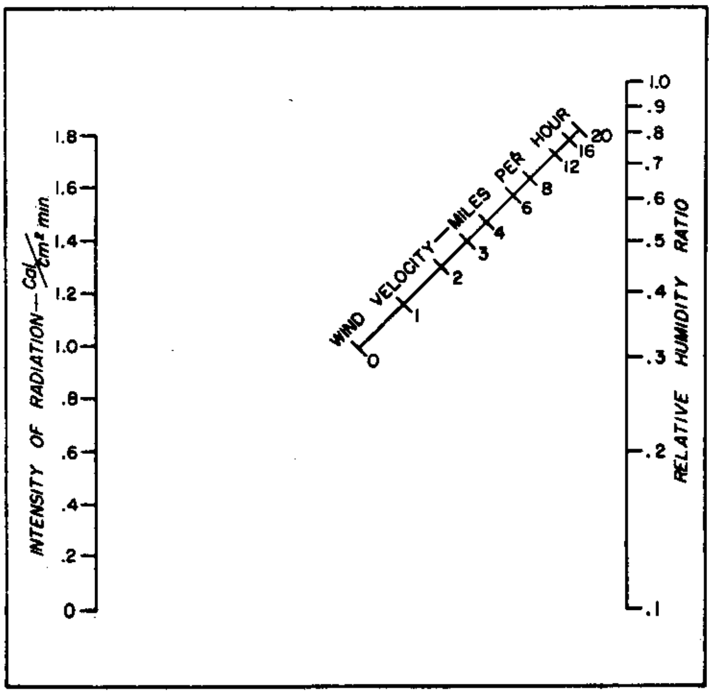
Because of the importance of radiation effects on the forest fuels, it is necessary to ensure that fuel moisture indicators are exposed under the conditions encountered by the fuels in which fires are most likely to start. Thus, if logging slash is the critical fuel, the indicator sticks should be exposed to full sunlight. If, however, the critical fuel is needle litter, or duff under the forest canopy, then the indicator sticks should be similarly exposed, preferably under some type of "standard" shade.

As an example of the variations in the several fire weather factors which result from different degrees of exposure, the following measurements were taken by Morris (1941) during the summer of 1940 in virgin forest and three different intensities of cutting of Douglas fir in the Willamette National Forest, Oregon.

Table 3

	Wind speed	Relative humidity	Temperature	Stick moisture
Clear cut :	2.7 mph	28.0%	75.5°F	7.5%
Heavy cut :	0.8	28.0	75.8	8.9
Light cut :	0.7	30.6	72.1	11.1
Virgin forest :	0.6	35.8	70.4	13.1

(Wind speed is the average daily value over the period July 15th to September 1st measured 8 feet above ground level; temperature, relative humidities and stick moisture content give the average of the 4.15 p.m. reading for the 32 rainless days during that period.)



NOMOGRAPHIC CHART FOR OBTAINING THE REDUCTION OF RELATIVE HUMIDITY AT A SURFACE EXPOSED TO RADIATION.
(G.M. BYRAM & G.M. JEMISON)

Figure 2

3. EXISTING METHODS OF PROVIDING SPECIAL FORECAST SERVICES

The existing methods of providing special forecast services in connexion with forest fires are designed to perform one or both of the following functions :

(a) Warn the public of the current state of fire danger to ensure that they will be particularly careful in the use of fire or take additional precautions against accidental fires being set on days of high hazard, and in some instances, avoid areas of extreme fire danger.

(b) Provide specialized information for organized fire-fighting services in order that they may be able to alert their staff and intensify preventive and detection measures. Special services may be provided to assist in actual fire-fighting operations.

There is a wide variation in the degree to which the weather service of any particular country is involved in the provision of warnings to the general public. In some countries such warnings are the sole responsibility of the weather service, while in others the weather service is merely responsible for providing weather information, which may be interpreted in terms of fire danger by the agency responsible for the protection of forests against fire. The latter situation presupposes a well-developed protection organization, which in general works very closely with the weather service.

3.1 Estimates of inflammability based on temperature and moisture observations from synoptic stations

Where the meteorological service of a country is responsible for estimating the state of fire danger, the resulting index is usually relatively simple in form. For reasons to be outlined in 3.2, when such indices have been derived by a forestry organization they are usually more complicated, but as a general rule any particular danger rating system becomes less complicated as time goes by.

The indices used primarily by meteorological services fall into two distinct classes : those which are based entirely on conditions from the current day; and those which employ some method of accumulating the effect of past weather. A very limited use has been made in these systems of the fact that the moisture content of most forest fuels has a high correlation from one day to the next.

3.1.1 Non-cumulative methods

3.1.1.1 Relative humidity (Canada, Democratic Republic of Germany, U.S.A.)

One of the simplest forms of indicating forest inflammability is based upon relative humidity, usually at some fixed time, or, alternatively, the minimum value for the day. In general a threshold value of 40 per cent is considered to be significant, but other values have been used. According to advice received from the German Democratic Republic, a value of 40 per cent at 10 a.m. is considered to be significant. Along the west coast of Canada and in the north-western United States, 40 per cent relative humidity has been widely accepted as a level when logging operators stop work in the woods, and many insurance policies are invalid if operations are carried on while the humidity is below this level.

3.1.1.2 Dew-point depression (Republic of Korea)

A corresponding value is used in the Republic of Korea, expressed in terms of dew-point depression rather than relative humidity. Information received from this source indicates that warnings are issued when the difference between temperature and dew point exceeds 15°C for more than one day. It can be seen from Figure 3 that this criterion is not too different from the 40 per cent rule.

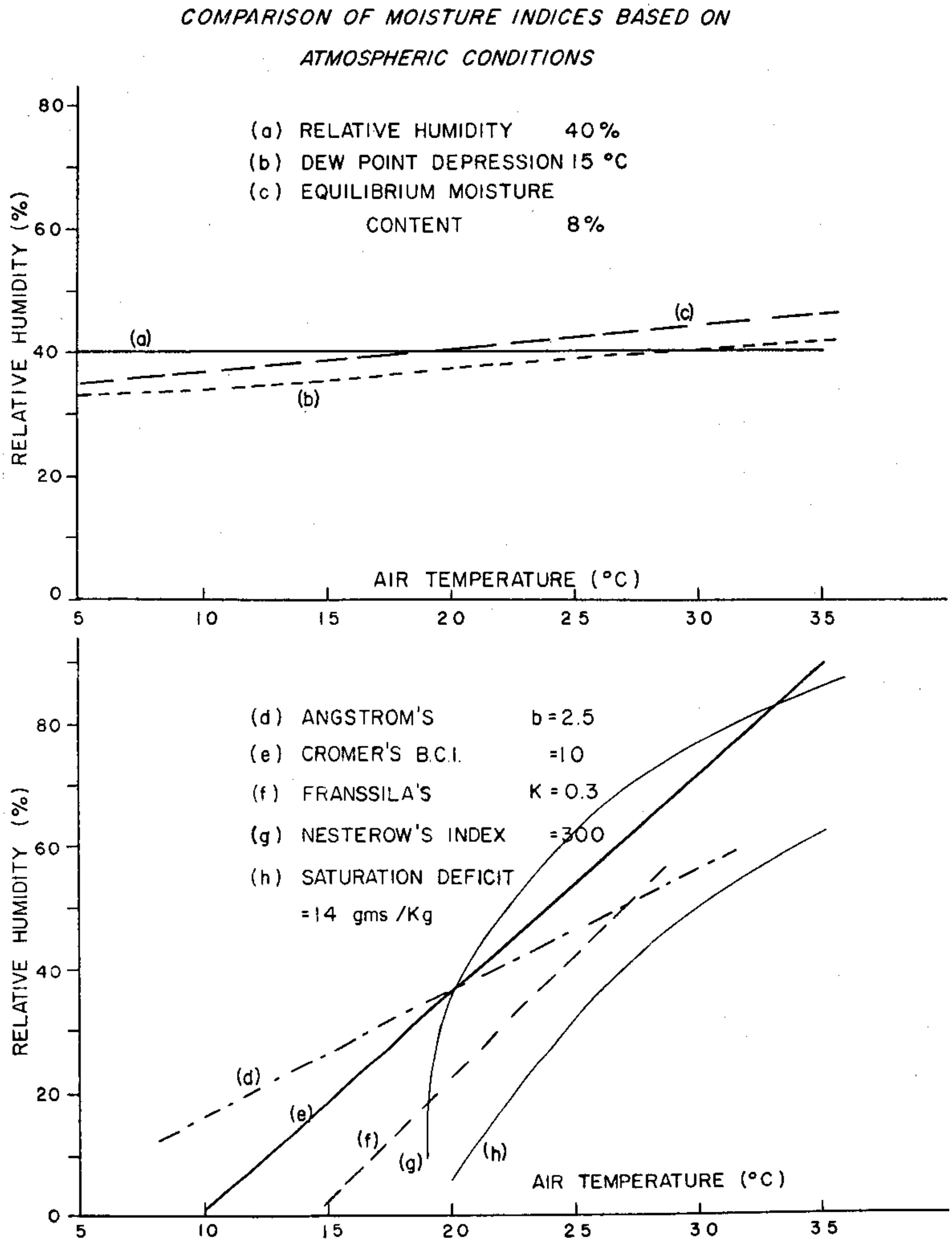

COMPARISON OF MOISTURE INDICES BASED ON
ATMOSPHERIC CONDITIONS
(a) RELATIVE HUMIDITY 40%
(b) DEW POINT DEPRESSION 15 °C
(c) EQUILIBRIUM MOISTURE
CONTENT 8%
RELATIVE HUMIDITY (%)
AIR TEMPERATURE (°C)
(a)
(b)
(c)
0
20
40
60
80
5
10
15
20
25
30
35
(d) ANGSTROM'S b = 2.5
(e) CROMER'S B.C.I. = 10
(f) FRANSSILA'S K = 0.3
(g) NESTEROW'S INDEX = 300
(h) SATURATION DEFICIT
= 14 gms /Kg
RELATIVE HUMIDITY (%)
AIR TEMPERATURE (°C)
(d)
(e)
(f)
(g)
(h)

Figure 3

3.1.1.3 Saturation deficit (Cypress, Israel)

A similar system based on saturation deficit, expressed as a mixing ratio (in grammes per kilogramme) is used in Israel. This system, which was developed by the Cypress Forest Service, makes use of three categories of fire hazard as follows :

Saturation deficit	Fire hazard category
30.4 - 40 g/kg	very high
22.4 - 30 g/kg	high
14.4 - 22 g/kg	moderate

By indicating the capacity of the air to take up moisture, this system is more sensitive to temperature than either of the two systems outlined above. This effect is illustrated in Figure 3.

The systems used in a number of other countries have provided this increased sensitivity to temperature by empirical means. Sample isopleths of each of these have been included in Figure 3 for easy comparison.

3.1.1.4 Ångström's risk factor (Sweden)

The Swedish Meteorological and Hydrological Institute employs a risk factor "B" which is computed for each synoptic station at 1300 hours Swedish time. This system, developed by Ångström (1942) relates B to temperature and relative humidity by the formula $B = 5R - 0.1\ (t - 27)$ where R is the relative humidity (expressed as a proportion) and t is the temperature, in degrees Celsius. "Risk" is assumed to exist for values of B less than 2.5.

3.1.1.5 Franssila's index (Finland)

In Finland, the degree of danger is indicated by a factor "k" called the forest fire danger index, which was developed by M. Franssila (1958). This index is based on the probability of the occurrence of at least one fire per day in the 3.56×10^6 hectare area surrounding the geophysical laboratory at Sodankyla, determined by the relative humidity and temperature at 1400 hours. This relationship is given in Figure 4.

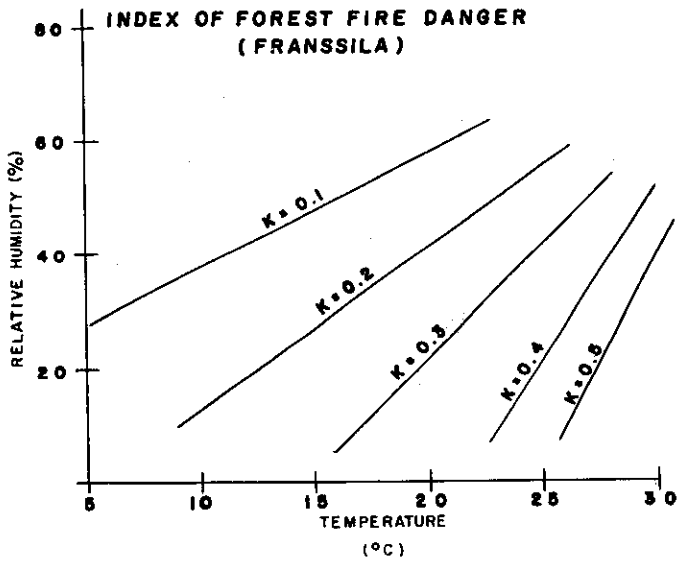


Figure 4

A marked increase in burned area for $k > 0.3$ is attributed by Franssila to the fact that thunderstorm activity is most common with meteorological conditions associated with the higher values of k.

3.1.2 Cumulative methods

3.1.2.1 Hygrothermographic index (South-eastern Australia)

A system developed by D.A.N. Cromer (Foley 1947) for New South Wales employs an alignment chart for calculating a burning conditions index from the relationship

$$I = .6T - .3H - 30$$

where T is expressed in degrees F and H is relative humidity in per cent. This calculation is based on observed values at noon or 3 p.m. local time. Cromer's work indicated that the moisture content of half-inch moisture sticks could be correlated with the summation of these daily values of burning conditions index calculated in the following manner :

> "Commencing with a day of rain the danger rating for that day is twice the BCI. On each day following the day of rain, the danger rating is increased by the value of the current day's burning condition index (excluding the day with rain). Summation of burning conditions indices recommences whenever .05 inch of rain is recorded at 9 a.m."

Symbolically this becomes $D = \sum_{i=1}^{n} (.6T - .3H - 30)$

where n refers to days since rain and $D = 2(.6T - .3H - 30)$ for $i = 0$.

The degree of danger is stated to be as follows :

Danger	Danger rating	Corresponding stick moisture
Extreme	over 99	under 7
High	51 – 99	8 – 11
Moderate	7 – 50	12 – 15
Low	below 7	above 15

This rating system was developed for New South Wales and works well in that area. However, tests in other areas indicate that in areas subject to long periods of dry weather with moderate to high temperatures there is a tendency for values to build up far in excess of the range of the danger rating (Foley 1947).

3.1.2.2 Nesterov's index (U.S.S.R.)

Another system generally similar in form was developed in the U.S.S.R. by Professor W.G. Nesterov. This system is used with some modification as the basis of the Polish warning system, and its applicability has been investigated in Bulgaria and in the Democratic Republic of Germany.

This system is expressed by the formula :

$$G = \sum_{i=1}^{n} (d \cdot t)$$

where G is the index of forest inflammability, n is the number of days with no rain, d is the humidity deficiency (in millibars) at 1.00 p.m. and t is the air temperature (in degrees Celsius) at 1.00 p.m. Days with less than 2.5 mm are reckoned as days without rain. Three categories of inflammability are recognized, namely :

I - 0 to 300 units

II - 301 to 1000 units

III - above 1000 units.

In recent years there have been several refinements of the Nesterov system. Dandre (1953) substituted (d + t) for the daily index and proposed modifications to allow for seasonal differences and to account for differences in the effect of showers and of rain. He also introduced an index of negative combustibility which serves to indicate the number of days to be expected before the woods become inflammable. Zhdanko (1960) refers to another modification in which the humidity deficit at 0700 hours is accumulated without any reference to temperature.

3.1.2.3 Modified Nesterov index (Poland)

For comparison, the modification developed by the Polish State Hydrological and Meteorological Institute follows :

(a) Rainfall less than or equal to 2.0 mm is not taken into consideration;

(b) Rainfalls of 2.1 to 5.0 mm per day reduce the previous value of G by 25 per cent before adding the current value of (t.d.);

(c) Rainfalls of 5.1 to 8.0 mm per day reduce the previous days value of G by 50 per cent before adding the current days value;

(d) With rainfalls of 8.1 to 10.0 mm summation is to be restarted on the day with rain;

(e) With rainfall greater than 10 mm a new calculation of G is commenced on the day following the one with rain.

The degree of fire danger is then related to the accumulated value of G by the following table :

Value of G	Degree of fire danger
300 or less	no danger
301 - 500	small danger
501 - 1000	average danger
1001 - 4000	great danger
Over 4000	exceptionally great danger

Calculation of the Index G begins as soon as the snow disappears in the spring and continues until the danger has disappeared in the fall. Isopleths of the index are plotted on a map outlining the areas affected by the various degrees of danger. Radio announcements are issued for an area whenever the value of G exceeds 500 units (in spring 300 units). These warnings stress the regions most seriously threatened, followed by an appeal for caution with fire.

3.1.2.4 Soil moisture index (Federal Republic of Germany, North-western U.S.S.R.)

A slightly different form of cumulative index has been developed in the Federal Republic of Germany to assist in indicating the degree of danger of bog and heath fires in northern Germany. This index, which is designed to indicate the degree of drying which has taken place in the soil, is derived by subtracting the daily potential evaporation from the amount of precipitation in the past 24 hours. Potential evaporation is determined empirically by multiplying the saturation deficit at 2 p.m. by a coefficient (the Haude factor), which varies with the season.

The daily moisture deficit is accumulated from the beginning of the growing season when the rooting zone is assumed to be saturated. Any accumulated excess of moisture above the zero line is neglected. The state of dryness of the soil and the current rate of drying can thus be estimated from the absolute value of the index and its slope. During periods of dry soil indicated in this way, warnings are issued whenever strong winds with light rainfall or widespread (lightning) storms are expected.

Zhdanko (1960) also obtained satisfactory results in the Karelian panhandle with a similar moisture balance equation which takes into account the run off, and makes use of an estimate of evaporation based on a radiation factor.

3.1.2.5 Effective humidity (Japan)

Another type of cumulative index used by the Japan Meteorological Agency as the basis for fire warnings in buildings is included because of the similarity of the problem to the one we are concerned with here. This index, known as the effective humidity is based on the fact that the moisture content of wood depends not only on the relative humidity at the time, but in varying degrees on the relative humidity over the past several days. So the effective humidity for the day is defined by

$$H_e = (1-r)\ (H_0 + rH_1 + r^2H_2 + r^3H_3 + \dots\dots\dots) \qquad \text{where}$$

r is a constant less than 1, indicative of the proportion of the effect of the humidity of the previous day, and where H_0, H_1, H_2, H_3 ...... are the values of the mean daily relative humidity for the period ending at the time the warning is issued, 1 day before, 2 days before, etc. By a simple transformation it is possible to calculate H_e on a continuing basis by the following relationship :

$$(H_e)_i = (1-r)H_i + r(H_e)_{i-1} \ .$$

which is the same form as the relationship developed for the build-up index referred to in section 3.2.8.

According to advice received from Dr. Daigo, in practice it has been found that terms beyond the 4th power of r can be neglected.

Although standards for issuing fire warnings vary with each locality, the criteria for Tokyo are as follows :

(a) an effective humidity of 60 per cent or less, and forecast of minimum relative humidity of 40 per cent or less, together with a maximum wind speed of 7 m/s or more.

(b) it is expected that winds of mean speed of 10 m/s or more will continue for an hour or more, in the absence of precipitation.

All of the systems which have been considered in this section provide an estimate of the moisture component of total fire danger which can be applied to forecast values of temperature and atmospheric moisture without any additional techniques to provide a forecast of this particular factor. It then becomes a simple matter to append a statement of the degree of fire danger expected to all public forecasts issued during the hazardous season.

3.2 Estimates of fire danger requiring supplementary information

All of the systems which have been considered so far essentially provide an estimate of the moisture content of potential forest fuels, and thus give an indication of the ease of inflammability. The systems to be discussed in this section are more truly indices of fire danger in the sense that they usually take into account the additional factors of wind and long-period drying in an attempt to provide a numerical estimate of burning intensity or resistance to control. Because of the fact that most of the systems discussed in the following sections have been developed by non-meteorological agencies, they are frequently based upon observations supplied by a supplementary network of special fire weather stations. As a result observations may be taken at non-standard times, under non-standard conditions, and frequently additional information such as direct measurements of fuel moisture or visual estimates of the state of the fuel are a fundamental part of the system.

It is not possible to cover in this publication all of the numerous systems that have been devised for local use. The information contained here is necessarily limited to an abbreviated account of some of the more significant types of rating system known to the members of the working group. Wherever practical, sufficient information is provided to make it possible to do some preliminary testing of each system. However, one or two systems do not lend themselves to such condensation; for these it has only been possible to indicate the general form of the rating system. In every case, however, it is recommended that the originating agency be contacted for more complete details.

3.2.1 Region 6 burning index (Western U.S.A.)

One of the simpler types of burning index is the one which has been in operation in western Washington and Oregon for several decades. Developed by the staff of the Pacific Northwest Forest and Range Experiment Station at Portland, Oregon, this index is a simple function of wind velocity and fuel moisture content. Separate tables are provided to take care of seasonal changes. Wind velocity is measured over a minute period at a height 10 feet above the ground and at least one hundred feet from the nearest major obstruction. Fuel moisture content is estimated by weighing standard sets of 1/2 inch ponderosa pine dowels, mounted 6 inches above the ground and fully exposed. Observations are made three times daily, at 0800, 1200 and 1630 hours Pacific standard time.

The following tables give the burning index in terms of wind velocity and fuel moisture content for the two seasonal periods.

Table 4

REGION 6 (U.S. FOREST SERVICE) BURNING INDEX

(a) Burning Index Table
(Until curing stage, but not later than July 15th)

Wind Speed	Half Inch Stick Moisture Content 3	4	5	6	7	8	9	10	11	12	13-15	16-25	Over 25
0 - 3	15	11	8	5	2	1a	1a	1a	1b	1b	1b	1b	0
4 - 6	21	17	13	9	6	3	2	1a	1a	1a	1b	1b	0
7 - 9	30	25	19	15	10	6	3	2	2	2	1a	1b	0
10 -12	40	34	28	22	16	11	6	3	2	2	2	1a	0
13 -15	53	45	38	32	25	19	14	8	4	3	2	2	0
16 -18	66	57	49	42	34	27	20	13	7	3	3	2	0
19 -27	90	77	67	57	45	38	28	20	12	4	4	3	0

(b) **Burning Index Table**
(After curing stage is reached or after July 15th)

Wind Speed	3	4	5	6	7	8	9	10	11	12	13-15	16-25	Over 25
0 - 3	19	15	11	8	5	2	1a	1a	1a	1b	1b	1b	0
4 - 6	26	21	17	13	9	6	3	2	1a	1a	1a	1b	0
7 - 9	35	30	25	19	15	10	6	3	2	2	1a	1b	0
10 -12	48	40	34	28	22	16	11	6	3	2	2	1a	0
13 -15	61	53	45	38	32	25	19	14	8	4	2	2	0
16 -18	75	66	57	49	42	34	27	20	13	7	3	2	0
19 -27	100	90	77	67	57	45	38	28	20	12	4	3	0

Half Inch Stick Moisture Content

(c) **Burning Index Class**

Burning Index Values	Burning Index Class
1b - 1a	1
2 - 3	2
4 - 8	3
9 - 15	4
16 - 24	5
25 - 35	6
36 - 48	7
49 - 63	8
64 - 80	9
81 -100	10

3.2.2 Model 8 burning index meter (Western U.S.A., Western Canada)

The rating system developed over the course of several decades by the staff of the Northern Rocky Mountain (later Intermountain) Forest and Range Experiment Station of the U.S. Forest Service utilizes weather information to describe the potential danger. By referring this to specific times, topographic locations and fuel types it is possible to estimate the expected behaviour of any particular fire.

This system is used by all protective agencies within the states of Nevada, Utah, Idaho, Montana, western Wyoming, eastern Washington and interior Alaska. It has also been found to give satisfactory results in south-eastern British Columbia.

Calculations are made with a simple plastic "slide rule" type of computer. Details are shown in Figure 5.

The system employs two general factors, one based on the cumulative effects of weather and the other based on the effects of current weather. These combined effects are then interpreted in terms of expected fire behaviour, for specific times, places and fuels.

The cumulative effect is based on records of the moisture content of large logs of 6 to 18 inches in diameter. It was found that the moisture trend of these logs could be adequately represented by the running average of the moisture content of the standard half-inch sticks over the previous 5 days. This running average was then calibrated in terms of a scale from 1 to 10 and the resultant figure is called the severity index. This figure provides a measure of fire intensity, and may be used directly as a guide to fire prevention activities.

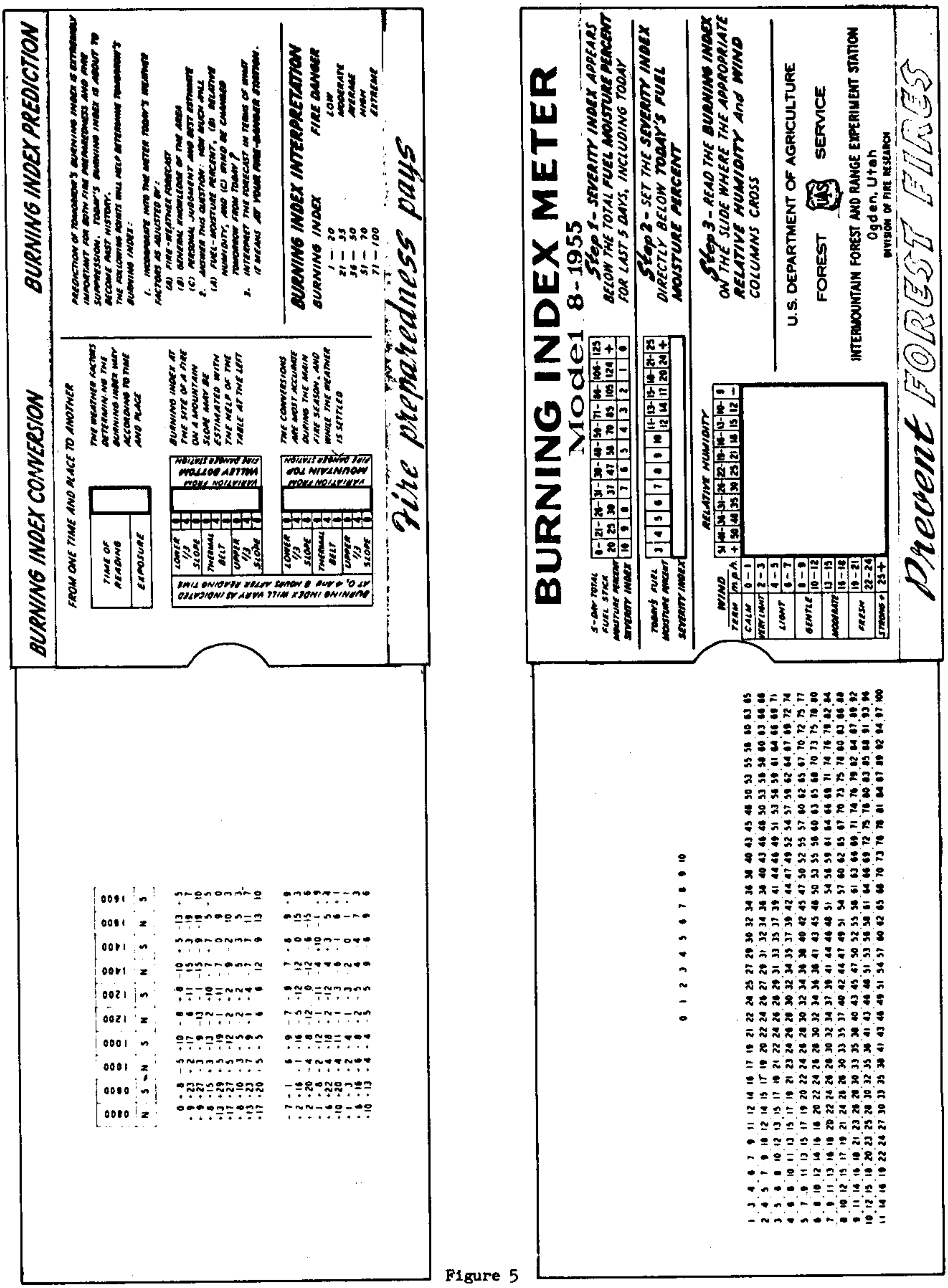

BURNING INDEX CONVERSION
FROM ONE TIME AND PLACE TO ANOTHER
BURNING INDEX PREDICTION
BURNING INDEX INTERPRETATION
BURNING INDEX
FIRE DANGER
1 — 20 LOW
21 — 35 MODERATE
36 — 50 AVERAGE
51 — 70 HIGH
71 — 100 EXTREME
Fire preparedness pays
BURNING INDEX METER
Model 8-1955
Step 1 - SEVERITY INDEX APPEARS BELOW THE TOTAL FUEL MOISTURE PERCENT FOR LAST 5 DAYS, INCLUDING TODAY
Step 2 - SET THE SEVERITY INDEX DIRECTLY BELOW TODAY'S FUEL MOISTURE PERCENT
Step 3 - READ THE BURNING INDEX ON THE SLIDE WHERE THE APPROPRIATE RELATIVE HUMIDITY And WIND COLUMNS CROSS
RELATIVE HUMIDITY
WIND
U.S. DEPARTMENT OF AGRICULTURE
FOREST SERVICE
INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Ogden, Utah
DIVISION OF FIRE RESEARCH
Prevent FOREST FIRES

Figure 5

Current weather effects are evident in variations in rate of spread, which is sensitive to changes in moisture in the atmosphere and in the fine fuels, as well as to variations in the wind speed.

The four factors considered so far are combined to give a burning index on a 100 point scale.

The component factors are normally measured during the mid-afternoon when fire danger is at its peak. Because this comes so late in the day it is useful for administrative purposes to calculate a predicted index for the following day.

Although outside the direct field of the meteorologist, it is noted here that tables are available to enable the responsible forest officer to interpret this burning index in the light of his knowledge of fuel type and topography, in terms of expected rate of spread and manpower requirements. This, of course, is the ultimate goal of any danger rating system.

Fuel moisture content is obtained from the weight of standard ponderosa pine indicator sticks. However, in this system, the sticks are exposed 10 inches above a half-inch layer of representative conifer needles, and 3 inches below a double layer of 14 mesh wire screen held taut in a frame 3 feet by 3 feet.

Wind velocity is the average afternoon value at 20 feet above ground (higher, if necessary, to avoid a disturbed flow). If spot estimates of wind must be used, the average is determined from three observations of 2 minutes each, spaced throughout the afternoon. Particulars of observing sites and methods of observation are set out in considerable detail in Hardy et al (1955).

Observations are normally taken between 1500 and 1700 mountain standard time with the exact hour specified by each administrative district.

3.2.3 Forest fire danger meter 8-100 (Eastern U.S.A.)

The Division of Fire Research of the Southeastern Forest Experiment Station of the U.S. Forest Service, Asheville, North Carolina, has developed a circular slide-rule type of meter for use in the hardwood or deciduous regions of the eastern U.S.A. The details of the relationships can readily be determined by reference to Figure 6. The factors are additive by means of the five concentric circular scales resulting in the value of the burning index shown opposite the outermost scale.

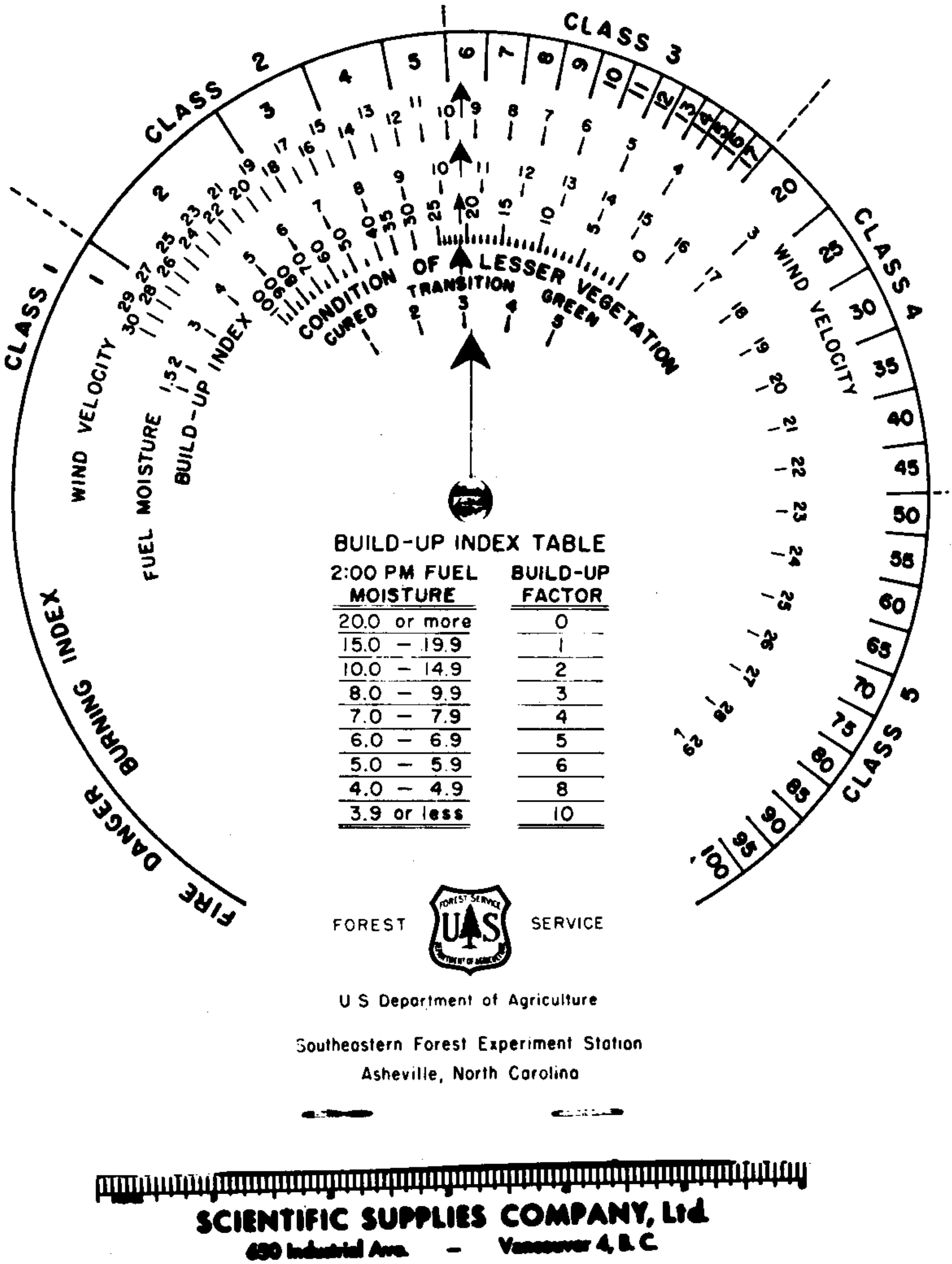
The basic time of measurement is 1400 hours local standard time. Fuel moisture content is determined by weighing standard sets of three flat basswood slats. These are exposed under representative natural forest conditions exactly 8 inches above the forest litter and with one side consistently exposed to the weather. Corrections to allow for the progressive loss of dry weight have been determined on the basis of length of exposure.

The build-up index is accumulative. The amount of rainfall in hundredths of an inch reported in the 24 hour period ending at 1400 hours is subtracted from yesterday's build-up index. The current build-up factor, obtained from today's fuel moisture content by means of the table on the front of the meter, is then added to the remainder to give the new build-up index for today. The build-up index does not go below zero or above 100.

Wind velocity as used in this system is a 4 minute average as measured at the 8 foot level, with the provision that the anemometer should not be nearer than 10 feet to trees 10 inches or larger in diameter.

The condition of lesser vegetation refers to the percentage of dead or "cured" material in the grasses, ferns or shrubs in the area, ranging from a value of 1 for the fully cured state to a value of 5 for the completely green state.

FOREST FIRE DANGER METER TYPE 8-100-O



2:00 PM FUEL MOISTURE	BUILD-UP FACTOR
20.0 or more	0
15.0 – 19.9	1
10.0 – 14.9	2
8.0 – 9.9	3
7.0 – 7.9	4
6.0 – 6.9	5
5.0 – 5.9	6
4.0 – 4.9	8
3.9 or less	10

Figure 6

3.2.4 Lake States burning index meter (North central U.S.A.)

A third type of meter developed for that section of the United States adjacent to the Great Lakes is shown in Figure 7. This particular meter is one of the few in use in the U.S. that does not require a direct measurement of fuel moisture content. It was developed at the Lake States Forest Experiment Station of the U.S. Forest Service. This meter essentially determines the average moisture content of light fuels in the open from the correlation with state of vegetation, precipitation, days since rain and relative humidity. This moisture factor is then combined with wind velocity to give a burning index which is designed to indicate the severity of burning conditions "in per cent of the worst probable". The burning index rating is broken down into seven classes characterized as follows :

Safe (0-1)	- Fires will not run beyond the heat of a camp-fire or burning brush pile;
Very low (2-3)	- Fires will start from an open flame but spread slowly and tend to go out;
Low (4-6)	- Fires will start from a lighted match and spread slowly (rapidly in dead grass) until extinguished;
Moderate (7-12)	- Fires will start rapidly from a match, burn briskly, and tend to spread rapidly as they increase in size;
High (13-24)	- Fires start readily from a match or flowing embers, spread rapidly, and tend to crown in young conifers;
Very high (25-49)	- Fires will start from burning tobacco or sparks, spread rapidly, and tend to crown generally. Spot fires common;
Extreme (50-100)	- Explosive conditions. Fires start readily from sparks, burn fiercely, and tend to crown and spot generally.

Calculations are based on observations made three times daily, at 0800, 1200 and 1700 LST from April 1st to October 31st. The number of days since rain is considered as 1 on the day for which precipitation is last recorded at 0800 and increased by 1 for each successive rainless day. However, if rainfall occurs between 0800 and 1200, or between 1200 and 1700, it is measured and taken into account in the 1200 and 1700 calculations.

Observations are made usually at the dispatching centre or protection headquarters. Details concerning the anemometer height and duration of period used for determining wind speed are not specified.

The condition of vegetation is rated as green when the grass and herbaceous vegetation are green and the deciduous trees are in full leaf (normally early June to mid-September in the Lake States) while dead is used when the grass and vegetation are cured and the hardwood leaves have fallen, typical of the spring and fall seasons. The intermediate rating is used during the normally short transition period.

3.2.5 California fire danger rating system (South-western U.S.A.)

It is the expressed desire of the U.S. Forest Service and the U.S. Weather Bureau to develop a uniform danger rating system throughout the country. The California fire danger rating system developed in 1958 by the U.S. Forest Service in co-operation with the U.S. Weather Bureau and the California State Division of Forestry, is the result of one attempt to provide a rating system flexible enough to permit modification for use in a variety of climatic zones and with a variety of fuels.

This rating system provides a burning index on a scale ranging from zero to 100 for three basic types of fuel, namely grass, brush and timber.

LAKE STATES

BURNING INDEX METER

Relative Humidity - %								Wind Velocity m.p.h.
80 up	70 to 79	60 to 69	50 to 59	40 to 49	30 to 39	20 to 29	10 to 19	
								0 - 3
								4 - 6
								7 - 12
								13 - 18
								19 - 24
								25 - up

Burning Index

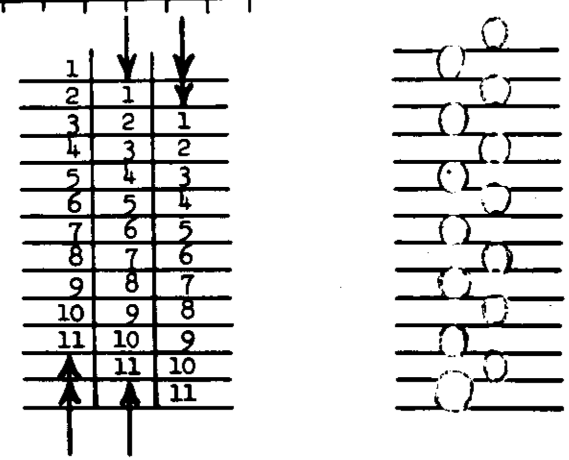
0	0	0	1	1	2	3	5
0	0	1	1	2	3	4	6
0	1	1	1	2	4	5	8
0	1	1	2	3	5	7	10
1	1	2	3	4	6	9	13
1	1	2	4	5	8	11	17
1	2	3	5	7	10	14	21
1	3	4	6	9	13	18	26
2	4	6	8	11	16	23	32
3	5	7	10	14	20	28	39
4	6	9	13	18	25	35	47
5	7	11	16	23	31	41	55
6	9	14	20	28	37	49	64
7	11	17	24	33	44	57	73
8	14	21	29	39	51	65	82
10	17	24	34	45	58	73	91
12	20	29	39	51	65	81	100
14	23	34	45	57	72	89	100

Condition of Vegetation

Green	Intermediate	Dead

Days Since Rain.

Precipitation (Inches)
.50- up
.45-.49
.40-.44
.35-.39
.30-.34
.25-.29
.20-.24
.15-.19
.10-.14
.05-.09
.00-.04



Directions: Set slide to show (under "Condition of Vegetation" prevailing) the number of days since the last rain of .50" or more. For subsequent rains of less than .50" insert a pencil in the hole opposite the amount of precipitation and retract slide as far as it will go. Advance slide one day for each day without rain thereafter.

"Burning Conditions" indicated opposite current "Wind Velocity" under current "Relative Humidity."

1949

Figure 7

The grass burning index is obtained by combining a spread factor with an estimate of the percentage of dead or cured grass. The spread factor is calculated from the wind speed and the calculated moisture content of the fine fuels. The fine fuel moisture content in turn is calculated from the half-inch stick moisture content and the relative humidity.

The brush burning index and the timber burning index are obtained from a combination of a spread factor and an intensity factor. The spread factor is common to all three types of index and is obtained from the same table as above. The intensity factor for the brush index is obtained from the number of days since new growth started and the half-inch moisture content, while the intensity factor for the timber index is obtained from the half-inch moisture content and from the build-up.

An allowance for slope is included in the calculation of the spread factor. This may be approximated by effectively increasing the wind speed by 15 per cent for slopes of 41-60 per cent and by 30 per cent for slopes greater than 60 per cent.

The build-up is calculated from an accumulated index of moisture content and rainfall, and is effectively an index of the moisture content of logs 6 inches in diameter.

The following tables have been condensed from the original tables to provide an indication of the main features of the system. Complete details should be obtained from the California Forest and Range Experiment Station of the U.S. Forest Service, Berkeley, California.

Calculations are based on observations made three times daily, at 0800, 1200, and 1430 Pacific standard time. Wind speed is based on the average afternoon velocity between 1200 and 1430 PST or, failing that, on the average of the two-minute wind velocity at 1200 and 1430 PST. Height of the anemometer is not specified but is assumed to be approximately standard.

Table 5

Table (a) Fine Fuel Moisture Content

Half inch M.C.	Relative Humidity 10%	30%	50%	70%	90%
3	2	5	7	10	16
8	3	6	8	11	18
13	4	7	9	12	18+
18	5	8	10	13	18+
23	6	9	11	14	18+
28	7	10	12	15	18+
33	8	11	13	16	18+
38	9	12	14	17	18+
43	10	13	15	18	18+

(b) Spread Factor

Fine Fuel M.C.	Wind Speed (MPH) 1	5	10	15	20	24+
2	13	17	30	47	70	92
4	10	13	23	37	56	72
6	7	9	17	28	44	54
8	5	7	13	20	33	41
10	4	5	8	15	24	29
12	2	3	5	9	14	18
14	0	0	0	3	7	8
16	0	0	0	0	1	2
18+	0	0	0	0	0	0

Table (c) Grass Burning Index

Percent Cured		Spread Factor (b) 5	10	20	40	60	80	100
Cured	5	11	25	47	67	91	100	
75%	4	9	20	40	57	78	93	
50%	3	7	15	31	44	59	71	
25%	2	5	10	21	30	41	49	
Green	1	2	3	7	10	14	16	

(d) Intensity Factor (Brush)

Half inch M.C.	Days since New Growth 0-10	11-20	21-30	31-40	81-100
1	70	74	78	82	95
3	54	58	62	65	78
8	26	31	35	38	51
13	12	17	21	24	37
18	8	12	16	19	32
19+	5	9	13	16	29

Table (e) Timber Build-up

Half Inch Stick Moisture Content	Build-up Addition
2.9 or less	1.3
3.0 - 3.9	1.0
4.0 - 4.9	0.8
5.0 - 5.9	0.6
6.0 - 6.9	0.5
7.0 - 8.9	0.4
9.0 - 12.9	0.2
13.0 - 19.9	0.1
20.0 and over (or ground covered with snow)	0

(i) Begin accumulating build-up not later than May 1st.

(ii) When precipitation has occurred multiply the amount in inches by 20, and subtract from accumulated build-up.

Table (f) Intensity Factor (Timber)

Half inch Stick M.C.	Build-up (e) 1	5	10	20	40	80	100+
1	57	67	71	81	90	95	100
3	46	56	60	70	79	84	89
8	30	39	44	53	63	68	72
13	19	28	33	42	52	57	62
18	16	25	30	39	49	54	58
21+	13	22	27	36	46	51	55

(g) Burning Index (Brush and Timber)

Intensity Factor	Spread Factor 10	30	50	70	90	100
10	1	4	6	9	10	11
20	3	8	14	19	23	26
30	3	10	18	24	30	30
40	5	15	25	35	42	47
50	6	18	32	43	52	58
60	7	22	38	52	63	69
70	8	26	44	60	73	81
80	9	29	50	68	83	91
90	10	32	56	76	93	100
100	11	35	60	82	100	100

3.2.6 Australia

Although still in the development stage, the fire danger tables being developed by the Australian Commonwealth Forestry and Timber Bureau are outlined here. These are based

Table 6

(a) Surface moisture content of eucalyptus litter as a function of air temperature and relative humidity during rainless periods.

Relative Humidity	Air Temperature (°f) 51-60	61-70	71-80	81-90	91-100	101-110
5				2.6	2.3	2.0
10			3.3	3.0	2.7	2.3
15		4.0	3.7	3.4	3.1	2.8
20	5.6	4.6	4.1	3.9	3.5	3.2
25	6.1	5.1	4.6	4.4	4.0	3.7
30	6.8	5.7	5.3	4.9	4.6	4.2
35	7.5	6.5	5.9	5.6	5.2	
40	8.3	7.3	6.6	6.2	5.8	
45	9.4	8.0	7.2	6.8		
50	11.0	9.1	8.2	7.4		
60	14.9	12.8				
70	20.6	17.3				

(b) Relationship between wind velocity measured at 5 feet above the ground in the forest and the velocity at 72 feet above ground in the open.

Open Station Wind Speed (mph)	Wind Speed inside the Forest at 5' level — Types of Eucalypt Forest: Regrowth 20-30'	Low Quality Fully stocked 40-60'	High Quality Fully stocked 100-150'
5	4.5	2.8	2.0
10	6.3	3.9	2.8
15	8.4	5.2	3.7
20	10.8	6.8	4.7
25	13.5	8.7	5.9
30	16.7	10.3	7.2
35	20.5	12.3	8.6

entirely on field experiments undertaken in a variety of fuel types, in which it was found that suppression difficulty was related to rate of spread and to moisture content of the surface litter. These factors are related to one another, and to the wind speed at 5 feet above ground level within the forest as indicated in Figure 8. These factors have then been converted into terms of meteorological elements for forecasting purposes covering three basic fuel types, namely eucalyptus litter, radiata pine litter, and grassland. The tables above give details of this conversion for eucalyptus, as outlined in MacArthur (1958).

From these tables and from Figure 8 it is possible to draw up tables of rate of spread and of suppression difficulty in terms of air temperature, relative humidity, and open station wind velocity. Temperature and relative humidity are measured at an open site. It is planned to include corrections for rainfall in the final tables.

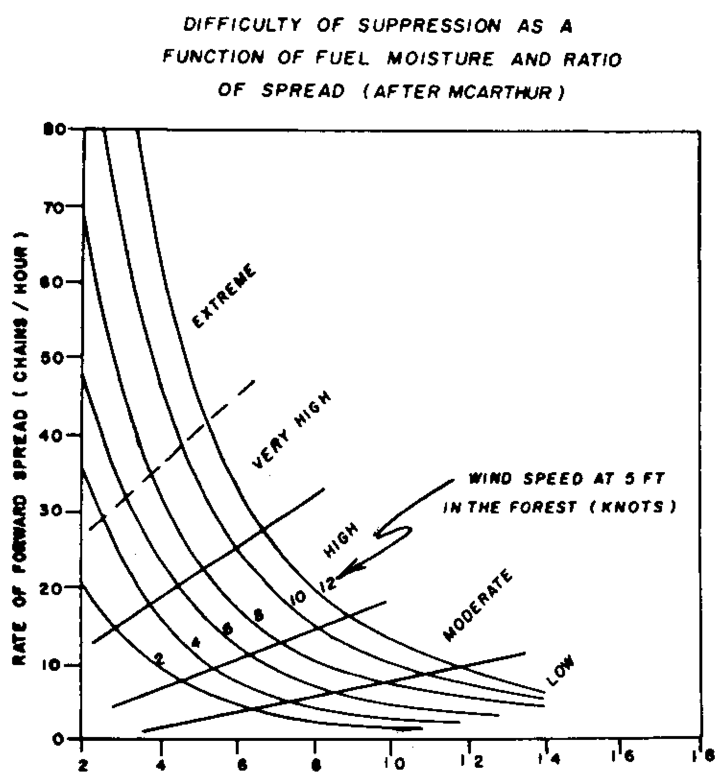


Figure 8. Moisture content of surface litter (% oven dry weight)

3.2.7 Canada

In Canada, the danger rating system has been developed on the basis of several decades of continuous field research by the Forest Fire Research Section of the Canadian Forestry Branch (now Canadian Department of Forestry). Sets of tables provide estimates of fire danger for each major fuel type based on observations of rainfall, relative humidity, and wind velocity taken at noon, local mean time. Current tables in this series allow for seasonal changes in vegetation and varying length of daylight by the use of two or three seasonal tables. Although different sets of tables have been, or are being prepared for all major fuel types, the general form of the tables is the same for all major forest types. Special correction tables have been designed for use in mountainous regions to allow for the intense drying conditions associated with low overnight relative humidity (MacLeod 1948).

The relationship between the various factors in the tables is indicated below.

Grass fire hazard index determined from :

(a) today's relative humidity;
(b) percentage of green grass;
(c) time since rain of 0.02 inch or more;
(d) a seasonal factor.

Forest fire hazard index determined from :

(a) today's danger index;
(b) today's drought index;
(c) a seasonal factor.

Danger index (for the district as a whole) determined from :

(a) an index of fuel moisture;
(b) drought index.

Index of fuel moisture determined from :

(a) yesterday's index of fuel moisture;
(b) depth of rainfall, if any;
(c) relative humidity;
(d) wind speed.

Drought index determined from :

(a) yesterday's drought index;
(b) depth of rain.

By definition, the <u>danger index</u> in this system refers to conditions over the district as a whole, while the various <u>hazard indices</u> refer to conditions,in particular fuel types such as "slash" or grass, which may be locally significant.

The danger and hazard indices in this system are based on a sixteen-point scale broken down into five <u>hazard zones</u> designated as <u>nil</u>, <u>low</u>, <u>moderate</u>, <u>high</u> and <u>extreme</u>.

Earlier tables in this series employed observations of temperature and evaporation, and modifications of these are still used in Quebec (Villeneuve 1948). Tests have been carried out to determine the suitability of these tables for use in France (Reneuve 1950), Australia (Foley 1947) and in Great Britain (Peace 1948).

The one feature of this rating system that appears to be unique is the use of the index from the previous day as one of the dependent variables. The high correlation between moisture contents on two successive days of even the finer fuels results in a significant improvement in estimates of fuel moisture content from meteorological parameters whenever this factor is included.

3.2.8 Western Canada

In British Columbia, fire danger has been estimated subjectively by consideration of wind speed and the moisture content of half-inch Douglas fir indicator sticks. In the Douglas fir zone (which covers most of the southern coast of the province) it is frequently necessary to restrict work and travel in the woods during periods of maximum danger.

The build-up index used as a guide for such restrictive measures is intended to indicate the moisture content of slow drying fuels. The index is designed to give a "damped" record of the half-inch fuel moisture, calculated by the following procedures :

> $I_n = 9/10\ I_{n-1} + 1/10\ M_n$ where I_n is the value of the index on the n'th day and M_n is the value of the half-inch stick moisture at 8 a.m. on the n'th day. (For purposes of calculation the following formula is more convenient :
>
> $$I_n - I_{n-1} = 1/10\ (M_n - I_{n-1})$$.)

Index classes of nil, low, moderate, high and extreme were determined for five years of record such that nil and extreme each occurred, on the average one day in eight, while each of the other classes occurred one day in four.

3.2.9 South Africa

Fire danger rating in South Africa is still in the development stage. However, according to Vowinckel (1960) the current procedure is based on the determination of a value for the moisture factor, called litter danger, which is then multiplied by a wind factor to give a value for the fire danger.

The litter danger is determined by means of the alignment chart (Figure 9) from observations of the moisture content of pinus patula indicator sticks exposed at the top and bottom of the relatively thick litter layer normally present in the South African pine plantations, under natural forest conditions. Specifications for the sticks call for a uniform density and dimensions of 0.4 cm by 0.4 cm by approximately 30 cm.

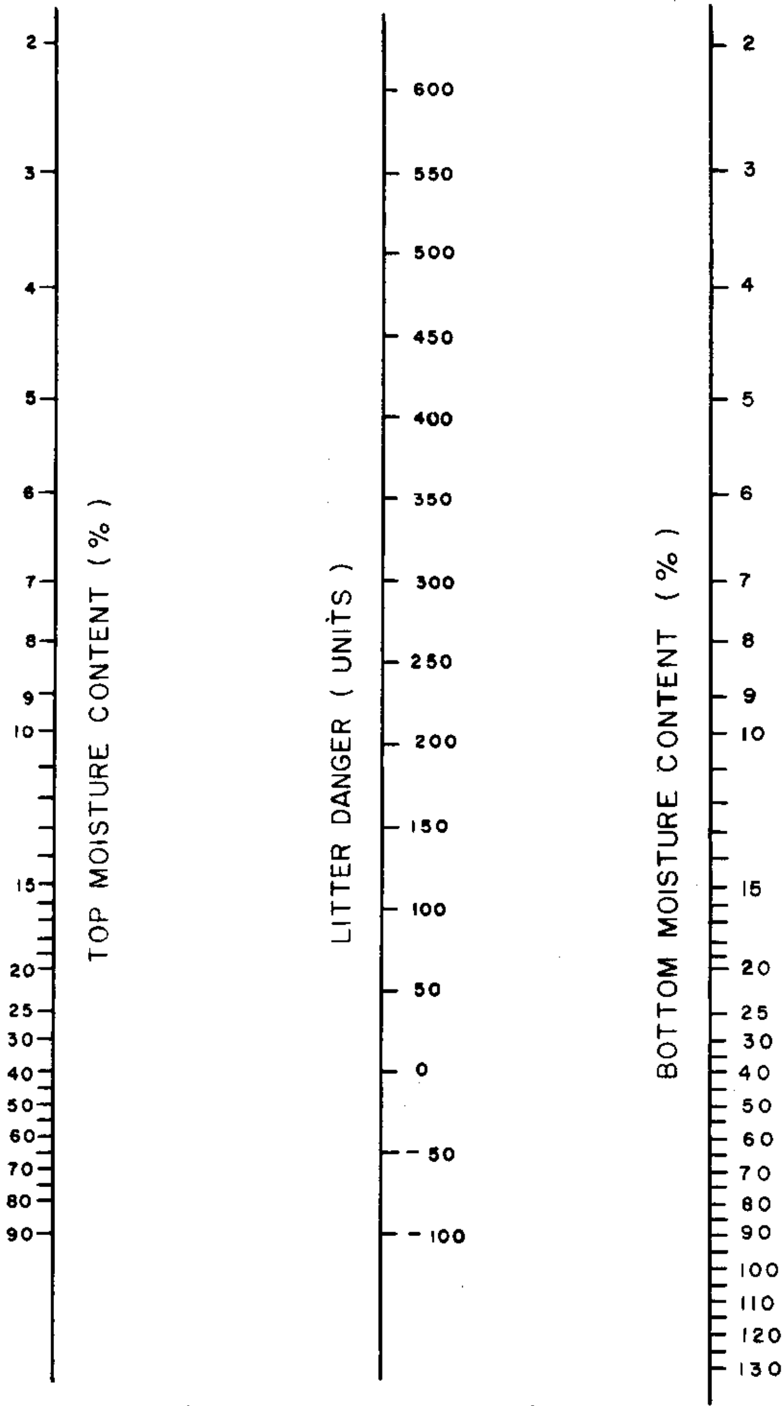
The wind factor is based on observations from exposed sites which will be more representative of general conditions over large areas than the low level winds initially used. This factor is related to these exposed site wind speeds by the following table :

Wind speed (knots) :	0	2	4	6	8	10	12	14	16	18	20
Wind factor :	1.0	1.0	1.2	1.6	2.1	2.5	2.8	3.3	3.8	4.4	4.8

Wind speed :	22	24	26	28	30	32	34	36	38	40
Wind factor:	5.7	6.7	7.0	7.3	7.9	8.1	8.7	9.2	9.9	10.3

Fire danger is classified according to the following :

Low :	100
Moderate :	100–399
High :	400–699
Very high :	700–999
Extreme :	1000 or more.



(AFTER VOWINCKEL)

ALIGNMENT CHART FOR FIRE DANGER RATING
UNION OF SOUTH AFRICA – SUMMER RAINFALL AREA

Figure 9

For forecasting purposes some of the variations in litter danger have been related to a number of meteorological phenomena. The following tentative relationships have been worked out for Cedara (Pietermaritzburg) following two years of records.

(a) Mean decrease in litter danger after cold fronts without rain

Season	Mean-decrease	Prefrontal value	Mean decrease
Summer	10	1 – 99	19
Autumn	35	100 – 199	62
Winter	97	200 – 299	144
Spring	135	300 or more	186

(b) Mean decrease in litter danger with rainfall

Initial danger value	Rainfall amounts (mm)				
	1-2.5	2.6-5.0	5.1-10.0	10.1-20.0	more than 20.0
100	42	83	92	90	83
101 - 300	112	154	-	218	215
more than 300	265	356	441	-	442

(c) Mean litter danger value with certain weather types

Season	Anticyclonic	Prefrontal	Postfrontal	Postfrontal (Coastal low)	Anticyclonic (N wind)
Summer	-	81	62	48	74
Autumn	26	226	90	8	138
Winter	142	390	250	122	-
Spring	203	488	170	-	-

This rating system has been applied primarily in the afforested areas forming a narrow belt along the eastern escarpment of the South African high veld stretching over several thousand miles. Comparisons of the rating with subjective estimates of experienced foresters indicate that the index does represent the fire danger in the "summer rainfall" area. However, in the "winter rainfall" area, the system breaks down, probably because of the different type of vegetation prevailing.

3.2.10 Southern England

Rouse (1960) has reported on a rating system being developed for use in southern England. In this system the degree of fire danger is indicated by four classes, nil, low, moderate and high. This degree of fire danger is tabulated in terms of a 100 point scale of fire danger rating index and a seasonal effect.

The fire danger rating index is obtained as a product of diurnal variable and a corrected basic danger rating. The diurnal variable is tabulated for various combinations of forecast relative humidity and wind speed. The corrected basic danger rating value is essentially a drying factor and is obtained from the average value of maximum temperature over the past 5 days (or since rain of 0.25 inch has fallen if this has occurred within 5 days) combined with a basic danger rating. This basic danger index provides a further cumulative effect and is derived from tables relating it to the previous days value of the basic danger rating and the amount of rainfall in the past 24 hours.

SUMMARY OF FIRE DANGER SYSTEMS

(a) Standard Weather Factors Required.

AREA	INDEX	COMPUTATION	SECTION	REMARKS
Republic of Korea	Temperature - dew point spread	-	3.1.1.2	No cumulative effect
German Democratic Republic. W.Coast North America	Relative Humidity	-	3.1.1.1	No cumulative effect
Cypress, Israel	Saturation deficit	-	3.1.1.3	No cumulative effect
Sweden	Ångström's Risk Factor	Formula	3.1.1.4	No cumulative effect
Finland	Franssila's Danger Index	From chart	3.1.1.5	No cumulative effect
New South Wales	Cromer's Hygrothermographic Index	Nomogram	3.1.2.1	Overestimates danger after long drought (No longer in general use)
U.S.S.R.	Nesterov's Index	Summation of product of air temperature and humidity deficiency with adjustments for rain.	3.1.2.2	No information about climatic range of validity of this index.
Poland	Modification of Nesterov's Index		3.1.2.3	
German Federal Republic	Index of soil drying	Accumulation of rainfall minus potential evaporation as obtained from saturation deficit	3.1.2.4	Designed as an aid for forecasting danger of bog and peat fires.
Japan	Effective Humidity	Formula	3.1.2.5	Designed for estimating danger from house fires
Canada	Forestry Branch Hazard Index	Tables	3.2.7	Separate tables for each forest type
Quebec	Fire Danger Index	Tables	3.2.7	Modified from 1938 version of Canada Forest Branch Tables.
Southeastern Australia	Commonwealth Tables	Tables	3.2.6	In development Stage.
Minnesota Wisconsin, Michigan	Lake States Burning Index	Cardboard Computer	3.2.4	State of vegetation required
North-western U.S.S.R.	Computed Moisture Balance	Evaporation from Romanov's nomograms	3.1.2.4	Runoff considered

(b) Fuel Moisture Measurement Required

AREA	INDEX	COMPUTATION	SECTION	REMARKS
Western Washington and Oregon	Burning Index	Tables	3.2.1	-
Nevada, Utah, Idaho, Western Wyoming, Eastern Washington, Interior Alaska, Southeastern British Columbia	Model 8 Burning Index	Plastic Slide Rule Computer	3.2.2	Corrections for topographic variation have been developed
"Hardwood" Forest Areas of Eastern U.S.A.	Burning Index	Circular Calculator	3.2.3	-
California	California Fire Danger Rating	Tables	3.2.5	Separate tables for grass, brush and timber fuel types
Western Coast Canada	Build-up Index	Formula	3.2.8	(A number of local rating systems are in use by logging operators here. Canada Forestry Branch tables being developed for B.C. fuel types)
Union of South Africa	Vowinckel's Fire Danger	Nomogram and Tables	3.2.9	Designed for plantations. Valid in "summer rainfall" area only.
Tasmania	Chipmon Index	Tables	Not discussed	Integrates 6 factors.
Southeastern Australia	Luke Danger Index	Tables	Not discussed	Modification discussed in (Whittingham 1960)
Southern England		Tables	3.2.10	-
New Zealand		No details available	-	-

3.3 Integrated fire weather services

In general, wherever fires in forests, bushland, or grassland are a significant problem during an appreciable part of every year, there is a well-organized fire weather service, flexible enough to take care of local conditions. The amount of information available to the members of the working group on this aspect varies considerably, so that illustrative material is mostly from those areas familiar to members of the group. The following headings are considered in discussing this type of integrated fire weather service :

(a) Issuing the forecast;

(b) Communications, distributing the forecast;

(c) Liaison and co-operation with forestry organizations;

(d) Research and training.

3.3.1 Issuing the forecasts

The form taken by fire weather forecasts will in general depend upon which of the functions mentioned in section 3 they are designed to serve. Thus forecasts intended to warn the public of the degree of danger in the woods will differ from those designed to assist forestry organizations in their planning, and these in turn will differ somewhat from the detailed forecasts required for fighting large fires or executing controlled burns.

The first type of forecast is usually issued in fairly general terms, and the degree of responsibility of the weather service for such warnings appears to vary considerably. In Australia, for example, such forecasts are issued twice daily as a routine by each of the six Divisional Offices, Forecasting and Warning Sections. In addition to forecasts of significant weather factors, forecasts of the fire danger class are included (except in the lowest classes). Special fire weather warnings are issued whenever the forecast danger for a given district is in the most extreme category, after consultation with the appropriate State Fire Authority.

In New Zealand, authority for issuing such fire danger warnings to the public rests with the New Zealand Forest Service, rather than the Meteorological Service. However, such warnings are broadcast by the Meteorological Service in conjunction with the nation-wide forecast broadcasts, whenever necessary. The text of such warnings is supplied by the New Zealand Forest Service, based in part on information received from the Meteorological Service. A similar arrangement exists in the Netherlands.

In the Federal Republic of Germany warnings are issued by the district weather offices within the framework of their regional forecast activity. The warning service is provided normally from March to October. Procedures vary from district to district depending upon the requirements. In northern Germany special warnings are given for the large areas of bog and heath land to be found there.

The distribution of warnings likewise varies from district to district. In some cases the fire weather warnings are issued directly by the weather office. In these cases indications of forest fire danger may be included within the framework of the normal weather report, after consultation with the forest administration. In most cases the forest station or corresponding land service station is informed of the existing fire danger, and these services are responsible for deciding whether or not an official warning should be sent out.

In addition some weather offices issue twice-weekly forecasts (for 3-4 days ahead) whenever the situation is dangerous. No specific danger rating system is employed, although meteorologists are guided by the appropriate sections in Weck (1950), which follows ideas presented earlier by Geiger.

From information received by members of the group, responsibility for issuing fire weather warnings to the public rests with the weather service or a meteorological institute in Finland, Israel, Japan (primarily for house fires), Poland, the Republic of Korea, Sweden, and the U.S.S.R. An interesting feature of the fire danger warning service provided in Poland is the use of a daily working chart outlining the boundaries of the various hazard zones, which is used as a basis for warning bulletins.

The responsibility for issuing such warnings to the general public is considered to be the function of the appropriate forestry organizations in Canada, France, the German Democratic Republic, the United Kingdom and the U.S.A.

The second phase of an integrated fire weather forecast service is the provision of forecasts in considerable detail for the primary purpose of alerting existing organizations responsible for the protection of forests, bush, and grassland against fire. Such agencies may be those whose primary aim is the protection of life and property against fire, as in the case of the Rural Fire Control Authorities in Australia. On the other hand, the service may be required by government and private organizations whose interest in protection is incidental to their main activity, e.g. logging, railway operations, construction. The latter type of organization may require a broader type of service than the agency strictly concerned with fire fighting, because of the need to plan the primary operations in the light of expected fire danger.

In many areas where forest fires are significant, legislation exists to restrict travel within wooded areas, or to forbid the use of open fires during periods of high hazard. Similarly there are many places where all work in the woods is stopped when fire danger becomes extreme; this may be controlled by legislation, or may be done on a voluntary basis as is commonly the case along the west coast of North America.

Because of the need for considerably more detail in this type of forecast than is required in the general forecast issued to the public, it is not always possible, or necessary, to provide uniform fire weather service over the whole country.

In Australia, this service is restricted to limited sections of the country, known as <u>strategic areas</u>. A strategic area is defined as an area in which fires could cause extensive damage to grass, timber or property, and danger to livestock and to people, and <u>where there is an organized fire protection association</u>. The boundaries of these areas are usually defined to coincide with the boundaries of large state forests or timber reserves (or groups of smaller reserves). Alternatively such an area could be defined to include a district which is heavily timbered and populated, or savannah or grass country supporting a large density of livestock.

Special forecasts are not generally issued for such areas until they become <u>OPERATIONAL</u> - that is until the district office has been notified by the fire control officer concerned that the fire hazard has reached dangerous levels. At this time forecasts are issued twice daily, but as soon as an extreme category of fire danger is reached, the forecasts are issued at six-hourly intervals (valid for twelve hours) and are then known as <u>fire weather warnings</u>.

In addition, operational forecasts are issued in considerably more detail, on request, for areas where large fires are burning or where controlled burning is planned.

In the developmental stage, fire weather forecasting in Australia was the function of forecasters specifically concerned with this problem, but was later taken over by the general forecasting staff under the guidance of research meteorologists in this field.

In Canada, each of the seven Dominion Public Weather Offices is responsible for issuing fire weather forecasts as required by government agencies engaged in the protection of forests against fire, and for private companies engaged in logging operations. There has been no attempt by the meteorological branch to formally interpret the expected weather conditions in terms of fire danger; this is done by the forestry organization or company receiving the forecast. There is an exception to this in British Columbia, where a meteorologist seconded to the provincial Forest Service interprets forecast weather in terms of fire danger to the Forest Service.

The service provided varies across the country according to the need. In some areas there is little modification of the general forecast other than the addition of forecasts of relative humidity. At the other extreme, in British Columbia, a specialized forecast service is being developed. Here it has been found useful to provide a detailed word picture of the current and expected synoptic situation in moderately technical terms. This is issued in the early morning, and is intended as a planning forecast. In the early afternoon, a specific forecast is issued for somewhat smaller regions, valid for the following day giving numerical values, for a number of specific locations, of surface wind, maximum temperature, minimum relative humidity, upper-level relative humidity, and probability of occurrence of measurable rainfall.

The short-range forecasting section of the Swedish Meteorological and Hydrological Institute has been responsible since 1959 for issuing daily warnings in considerable detail, for the use of forest-watching personnel. These forecasts, based on Ångström's method, are issued each morning during the spring and summer, for each of the 23 forecast districts within the forest area of central and northern Sweden. Such forecasts are a particular requirement in the northern areas for the planning of daily aircraft patrols, in order that unnecessary patrolling may be eliminated.

Special services of this type have been provided in France since 1950. Each of the six meteorological offices concerned is responsible for issuing warnings to the provincial office in charge of forest protection against fires, suiting the type of service to the local need. In general one or two bulletins daily are issued during the hazardous period. These do not get general distribution.

Supplementary forecasts are issued on request for areas where large fires are burning. At such times the protection organization is mainly interested in the state of the sky and the wind.

In the U.S.A. the situation is a complex one, as would be expected from the variety of climatic regions represented. There are approximately forty offices located in the more heavily forested regions, concerned with issuing detailed forecasts of wind, temperature, relative humidity, precipitation and fuel moisture for the use of forest protection organizations. Because of the range of intensity and variations in the length of the fire season this service is provided by three types of forecaster :

(i) full-time fire weather personnel who concentrate on fire weather research during the season of low fire danger;

(ii) fire weather personnel who are detailed to other duties (e.g. fruit frost forecasting) during the non-fire season; and

(iii) regular forecasting staff at field stations who provide fire weather service as part of their regular duties.

Special forecasts are issued upon request for areas where fires are burning, or where controlled burning is planned. In the mountainous areas of the western states the Weather Bureau operates mobile forecast units and observation stations mounted on heavy trucks. These are equipped with radio receiver and transmitter, and can usually be driven directly to the scene of the fire. In this way the forecaster can apply his detailed local knowledge of topography and local conditions to provide forecasts which require a minimum of interpretation by the fire superintendent. Apart from the merits of extremely local forecasts, the use of such mobile units does ensure that the forecaster becomes thoroughly familiar with local conditions in his area, and becomes personally known to the men engaged in fighting fires, usually with a resulting increase in respect to his forecasts. The decision as to when and where to send such mobile units in the event of an outbreak of large fires rests with the fire weather forecaster. In some cases a forecaster may attend large fires without the use of such a mobile unit, in which case he is dependent upon available methods of communication for his information.

Private logging companies, and groups of such companies organized into "Protective Associations" make a great deal of use of the special fire weather forecasts to plan their operations, and at least one commercial meteorologist is able to sell his services to such private organizations by interpreting Weather Bureau forecasts in the light of his personal knowledge of local conditions and of fire weather problems.

The information available to the working group relating to the provision of such service in the U.S.S.R. indicates that detailed forecasts of forest inflammability are worked out according to the Nesterov system applied to long-term weather forecasts issued by the Central Forecasting Institute and the branches of the Hydrometeorological Service. Regular forecasts are issued for the use of workers in the Forest Economy Service throughout the period of fire danger. Forecasts are regularly worked out for twenty-four hours and for three days in advance. During certain periods forecasts are issued for four to seven days and for one month in advance. Current fire danger is presented in map form for all forest areas within the U.S.S.R.

Special forecast service is provided to organizations responsible for the protection of forests against fire in a number of other countries where this service is simply a part of the routine duties of the general forecasting staff. Among these may be listed Netherlands, New Zealand and the United Kingdom.

Other forecast requirements

So far there has been no mention of the need for specialized forecast services not directly related to fire behaviour, but often required by forest protection organizations engaged in the business of detection and suppression of forest fires. These include the specialized aviation forecasts required for aircraft engaged in fire patrol, water bombing of fires, transportation of men and supplies to inaccessible areas, or dropping of trained fire-fighters by parachute. A study of this particular phase of the problem has been undertaken by the working group set up by Resolution 11 (CAgM II) under Mr. P.M.A. Bourke, and published as WMO Technical Note No. 32.

The factor of visibility is a significant one to the extent that it may affect the detection of smoke from a look-out tower or aircraft. This is a normal meteorological problem and requires no elaboration here. However, because of the elevation of the look-out towers the occurrence of convective cloud along the higher ridges and mountainous areas must be considered as an obstruction to visibility.

As in most applied fields of meteorology, there is a definite requirement for forecasts with a valid period longer than 48 hours. In fact many protection agencies refer to this as one of their major requirements. At the moment such longer range forecasts, specifically designed for purposes of the protection of forests against fire, are being issued by the Central Forecast Institute of the U.S.S.R. Hydrometeorological Service for periods of 3 days, and when required for periods of 4 to 7 days and one month in advance. These are worked out according to techniques developed by K. I. Kasnin and M. V. Grichenko (communication to working group).

In the U.S.A. five-day forecasts and monthly weather outlooks are issued regularly by the extended forecast section of the U.S. Weather Bureau, and these are used by the fire weather forecasters in their work. A study of the application of extended forecast techniques to fire weather forecasting has been made by Beers and Colson (1960).

Although a number of services and institutes do provide some forecast advice to forest protection agencies for periods 3 to 4 days ahead, the problems are entirely meteorological and there does not appear to be any need for additional techniques to provide this service.

3.3.2 Communications and distribution of the forecast

An accurate forecast can be another tool in the hand of the fire-fighter, but only if it is received by him with a minimum loss of time. Because forest land is usually relatively undeveloped land, communications are often a problem. In some areas it is quite practical for the meteorological service to obtain all the necessary information by normal meteorological channels, and to distribute the forecast by telephone for further distribution by press and public radio. In other areas lack of adequate communications must be remedied before desirable fire weather services would be of any value.

In Australia, for example, the collection of supplementary data and subsequent distribution of special forecasts are so dependent upon communications that detailed communication plans are set up by each Divisional Office to meet local needs. Plans must be made for special emergency communications in the event of disastrous fires. Telephone, telegraph and radio are utilized in addition to normal meteorological communications.

The Canadian Meteorological Branch, in common with a number of other services, assumes responsibility only for providing forecast material to the principal offices of the various forest protection organizations. Further distribution is made by these organizations through their own communications network. The radio networks of the various provincial forest services are the principal means of dissemination.

In the U.S.A., radio communications play a major part in the collection of special reports and the distribution of forecasts; various State and Federal communications networks are employed as well as a special fire weather channel.

3.3.3 Co-operation with other agencies, research and training

As with any branch of applied meteorology, close liaison is necessary if the meteorologist is to understand fully the needs of the forest protection organizations, and if the protection official is to make the most efficient use of existing meteorological information and techniques.

In many countries this can be accomplished adequately by normal contacts between the two services. In others the problems are complex enough that the most efficient service can only be provided by some sort of formal arrangement of liaison officers.

One feature which seems to be common to a great many countries is significant enough to mention here. This is the fact that the meteorological organizations are centralized agencies, at the national level, while forest protection services are often decentralized agencies, usually operating at the state or provincial level, and in some countries at the community level. In Australia, for example, it is necessary for the Commonwealth Bureau of Meteorology to deal with all three levels of administration.

In most countries where the forest fire problem is an important one, co-operation between meteorological service and forest protection groups is fostered by having meteorologists attend forestry conferences, lecture to forestry courses, and attend large wild fires or controlled burns whenever possible.

In Australia and the United States the meteorological services sponsor regular annual or biennial fire weather conferences attended by foresters and meteorologists.

In the United States, in addition to the fire weather service outlined previously, there are a number of meteorologists working directly with State Forestry personnel, or attached to the numerous Forest Experiment Stations across the country. There are also research meteorologists attached to special co-operative projects, such as Project Skyfire, designed to investigate the possibility of reducing lightning fire occurrence.

In South Africa a meteorological liaison officer has been appointed in the Department of Forestry to work on the problems of fire danger rating and fire weather forecasting. A similar situation exists in Canada, where one meteorologist is seconded from the Meteorological Branch to the Division of Forest Research of the Canada Forestry Branch and another one is seconded to the Protection Division of the British Columbia Forest Service.

In any country some degree of research is necessary for the development of a fire weather service. In WMO Technical Note No. 10, Bourke makes reference to the fact that the bulk of the work on plant diseases had been done by the plant pathologist and by the entomologist. In the study of fire weather relationships the meteorologist and the physicist are now playing important rôles, although most of the early work has been done by foresters. The complexity of the problems that remain to be solved is such that close co-operation between workers in the two fields is extremely desirable, if not essential.

Another important phase of the problem that involves a high degree of co-operation is the training of forestry personnel to enable them to appreciate the limitations of meteorology as well as to provide them with sufficient basic training to enable them to interpret the forecasts in terms of local conditions. In Australia this is being achieved by giving selected foresters from all the states a short course in meteorology at the Central Training School of the Bureau of Meteorology and by preparation of a manual of meteorology for foresters. In Canada this is being accomplished by having meteorologists take part in courses organized by forest protection groups, provide lectures to undergraduates in forestry, and provide articles on meteorology for forestry publications. An intensive short course has been given in meteorology for research foresters. In Poland, a Manual of Agricultural Meteorology for students of the Higher Agricultural and Sylvan Schools (Molga, 1958) includes a chapter on agrometeorological forecasting. In addition,a popular monthly magazine is published for distribution to all observers, containing articles on this subject.

In the U.S.A. both federal and state agencies co-operate in conducting intensive short courses on fire behaviour. The Weather Bureau provides the major portion of the instruction in these classes. Personnel of the U.S. Forest Service and the U.S. Weather Bureau are co-operating in the preparation of a Fire Weather Handbook primarily designed for forest protection staff.

Because of the specialized nature of the problem, training in this field has generally been a function of the various state services, rather than of the universities, although specialists in this field do from time to time provide instruction at these institutions, and a number of graduate research studies have been concerned with fire weather relationships.

LIST OF REFERENCES

The following list represents a selection of the published material relevant to this report.

In general the material is limited to that which is familiar to one or more members of the working group, and reference has been made to most of the individual items in the body of the report. A limited amount of unclassified material is included for completeness.

Wherever possible each entry has been classified according to the principal field of interest, according to the following legend :

A. Effect of weather factors on fuel moisture and fuel moisture indicators;

B. Fire behaviour;

C. Fire danger rating systems;

D. Fire weather forecasting, synoptic studies and objective forecasting aids;

E. Fire weather measurement, spatial variations in fire weather elements;

F. Lightning as applied to forest fires;

G. General reference.

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