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Weather Guide for the Canadian Forest Fire Danger Rating System

B.D. Lawson and O.B. Armitage

Canada

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WEATHER GUIDE FOR THE CANADIAN FOREST FIRE DANGER RATING SYSTEM

B.D. Lawson¹ and O.B. Armitage²

Canadian Forest Service
Northern Forestry Centre
2008

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ABSTRACT

The *Weather Guide for the Canadian Forest Fire Danger Rating System* is intended primarily for operational wildland fire management personnel and forest fire weather practitioners responsible for gathering, processing, and forecasting fire weather information in support of safe and effective suppression and use of fire. Accurate and representative weather observations that meet prescribed standards and specifications are necessary for accurate and representative calculation of all components of the Canadian Forest Fire Danger Rating System. Weather-dependent components or modules are calculated or computed for effective use of the system's two main subsystems, the Canadian Forest Fire Weather Index (FWI) System and the Canadian Forest Fire Behavior Prediction (FBP) System. This weather guide includes detailed specifications for locating and instrumenting fire weather stations, taking weather observations, and overwintering the Drought Code component of the FWI System. The sensitivity of the FWI System components to weather elements is represented quantitatively. The importance of weather that is not directly observable is discussed in the context of fuel moisture and fire behavior. Current developments in the observation and measurement of fire weather and the forecasting of fire danger are discussed, along with the implications for the reporting of fire weather of increasingly automated fire management information systems.

RÉSUMÉ

Le *Guide sur les conditions météorologiques de la Méthode canadienne d'évaluation des dangers d'incendie de forêt* (MCEDIF) s'adresse principalement au personnel chargé des opérations de gestion du feu en forêt et aux spécialistes de l'indice forêt-météo chargés de la collecte et du traitement de l'information sur les conditions météo propices aux incendies de forêt et de l'établissement de prévisions à l'appui d'activités sécuritaires et efficaces de suppression et d'utilisation du feu. Il faut disposer d'observations météorologiques précises et représentatives, conformes aux normes prescrites et aux spécifications, pour effectuer des calculs précis et représentatifs de toutes de toutes les composantes de la Méthode canadienne d'évaluation des dangers d'incendie de forêt. Les éléments ou modules tributaires des conditions météo sont calculés de manière à permettre l'utilisation efficace des deux composantes principales de la MCEDIF, soit la Méthode canadienne de l'indice Forêt-météo (IFM) et la Méthode canadienne de prévision du comportement des incendies (PCI) de forêt. Le présent guide expose notamment en détail la marche à suivre pour localiser et instrumenter des stations météorologiques, effectuer des observations météo et ajuster l'indice de sécheresse de la Méthode IFM en fonction des précipitations hivernales. La sensibilité des composantes de la Méthode IFM aux éléments météorologiques est représentée quantitativement. Le guide traite de l'influence des conditions météo non directement observables sur l'humidité

du combustible et le comportement du feu. Il fait état des progrès en matière d'observation et de mesure des conditions météo propices aux incendies et de prévision du danger de feu ainsi que des incidences sur la communication des conditions météo propices aux incendies de l'automatisation grandissante des systèmes d'information sur la gestion du feu.

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FOREWORD

For nearly 30 years the publication *Weather in the Canadian Forest Fire Danger Rating System – A User Guide to National Standards and Practices* (Turner and Lawson 1978) has served as the primary reference for the collection of fire weather data in Canada.

Although the basic weather inputs into the Canadian Forest Fire Danger Rating System (CFFDRS) have changed little, data collection technology has moved forward significantly over the years. In addition, continued research and technical observations related to the CFFDRS have increased our understanding of the interactions among weather, forest fuels, and fire behavior, which form the basis of the system. These observations have been published in a variety of documents. As a result, it has become increasingly difficult for practitioners to keep abreast of recent developments and to readily access the information that could be useful to them.

In 2006 the Forest and Fire Meteorology Working Group, operating under the mandate of the Canadian Interagency Forest Fire Centre, proposed to update the 1978 document to bring it into line with current technology and practices and to reflect recent scientific findings. In addition, the group sought to expand the scope of the guide so that it would become a general reference for issues relating to fire weather and fuel moisture as they apply to the CFFDRS.

The goal was to produce a consolidated, up-to-date reference for this material, which would be useful for both new and experienced practitioners, as well as other interested parties. Consequently, the document has been published electronically in a form that will facilitate the incorporation of updates and new findings as they become available.

Forest and Fire Meteorology Working Group,
Canadian Interagency Forest Fire Centre, 2007

PREFACE

The Canadian Forest Fire Danger Rating System (CFFDRS) encompasses a number of publications that document equations and interpretive material defining and describing this national danger rating system, which have been approved by the Canadian Forest Service (CFS). At present, these publications are physically available in a three-ring binder titled "Canadian Forest Fire Danger Rating System–Users' Guide."¹

The publication covering fire weather matters related to the CFFDRS that is currently included in the CFFDRS user's guide is titled *Weather in the Canadian Forest Fire Danger Rating System – A User Guide to National Standards and Practices*, by J.A. Turner (deceased 1979) and

B.D. Lawson (former member of the CFS Fire Danger Group, retired from CFS in 1996). This regional publication (CFS Information Report BC-X-177, 1978; also available in French) has served as a national weather guide for many years, but has gradually become outdated because of technological and scientific changes in the collection and management of weather data, the computation of components of the danger rating system, and some of the CFFDRS components themselves. An abbreviated version of the 1978 publication was included as Chapter 12 (in Part B, Forest Fire Meteorology) of Environment Canada's *Forest Fire Management: Meteorology – A Training Manual* (Environment Canada 1987).

¹Canadian Forestry Service. 1987. Canadian Forest Fire Danger Rating System – Users' Guide. Can. For. Serv., Fire Danger Group. [Ottawa, ON.] Three-ring binder (unnumbered publ.).

Considerable work toward a national weather guide was done by the CFS in 1984, with extensive suggestions for revisions to BC-X-177 being submitted by M.E. Alexander, Northern Forestry Centre, and others. In the preparation of the new weather guide, B.D. Lawson obtained these paper files from CFS and reviewed them, along with new comments from B.M. Wotton, Great Lakes Forestry Centre.

Like its predecessor, the new weather guide will assist those responsible for establishing fire weather stations for danger rating networks and operating short-term applications such as campaign wildfires² and prescribed burns. This weather guide specifies the standards required for the basic fire weather observations that are used to calculate components of the Canadian Forest Fire Weather Index (FWI) System and the Canadian Forest Fire Behavior Prediction (FBP) System, the two principal subsystems of the CFFDRS.

The weather guide also provides procedures and adjustments for nonstandard weather situations and weather-recording practices that should be of interest to all fire weather observers. The weather guide does not, however, include an availability list for weather instrumentation availability, nor is it a detailed instruction manual for taking weather observations with specific instruments.

Although this weather guide references the *Guide to Agricultural Meteorological Practices* of the World Meteorological Organization (WMO 1968), it deviates in one important respect from the WMO-recommended standard for a clearing size for a forestry weather station, as follows.

In its original publication, the WMO (1968) stated that, "current information suggests that the diameter of the clearing should be at least 10 times, preferably 20 times the tree height of the surrounding forest." In a 1982 supplement (WMO 1982), the WMO revised its recommendation on clearing size, stating that "to minimize the effect of forest vegetation on air flow, the anemometer mast should be located in the centre of an opening in the forest with diameter of at least 20 times the height of the surrounding trees." This larger recommended clearing size was retained by WMO in its 1993 forestry supplement (WMO 1993). However, for continuity with established CFS practice, the current weather guide retains the long-standing recommendation for forest fire weather station clearings in Canada that the anemometer be located in the centre of a clearing with diameter at least 10 times the height of the surrounding trees.

²A campaign fire is "a fire of such size, complexity and/or priority that its extinction requires a large organization, high resource commitment, significant expenditure, and prolonged suppression activity (synonym: project fire)." Merrill, D.F.; Alexander, M.E. 1987. Glossary of forest fire management terms. 4th Ed. Natl. Res. Coun. Can., Can. Comm. For. Fire Manag., Ottawa, ON. Publ. NRCC 26516.

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The authors acknowledge Nick Nimchuk, Alberta Sustainable Resource Development, Forest Protection Division, and Eric Meyer, British Columbia Ministry of Forests and Range, Protection Program, who spearheaded the effort to update the old weather guide. Together, they initiated support for the project at the national level and secured the necessary contract funding from their respective provincial fire management agencies. A project to update the weather guide was proposed and approved by the Forest and Fire Meteorology Working Group, Canadian Interagency Forest Fire Centre, which was chaired at the time by Nick Nimchuk.

Gordon Miller, former director general, and Brenda Laishley, head of Publications, Northern Forestry Centre, Canadian Forest Service, facilitated the publication process.

Alice Solyma, librarian, Pacific Forestry Centre, Canadian Forest Service, helpfully provided out-of-print versions of the World Meteorological Organization standards.

We are indebted to Marty Alexander, senior fire behavior research officer, Northern Forestry Centre, Canadian Forest Service, for his extensive suggestions for updating the weather guide, and for contributing an appendix on latitude considerations, which will allow the Canadian Forest Fire Weather Index System to be adapted for use in other countries.

We sincerely thank the following reviewers for their constructive contributions: Richard Carr, Roger Desjardins, Bill Droog, Mike Flannigan, Jim Goosen, Ben Janz, Nathalie Lavoie, Rob McAlpine, and Mike Wotton.

THE AUTHORS

Bruce Lawson retired from the Canadian Forest Service (CFS) in 1996 after 30 years as a forest fire research officer and head of the Pacific and Yukon regional fire program. He was a member of the CFS Fire Danger Group, contributing research and technology transfer to the development of the Canadian Forest Fire Weather Index System and the Canadian Forest Fire Behavior Prediction System. In 1996, he began consulting in forest fire science and management, mostly with Ember Research Services Ltd., undertaking projects in the documentation of wildfire behavior, development of fire management plans for parks and protected areas, assessment of community fire risk, and

investigation of the cause and origin of fires for court cases.

Brad Armitage started working in fire research with the Pacific Forestry Centre of the CFS in 1989. While employed by the CFS, he worked on a number of fire research projects, including ignition probability modeling, FBP System testing, prescribed burning, and site preparation. In 1994 he started Ember Research Services Ltd. and began consulting in forest fire science and management for a variety of provincial and territorial governments and for private industry clients.

THE PUBLICATION

Publication of this weather guide was funded by the provinces of British Columbia and Alberta and by the Canadian Forest Service (CFS). This publication is a revision of the 1978 CFS publication BC-X-177, titled *Weather in the Canadian Forest Fire Danger Rating System — A*

User Guide to National Standards and Practices, by J.A. Turner and B.D. Lawson. Like its predecessor, this weather guide is intended for nationwide use as a standard reference for fire managers and researchers using the Canadian Forest Fire Danger Rating System.

INTRODUCTION

Weather accounts for all of the essential inputs to the Canadian Forest Fire Weather Index (FWI) System, and these weather inputs, together with outputs from the FWI System, are also required to calculate outputs from the Canadian Forest Fire Behavior Prediction (FBP) System. The FWI and FBP systems are the two principal subsystems of the Canadian Forest Fire Danger Rating System (CFFDRS) (Fig. 1).

(rain accumulated over 24 h, temperature, relative humidity, and wind speed) are generally taken daily at noon local standard time (LST) or 1300 local daylight time (LDT). (The term "noon" is used throughout this weather guide, even though most of Canada now implements daylight saving time over the entire fire season; therefore, 1300 LDT is generally an acceptable approximation of solar noon.)

The four weather elements that are measured and used as inputs to the FWI and FBP systems

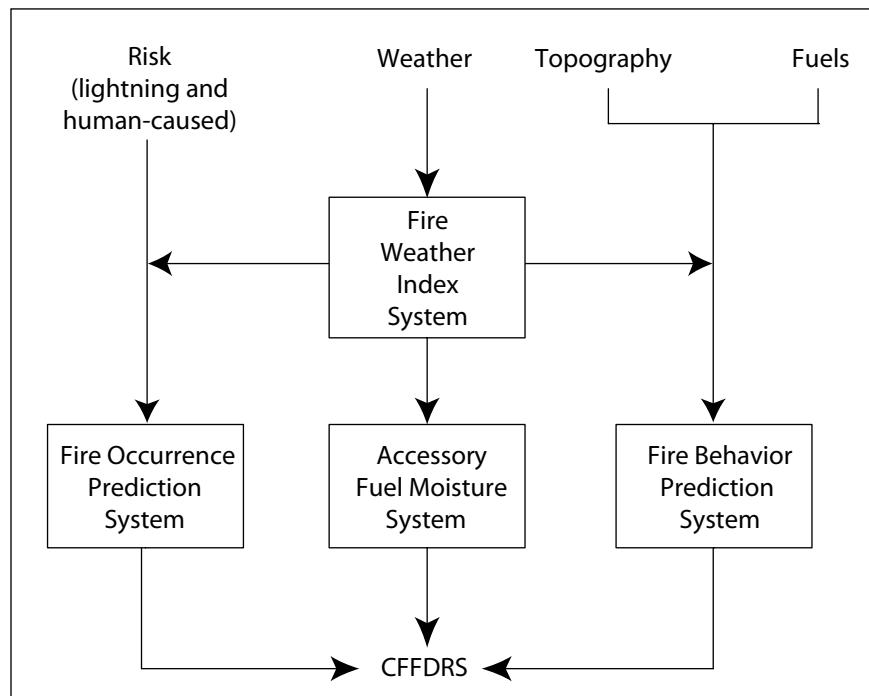


Figure 1. Structure of the Canadian Forest Fire Danger Rating System (CFFDRS) (adapted from Stocks et al. [1989]).

The six standard components — three fuel moisture codes and three fire behavior indexes — of the FWI System (shown in Fig. 2) provide numeric ratings of relative potential for wildland fire. The FWI System refers primarily to a standard pine fuel type but is useful as a general measure of forest fire danger in Canada (Van Wagner 1987). The three fuel moisture codes

follow daily changes in the moisture content of three classes of forest fuel with different drying rates. Each moisture code is calculated in two phases — one for wetting by rain and one for drying — and is arranged so that higher values represent lower moisture contents and hence greater flammability (Van Wagner 1987).

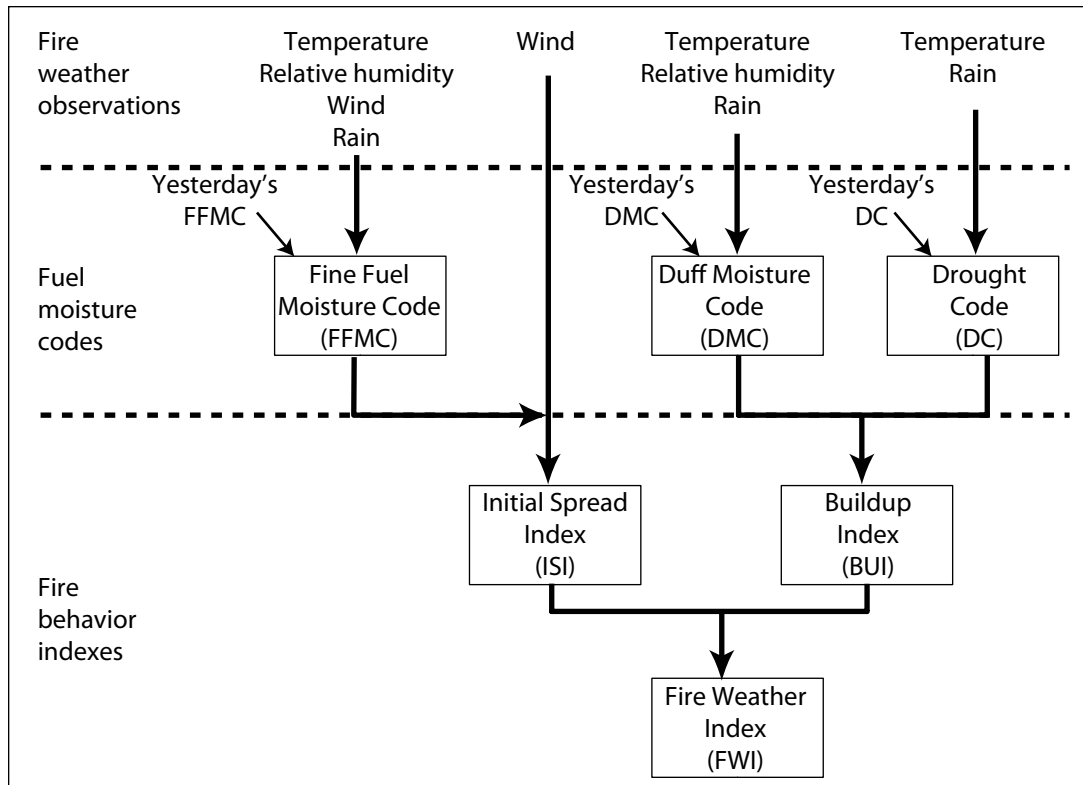


Figure 2. Structure of the Canadian Forest Fire Weather Index System (adapted from Canadian Forest Service [1984]).

The Fine Fuel Moisture Code (FFMC) is a numeric rating of the moisture content of litter and other cured fine fuels. The FFMC is an indicator of the relative ease of ignition and flammability of fine fuels.

The Duff Moisture Code (DMC) is a numeric rating of the moisture content of loosely compacted organic (duff) layers of moderate depth. The DMC is an indicator of fuel consumption in moderate duff layers and medium-sized downed woody material.

The Drought Code (DC) is a numeric rating of the moisture content of deep, compact organic

layers. The DC is an indicator of seasonal drought effects on forest fuels and the amount of smoldering in deep duff layers and large logs.

Some physical properties of the forest floor layers associated with the three fuel moisture codes are summarized in Table 1, where the drying rates of DMC and DC, represented by time lag (i.e., time to lose $1 - 1/e$ where e is the natural base of logarithms, which has the value of 2.7182818... or about two-thirds of the free moisture content above equilibrium), have been revised from those published earlier by Van Wagner (1987).

Two intermediate fire behavior indexes represent fire spread rate and amount of available fuel. The Initial Spread Index (ISI) is a numeric rating of the expected rate of fire spread, which combines the effects of wind and FFMC on rate of spread without the influence of variable quantities of fuel. The Buildup Index (BUI) is a numeric rating of the total amount of fuel available for combustion, which combines DMC and DC.

The final fire behavior index, the Fire Weather Index (FWI), combines ISI and BUI to represent the intensity of a spreading fire as energy output rate per unit length of fire front. This numeric rating of fire intensity is suitable as a general index of fire danger throughout the forested areas of Canada.

One basic value of each FWI component is calculated per day to represent fire danger conditions during the midafternoon peak burning period, assuming a normal diurnal weather pattern (Van Wagner 1987). For rainy days, calculation of the various fuel moisture codes has been standardized by taking into account first the effect of the rain, and then the appropriate degree of drying.

These six standard components of the FWI System are predictors of daily fire potential

(Alexander and DeGroot 1988). Because one value per day is determined for each component, the FWI System does not indicate hour-by-hour changes, nor does it account for variations in fuel type from season to season or from place to place. However, it does provide reference scales that permit comparisons of fire danger with other days and other locations. The FWI System makes it possible to reconstruct past fire danger conditions if suitable historical weather records are available. Thus, a "fire climatology" can be developed for comparison with known fire activity (Turner 1973; Stocks 1974; Kiil et al. 1977; Harrington et al. 1983; Amiro et al 2004; Parisien et al. 2004; Girardin et al. 2006; Lavoie et al. 2007). The fuel moisture codes continue to be studied for correlation with observed fuel moisture content of litter and forest floor strata within a wide range of ecosystems (Otway et al. 2007) and on burned and unburned sites (Abbott et al. 2007a). Each fuel moisture code conveys direct information about various aspects of wildland fire potential. For example, fires are not likely to spread in surface litter with an FFMC less than about 74, the duff layer does not contribute to frontal fire intensity until the DMC reaches 20, and ground or subsurface fire activity tends to persist at DC values greater than 400 (Stocks et al. 1989).

Table 1. Physical properties of forest floor layers associated with the fuel moisture codes of the Canadian Forest Fire Weather Index System

Fuel moisture code	Forest floor layer	Nominal depth (cm)	Nominal load (kg/m ²)	Bulk density (g/cm ³)	Rain capacity (mm)	Saturated moisture content (%)	Standard time lag ^a
FFMC ^b	Litter	1.2	0.25	0.021	0.62	250	2/3
DMC ^c	Loosely compacted duff	7	5	0.071	15	300	15 ^d
DC ^e	Deep compacted organic layer	18	25	0.139	100	400	53 ^d

^aTime lags of the fuel moisture codes vary with weather conditions. Tabulated values represent standard drying conditions (temperature 21.1° C, relative humidity 45%, wind speed 13 km/h, July) and were derived by S.W. Taylor (Canadian Forest Service [CFS]) and verified by B.M. Wotton (CFS) and C.E. Van Wagner (CFS, retired).

^bFFMC = Fine Fuel Moisture Code.

^cDMC = Duff Moisture Code.

^dDiffers from time lag presented in Van Wagner (1987), which is slightly in error.

^eDC = Drought Code.

The Daily Severity Rating (DSR) was described by Van Wagner (1987) as an optional component of the FWI System that is computed directly from the FWI. The DSR weights the FWI as it rises, in a manner deemed to reflect difficulty of control in more direct proportion to the work required to suppress a fire. The FWI itself is not considered suitable for averaging and should be used only as a simple daily value. Any averaging, whether spatially over a number of stations on a given day or at a single station over any period of time, is better accomplished through the DSR.

The DSR averaged over an entire fire season is termed the Seasonal Severity Rating (SSR), which can be used as an objective measure of fire weather from season to season or of fire climate from region to region.

The standard daily FFMC describes the afternoon state only (as forecast from noon weather observations), and other means are required to describe fine fuel moisture at other times of the day. Van Wagner (1977) developed an hourly FFMC for which hourly weather observations are used to calculate an FFMC for each hour around the clock. Similarly, Lawson et al. (1996) presented look-up tables and computer coding for a diurnal FFMC calculated for each hour around the clock without the need for hourly weather data. This diurnal FFMC was an update of earlier tabular versions (Muraro et al. 1969; Van Wagner 1972; Alexander 1982b). Hourly and diurnal FFMC models are compared in Appendix 2.

Currently, several Canadian fire management agencies use the hourly FFMC, together with hourly wind speed and direction, as inputs to the FBP System (Forestry Canada Fire Danger Group 1992), when quantitative estimates are required of variables such as head fire spread rate, fuel consumption, fire intensity, and fire description for some 16 discrete fuel types. The FBP System is intended to supplement the experience and judgment of operational fire managers. FBP System applications are more site specific and time sensitive than FWI applications. Therefore, as noted by the Forestry Canada Fire Danger Group (1992), the hourly FFMC computational method is preferable for the prediction of fire behavior to both the standard daily FFMC, which has a standard diurnal curve embedded in it, and the single diurnal curve in the table presented by Van Wagner (1972). In this way, hourly weather variations, rather than average diurnal weather trends, can be reflected in the fire behavior predictions.

The Accessory Fuel Moisture (AFM) System of the CFFDRS (Fig. 1) includes several fuel-specific moisture codes of the FWI System. Two examples illustrate the wide range of weather and fuel characteristics covered by such nonstandard moisture codes. First, a sun-exposed fine fuel moisture model was developed to represent the moisture content of reindeer lichen (Pech 1989), for which the equilibrium moisture content with exposure to sun is 3%–4% lower than for shaded litter, the fuel represented by the FFMC. At the other end of the scale for exposure of fuel to weather elements is the sheltered duff moisture code (Wotton et al. 2005), in which a modified DMC represents the moisture content of forest floor fuels adjacent to tree boles, an area where lightning strikes usually ignite the forest floor. These fuels are consistently lower in moisture content than less sheltered areas of the stand, because of greater interception of precipitation by tree crowns. Development of the AFM System is continuing (Alexander et al. 1996), without a defined end point or specified official content.

The Canadian Forest Fire Occurrence Prediction (FOP) System is envisioned as a national framework of both lightning- and human-caused fire components (Alexander et al. 1996). Although elements of an FOP System have been developed using one or more FWI System components (Anderson 2002; Wotton and Martell 2005), they have not yet been implemented on a national basis to predict the number of fires in specific areas.

Recent progress has been made on developing probabilistic models of sustained flaming (Lawson and Dalrymple 1998; Beverly and Wotton 2007) and smoldering ignition (Lawson et al. 1997; Anderson 2000; Otway et al. 2006).

Conceptually, the CFFDRS deals with the prediction of fire occurrence and behavior from point-source weather measurements (i.e., a single station within a fire weather network) (Lee et al. 2002). The system does not account for spatial variation in weather elements between points of measurement. Models and other systems external to the CFFDRS must be used to handle such interpolation (see subsection "Implications of Fire Weather: Fire Management Information Systems" within the section "Fire Weather Forecasting"). However, Lee et al. (2002) emphasized the inherent difficulty of obtaining sufficiently accurate and timely forecasts of the fire weather elements (most notably wind speed), especially for rugged terrain. Those

authors also noted the resulting limitations on any computerized decision-support systems that depend in whole or in part on the CFFDRS as a means of predicting wildland fire occurrence and behavior.

Computer-based fire management systems have been used in Canada since the early 1970s (Lee et al. 2002). In 1992, the CFS began investigating the use of geographic information systems (GIS) for constructing these fire management information systems, which culminated in development of the spatial fire management system (sFMS). The fire-weather-related implications of this

technological advancement for the CFFDRS are discussed later, under the heading "Implications of Fire Weather: Fire Management Information Systems."

The development of remote automatic weather stations (see the subsection entitled "Automatic Weather Stations" within the section "Fire Weather Stations") and associated communications technology in the 1980s and 1990s permitted collection of weather data from isolated locations in almost real time on a provincial and even a national basis (Taylor and Alexander 2006).

ELEMENTS OF FIRE WEATHER

The four weather elements needed to calculate the six components of the FWI System are rain, temperature, relative humidity, and wind speed (Fig. 3). These elements influence the ease with which fires can be started, the rate of spread, and the difficulty of controlling fires that are already burning. Variation in day length throughout the season affects both the DMC and the DC and is accounted for by monthly adjustment in their respective daily drying factors. For these two slow-reacting moisture codes, the amount of moisture lost daily by their representative fuels is dependent as much on the time available as on the noon atmospheric conditions. In contrast, the midafternoon moisture content of the fast-drying fuels represented by the FFMC is less dependent on day length (Van Wagner 1987). The effect of latitude on day length within the context of DMC and DC drying factor adjustments for countries at various latitudes is discussed in Appendix 3.

When wind speed is determined, wind direction is also recorded, even though it is not required for FWI System calculations. Wind direction is a required input for calculations in the FBP System, is useful for interpolation of wind speed, and is important to those forecasting fire weather.

Temperature

The noon (dry-bulb) temperature (measured in degrees Celsius) is required for the calculation of all three fuel moisture codes, FFMC, DMC, and DC.

Temperature, together with relative humidity and wind, affects the rate at which the FFMC recovers after it has been reduced by rain. The recovery of the FFMC for three levels of temperature, relative humidity, and wind is illustrated in Table 2.

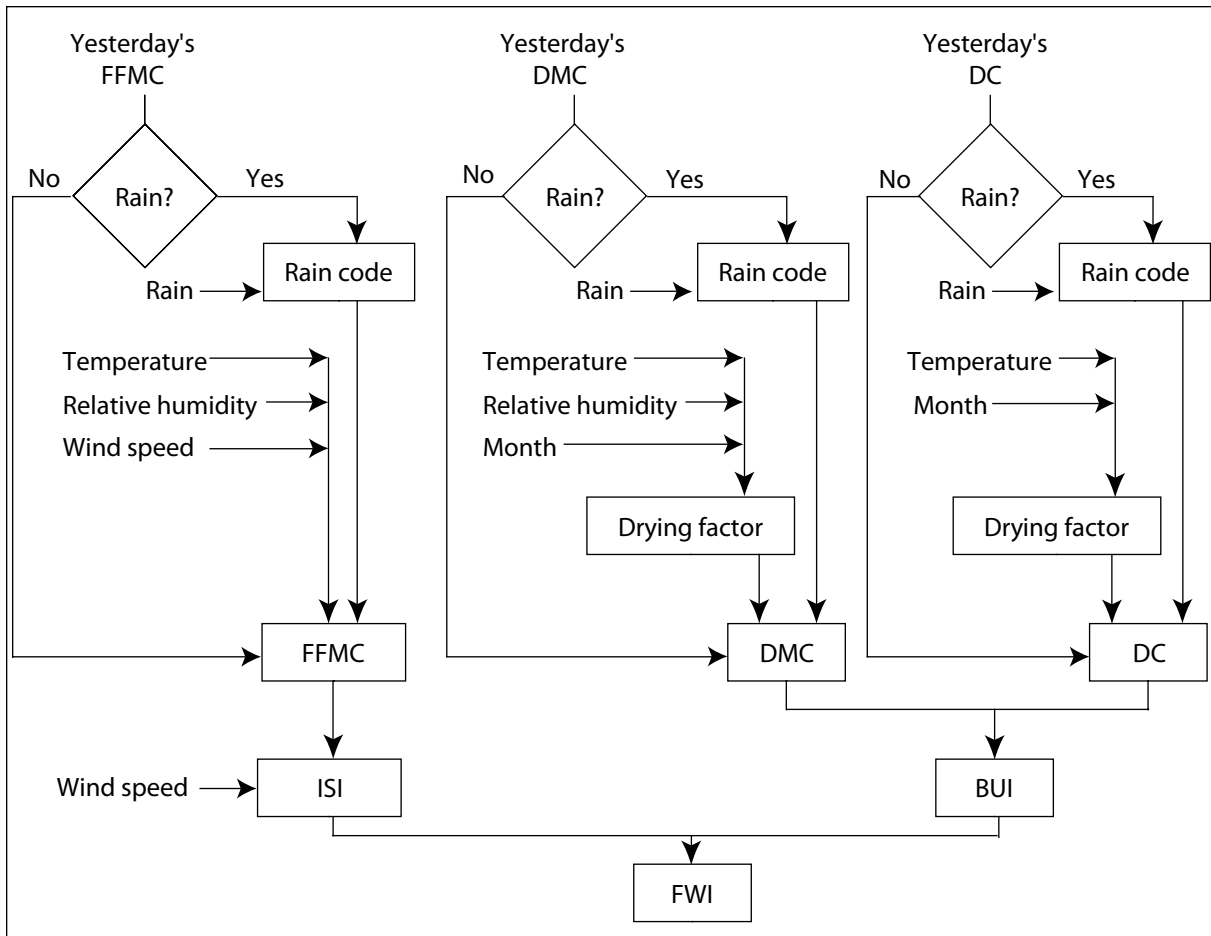


Figure 3. Schematic diagram for calculating the six standard components of the Canadian Forest Fire Weather Index System (adapted from Lawson [1977]). FFMC = Fine Fuel Moisture Code, DMC = Duff Moisture Code, DC = Drought Code, ISI = Initial Spread Index, BUI = Buildup Index, FWI = Fire Weather Index.

Table 2. Recovery of Fine Fuel Moisture Code (FFMC) after rain with three levels of temperature (temp.), relative humidity (RH), or wind speed (WS), with starting FFMC of 70

Days since rain	FFMC with variable temperature, RH = 45%, WS = 18 km/h			FFMC with variable relative humidity, temp. = 20 °C, WS = 18 km/h			FFMC with variable wind speed, temp. = 20 °C, RH = 45%		
	10 °C	20 °C	30 °C	65%	45%	25%	4 km/h	18 km/h	32 km/h
0	70	70	70	70	70	70	70	70	70
1	80	84	87	79	84	88	82	84	85
2	84	87 ^a	89 ^a	82	87 ^a	91 ^a	86	87 ^a	87 ^a
3	85 ^a			85 ^a			87 ^a		

^aEquilibrium.

Temperature and relative humidity are both required for calculating the drying phase of the DMC, whereas only temperature is needed to calculate the drying phase of the DC. However, the drying factors for both DMC and DC are modified by a day-length factor that varies by month.

Relative Humidity

The ability of the atmosphere to retain moisture depends in large part on atmospheric

temperature. The higher the temperature, the more moisture the atmosphere can retain. Relative humidity (expressed as a percentage) is the fraction of moisture present in the atmosphere at a given temperature relative to the total amount of moisture that the atmosphere could retain at that temperature. On a normal day when no significant moisture is added or removed from the atmosphere, relative humidity varies with temperature in a recognizable pattern (Fig. 4).

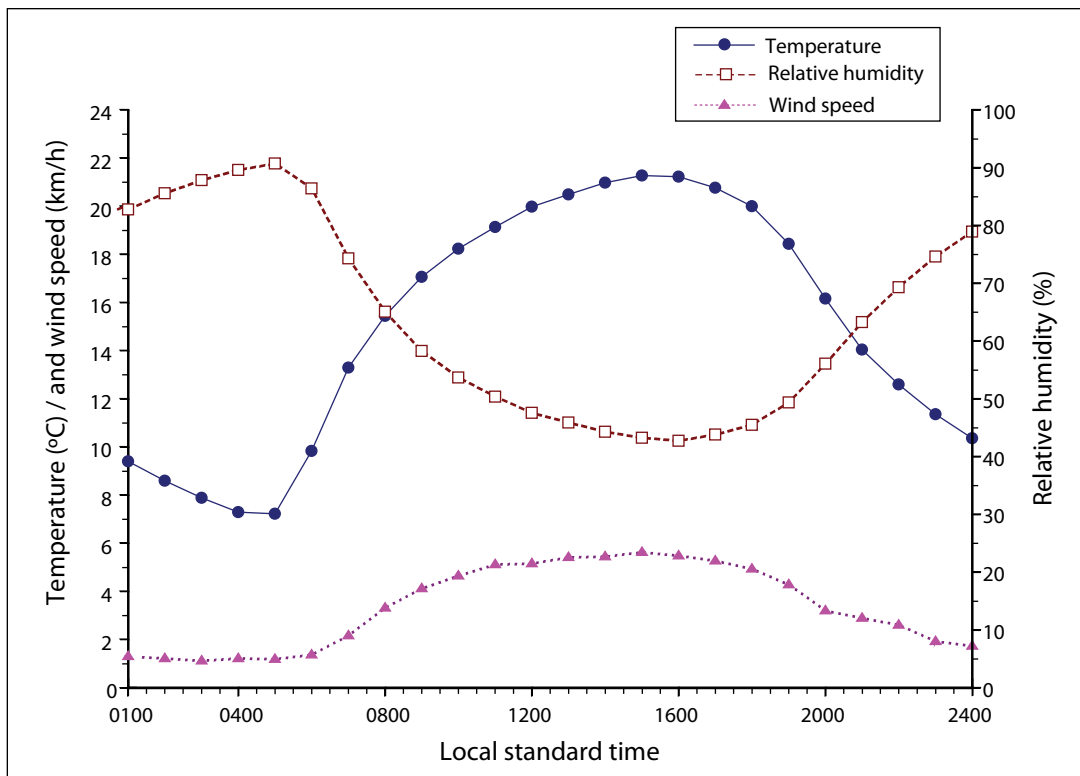


Figure 4. Daily patterns of temperature, relative humidity, and wind speed in July for a typical continental station, Leighton Lake, B.C.

In the early days of organized forest fire control, the term “fire weather” meant “relative humidity,” and this weather element is still used today to quickly assess fire danger. However, the complexity of the problems that require fire weather inputs demands a more sophisticated approach. In particular, the FWI System requires noon relative humidity for determination of both FFMC and DMC.

Relative humidity affects the day-to-day (or hour-to-hour, in the case of hourly FFMC) drying rate of the FFMC in a nonlinear (logarithmic) way. This is discussed in more detail in the section “Sensitivity of CFFDRS Components to Weather Changes”. Relative humidity also affects the equilibrium moisture content (EMC), which is the lowest moisture content that a fuel will reach for a given combination of weather conditions. It is

useful to keep in mind that the EMC for the FFMC covers a range that is greater than the range of flammability; for example, the EMC at relative humidity of 100% is 35%, which is above the upper limit for fine fuel ignition of about 30% moisture content, whereas the EMC at relative humidity of 10% is about 2%–3% (Van Wagner 1987).

By contrast, the DMC is based on an assumption of constant EMC (20%), i.e., does not vary with relative humidity. This assumption means that regardless of how high the DMC climbs, the lowest level of implied forest floor moisture is 20%. The daily drying factor that is added to the DMC varies linearly with temperature and relative humidity, but again, as with the FFMC, the relation between relative humidity and implied forest floor moisture content in the DMC is nonlinear (logarithmic). DMC is discussed in more detail in the subsection “Duff Moisture Code and Drought Code.”

Wind

Wind (measured in kilometers per hour) influences the FWI System in two ways. A relatively weak effect is felt in the daily change in the FFMC, for which wind speed chiefly affects the rate of recovery after rain. A much stronger effect is built into the ISI to reflect the joint influence of wind and moisture content of fine surface fuels on a fire’s rate of spread.

As a rule of thumb, the ISI doubles in value for each increase of 14 km/h in wind speed, with FFMC held constant (Table 3). At the same time, with wind held constant, an increase of five to seven FFMC units is required to double the ISI under moderate to severe conditions (Table 3).

Table 3. Effect of wind on Initial Spread Index (ISI)

FFMC ^a	ISI at various wind speeds			
	5 km/h	19 km/h	33 km/h	47 km/h
77	1	2	5	9
80	2	3	6	12
83	2	4	9	17
86	3	6	13	26
89	5	10	20	40
92	7	15	30	61
95	11	23	46	93
98	17	34	68	138

^aFFMC = Fine Fuel Moisture Code.

Rain

The moisture content of forest fuels can be raised to 300% or more by contact with liquid water, while a maximum fiber saturation value of about 30% for dead woody fuels in a saturated atmosphere is possible (Schroeder and Buck 1970). Precipitation, usually in the form of rain, is the only factor that allows FFMC to fall below 73. Expressed another way, rain is needed if fine fuel moisture content is to exceed 31% (a value derived from the following standard conversion formula: moisture content [%] = 147.2 [101 – FFMC]/59.5 + FFMC; if FFMC = 73, moisture content = 31%). For further discussion on the derivation of this equation (FFMC/MC) see Van Wagner (1987). Rain is also the only means by which DMC and DC can be reduced to values lower than those recorded the previous day.

The total rainfall over 24 h (measured in millimeters) must exceed certain threshold amounts before it is considered to have any effect on the moisture content of the fuels represented by the three fuel moisture codes. These threshold values are specific to each fuel moisture code (Table 4). The effectiveness of any given rainfall in reducing the value of each moisture code varies with the amount of the rainfall and the value of the code before the rain started. These variations in effectiveness are built into the FWI System to reflect what is known about interception and rates of absorption (Table 5). Precipitation is measured in the open, but its effects are related to fuel moisture content within forest stands.

Table 4. Threshold rain values for fuel moisture codes

Fuel moisture code	24–h rain (mm)
Fine Fuel Moisture Code	> 0.5
Duff Moisture Code	> 1.5
Drought Code	> 2.8

From time to time during the fire season, precipitation may occur as hail or snow. In many cases precipitation that falls in this form will melt in the interval between observations, so the equivalent depth of water is entered into the weather record as if it had been rain.

If the snow (or hail) remains on the ground at observation time, the calculation of the three moisture codes continues, using the water equivalent of snow that has fallen since the previous observation (where 1 cm of snow = 1 mm of rain). However, the ISI and FWI both have the value zero under these conditions and retain this value until the snow or hail has melted.

Table 5. Effects of rain on the fuel moisture codes

24-h rain (mm)	Today's rain code (% reduction of yesterday's value)		
	FFMC ^a (yesterday = 90)	DMC ^b (yesterday = 30)	DC ^c (yesterday = 100)
0.6 ^d	86 (4)		
1.6 ^e	68 (24)	29 (3)	
2.9 ^f	48 (47)	25 (17)	195 (3)
5.0	33 (63)	20 (33)	192 (4)
10.0	19 (79)	15 (50)	178 (11)
20.0	14 (84)	12 (60)	155 (23)
40.0	10 (89)	10 (67)	114 (43)

^aFFMC = Fine Fuel Moisture Code.

^bDMC = Duff Moisture Code.

^cDC = Drought Code.

^dJust exceeds threshold value for FFMC.

^eJust exceeds threshold value for DMC.

^fJust exceeds threshold value for DC.

Supplementary Weather Elements

Fire weather observation programs are built around the needs and standards of the FWI System, but additional information that is not part of the FWI System is often required for fire management purposes and for fire weather forecasting. Standards for such supplementary information are specified by individual forest management agencies to meet regional requirements.

The following are examples of the additional information that may be required:

- Basic fire weather elements: Observations of basic fire weather elements, including extremes of relative humidity and temperature, may be recorded at times other than noon.
- Wind direction: Fire weather forecasters use wind direction to relate local wind patterns to broad-scale wind flow and topographic features. Wind direction is a required input for the FBP System.
- Lightning occurrence: Most of the forested area of Canada is covered by automatic networks for lightning detection and location, and the data are readily accessible to fire weather forecasters.
- Cloud conditions: Information about the development and movement of lightning-producing clouds (Mullock 1982) and ceiling heights may be required for deployment of aircraft and for fire weather forecasting.
- Dew: The effect of dew on fuel moisture is generally limited and dissipates by noon

(see subsection entitled "Dew and Frost" within the section "Weather Not Directly Observable").

- Upper atmosphere profiles: See subsection entitled "Low Level Jet" within the section "Weather Not Directly Observable."
- Solar radiation: Some automatic weather stations record the duration of bright sunshine (defined by the World Meteorological Organization [WMO 2006] as direct solar irradiance > 120 W/m²). The US National Fire Danger Rating System (NFDRS) calculates 10-h fuel moisture on the basis of solar radiation measured hourly. Sixty 1-min samples are averaged over a 1-h period before data transmission (NWCG 2005).
- Fuel moisture: Some automatic weather stations have sensors that measure variables related to the fuel moisture content of wooden dowels (see subsection "Automatic Weather Stations" within the section "Fire Weather Stations"). However, the US NFDRS recommends that direct measurements of fuel moisture sticks be used in calculations for that system (NWCG 2005).
- Snow depth: Snow depth is used for start-up and shut-down of FWI System calculations at the beginning and end of each fire season.
- Atmospheric pressure: Various weather models require input of atmospheric pressure, including adjustment of temperature and humidity to reflect elevation.

WEATHER OBSERVATION PRACTICES

Weather observation practices have been carefully specified and must be followed as closely as possible to ensure the effectiveness of management decisions that are based on the results. Such standards are essential for relatively permanent fire weather stations that form a regional network. It may be necessary to relax the standards for short-term stations set up to provide on-the-spot weather reporting for specific purposes.

Time of Observations

Basic Observation Time

Weather readings are taken at “noon,” 1200 LST or 1300 LDT when and where the latter is in effect. Weather recorders should be set to the exact hour, without correcting for “sun noon” differences at individual weather station locations.

Noon was chosen as the basic observation time to ensure that weather readings are taken late enough in the day to indicate conditions during the period of afternoon peak fire activity but early

enough that codes, indices, and forecasts will be available for planning and operational purposes. Weather observations should be taken within 15 min of the specified time. If this specification is followed, temperature, relative humidity, and wind are unlikely to be sufficiently in error to reduce significantly the accuracy of the FWI System calculations (Table 6).

Table 6 shows that around noon at typical Canadian weather stations, the temperature is increasing by, on average, less than 1 °C per hour, the relative humidity is dropping by less than 4% per hour, and wind speed is increasing by about 0.5 km/h per hour. Table 6 is based on data for all days between May and October, including cloudy, rainy, and clear days. Somewhat larger changes in temperature, relative humidity, and wind speed, as much as 60% greater than the hourly rates of change shown in Table 6, can be expected on clear days, and of course the rates of change for any of these weather elements on any particular day could greatly exceed the average shown.

Table 6. Average hourly rates of change of temperature, relative humidity (RH), and wind speed at noon local standard time for select stations

Station	Latitude	Longitude	Change in temperature (°C/h)	Change in RH (%/h)	Change in wind speed (km/h per hour)
Gander, NL	48.96	-54.61	0.55	-2.6	0.66
Chatham, NB	47.00	-65.45	0.74	-3.5	0.69
Bagotville, QC	48.30	-71.00	0.70	-2.8	0.61
Kapuskasing, ON	49.42	-82.42	0.75	-2.8	0.50
The Pas, MB	53.81	-101.24	0.64	-3.2	0.42
Fort McMurray, AB	56.72	-111.40	0.89	-4.2	0.60
Prince George, BC	53.91	-122.78	0.77	-3.0	0.47
Port Hardy, BC	50.72	-127.47	0.52	-2.2	0.58
Whitehorse, YT	60.73	-135.08	0.66	-2.4	0.26
Average			0.69	-3.0	0.53

Source: Turner and Lawson (1978); reprinted with permission of Pacific Forestry Centre.

Deviations from Basic Observation Time

Deviations from the basic observation time of 1200 LST may be specified at the regional level for stations that are close to time zone boundaries, are at high latitudes, or both.

Van Wagner (1987) quantified the effects of latitude on calculated values of FFMC, DMC, and DC. Recommended day-length factors for DMC and seasonal adjustments for DC for more southerly latitudes than Canada are discussed in Appendix 3. However, Van Wagner (1987) noted that it was fair to question whether the FWI System should take into account the effect of latitude within Canada on FFMC, since this code incorporates no allowance for day length. Van Wagner's (1987) comparisons of standard daily FFMC against hourly FFMC calculated from weather observations taken at 1600 (calculated as FFMC at 1600 minus standard FFMC) produced discrepancies ranging from 1.1 for stations at 48° N to 2.5 for stations at 66° N.

Van Wagner proposed that the basic observation time could be delayed progressively from noon at lower latitudes to about 1400 at higher latitudes to eliminate much of the discrepancy in standard daily FFMC and to accurately account for daily peak fire danger conditions at higher latitudes. The FFMC discrepancy occurs because the time of maximum temperature and minimum relative humidity in "high summer" (the several-week period around summer solstice) is progressively later as latitude increases. Standard daily FFMC has a built-in forecast mechanism that assumes that daily peak conditions occur at 1600 h LST, but north of 60° latitude, the daily peak of temperature and trough of relative humidity tends to be delayed until 1800 LST or even later, and tends to persist for longer than the 1 h or so that is typical for midlatitudes, particularly around high summer.

Kiil and Quintilio (1975) compared June diurnal relative humidity cycles for a 10-year period and found that maximum humidity overnight was significantly lower in the Northwest Territories than at lower latitudes. As expected, maximum overnight temperatures were higher at high latitudes, reflecting the absence of the long, cool, moist nights that are common in the south. Both Kiil and Quintilio (1975) and Ward and Mawdsley (2000) noted that northern fires are known to burn with high intensity around the clock, presumably because of the combined effects of lack of recovery of fuel moisture and ambient weather conditions conducive to rapid fire spread.

According to Van Wagner (1987), the above discrepancies were not judged serious enough to warrant an official recommendation that procedures be revised to adjust the basic observation time for latitude, since the standard daily FFMC measures peak flammability reasonably well at all latitudes.

However, one other factor contributes to the underprediction by the FFMC of daily peak fire danger conditions north of 60° latitude during high summer. In the Yukon Territory and the Northwest Territories, the basic observation time of 1200 LST can deviate significantly from "sun noon" (Paul 1974) because of regional adoption of politically rather than geographically based time zones and the longitudinal location of fire weather stations within the time zones.

Inuvik, N.W.T., offers a good example. Located geographically near the Arctic coast and just east of the Yukon's eastern boundary, Inuvik lies two universal time zones west (i.e., behind) the political time zone of mountain standard time (MST) in which it functions. Universal time (UT) is defined as "the time of the zone centred on the zero (prime) meridian through Greenwich, U.K., with each of the other time zones a definite number of hours ahead or behind UT to a total of 12 hours" (Dominion Bureau of Statistics 1971). As such, 2000 Greenwich Mean Time (GMT) or 20 z corresponds to mountain standard time of 1300 (i.e., z minus 7 h). Even the Pacific standard time (PST) zone (z minus 8 h) in which British Columbia and Yukon function is geographically too far to the east, on the basis of universal time (UT) zones, to capture Inuvik. Inuvik, as well as most of the Yukon, lie geographically in a z minus 9 h time zone that is simply not used in Canada.

The UT zones are the idealized 24 time zones that resulted when standard time was established at a world conference held in Washington, D.C., in 1884. Ideally, each time zone covers an area defined by two meridians of longitude 15° apart. However, in practice, because of political and geographic considerations, the boundaries of individual time zones are extremely irregular, exemplified by the pronounced extent to which the Yukon and Northwest Territories fall within geographically "incorrect" time zones. The territory of Nunavut is unaffected, as western Nunavut operates in the mountain time zone and the central portion of the territory operates in the central time zone, essentially a "political" match to the correct geographic time zones.

The following compromise is recommended to the problem of Yukon and the Northwest Territories operating one and two time zones, respectively, ahead of what geography alone would dictate: for these two territories, basic observation time for fire weather should be moved ahead by 1 h, to 1300 PST for Yukon and to 1300 MST for the Northwest Territories. Although communities in the northwest portion of the Northwest Territories (such as Inuvik) could justify a 2-h adjustment of basic observation time, it is assumed that such a change would introduce additional problems, such as marked delays in the availability of fire danger information and significant changes to long-standing calibrations of FWI System components.

Recording Practices

The standard noon weather observations (rain, temperature, relative humidity, and wind) and the FWI System calculations should be recorded daily on a permanent monthly form. One such form for manually recording weather observations and table-based FWI System calculations is provided on the inside back cover of the FWI System tables (Canadian Forest Service 1984). However, that form does not contain columns for remarks or other weather variables, such as cloud cover, visibility, and maximum and minimum temperatures. These data, which are of value to fire weather forecasters, may be added to forms and the relevant collection procedures may be specified by regional fire weather authorities.

Precision Standards and Accuracy of Measurement

The terms accuracy, precision, and sensitivity are all used from time to time in connection with fire weather measurements and danger rating scales. A few words of explanation may clear up confusion among them.

The accuracy of a measurement is related to the instrument or technique of measurement. When an instrument is described as having an accuracy of ± 5 units, this generally means that a series of measurements of some constant property made with the instrument were mostly (95% of the time) within 5 units of the correct value.

Precision is concerned with the size of the unit (or the number of decimal places) used in taking and recording a given measurement. To say that a given length is 6 m implies that

the true measurement lies somewhere between 5.5 and 6.5 m. The same length expressed as 600 cm implies a precision of 1 cm (i.e., the measurement fell between 599.5 and 600.5). Precision may be expressed as a fraction (e.g., 0.5 °C) or as a round number (5%).

In general, to take full advantage of the accuracy of a particular measuring system, the precision is specified to the next whole unit below the range of accuracy of the equipment. For example, relative humidity is normally measured and recorded to the nearest whole percent, even though the accuracy of the equipment may be $\pm 5\%$.

Sensitivity relates to the amount of change in a measurement or a derived index that is produced by a given change in the property being measured or in one of the component factors. As such, sensitivity is a relative property. For example, some types of relative humidity sensor are more sensitive to changes in relative humidity at lower values than they are near saturation.

Precision standards for recording, and the accuracy of weather instruments required for measuring temperature, relative humidity, wind and rain as inputs to the CFFDRS are specified in the subsections immediately following, while sensitivity of calculated CFFDRS components to weather changes is discussed in its own section.

Temperature

The FWI System tables (Canadian Forest Service 1984) offer the following instruction for measuring temperature:

Observe the dry-bulb and wet-bulb temperatures, using ventilated thermometers, and record to at least the nearest one-half (0.5) degree Celsius. The preferred instrument is an electric fan psychrometer housed in a Stevenson screen.

These instructions reflect the normal precision required for dry-bulb temperature observations for FWI System calculations, which is the nearest 0.5 °C. The accuracy of the thermometers or temperature sensors should therefore be better than this (i.e., they should be accurate to ± 0.1 °C).

Wet-bulb temperatures are measured to the same precision, with thermometers having comparable accuracy and response time to those used for dry-bulb temperatures.

A precision of ± 0.5 °C for the wet- and dry-bulb temperatures leads to a precision of ± 1 °C in the wet-bulb depression, such that calculated values of relative humidity from Table 10 in the standard FWI System tables (Canadian Forest Service 1984) are significant only to the nearest 5%.

Relative Humidity

The FWI System tables (Canadian Forest Service 1984) give the following instructions for measuring relative humidity:

Determine the relative humidity from dry-bulb and wet-bulb temperatures and record to the nearest percent. Three RH tables are included in this publication for use within the following elevation ranges:

RH Table	Elevation (m)
10A	0 to 305
10B	306 to 760
10C	761 and higher

Use the table appropriate for the station elevation.

The general accuracy of RH values determined from ventilated wet- and dry-bulb temperatures will be well within the requirements for fire weather, provided the thermometers are accurate to the limits specified in the previous section.

Relative humidity values taken from recording hygrographs are generally significant only to the nearest 5%, provided conditions are not changing rapidly. As for calculated values of relative humidity, hygrograph readings may be recorded to the nearest percent.

Electric fan psychrometers, either within a Stevenson screen or as portable models, should be run for at least 20 s before any measurements are taken, to be sure that the full wet-bulb depression has been reached. Sling psychrometers must be twirled for at least 20 s to ensure that constant values have been reached before temperatures are read (first the wet-bulb and then the dry-bulb temperatures). Care must be taken to shield the unit from direct sun when twirling and taking readings.

Wind

The FWI System Tables (Canadian Forest Service 1984) give the following instructions for measuring wind:

Measure and average wind speed over at least a 10-minute period and record to the nearest whole km/h. Wind speed should be measured with a cup-type counting anemometer, not with an instantaneous wind indicator. Preferably, the anemometer should be located in the open at a height of 10 m above the ground.

Interpretation:

As noted in these instructions, wind is usually measured by a wind vane and cup or a propeller anemometer. Wind speed should be recorded as an average of the preceding 10 min of observations. Modern wind-measuring systems contain not only the sensors but also a processing and recording system that takes care of the averaging and which may also compute standard deviations, extremes, and gustiness. Peak gust is the maximum observed wind speed over a specified time interval (e.g., the last full hour in an hourly weather reporting system). Anemometers should have a response length of less than 5 m, which is a measure of the equipment's responsiveness to a change in wind speed. The 10-min averages of wind speed should be based on 0.25-s samples.

As mentioned in the subsection "Supplementary Weather Elements" in the section "Elements of Fire Weather," wind direction is a required input to the FBP System; as such, it has become a standard weather observation at fire weather stations. Wind direction should be reported in degrees, to the nearest full degree. As with wind speed, recorded wind direction should represent a 10-min average. Wind direction is defined as the direction from which the wind blows, measured clockwise from geographic north (i.e., true north). Wind direction should be measured with an accuracy of 5°.

Rain

The FWI System Tables (Canadian Forest Service 1984) provide the following instructions for measuring rain:

Measure the rain accumulated in the 24-hour period from noon to noon, and record to the nearest one-fifth (0.2) mm. Locate the rain gauge on the ground in the open.

In the case of snow, measure the average depth in cm and record the water equivalent as the same number of mm. For example 2.4 cm of snow is reported as 2.4 mm of rain.

These instructions specify that rainfall is to be measured with a precision of at least 0.2 mm.

In practice, even though the accuracy of tipping-bucket rain gauges or manually interpreted rain-gauge graduates is 0.2 mm, rainfall is recorded to the nearest 0.1 mm (i.e., the next smaller unit of precision below the accuracy of the equipment).

In the case of snow or hail and when it is reasonable to suppose that the amount collected in the rain gauge is an accurate sample, the actual depth of the meltwater is used. For heavier snowfalls or hailstorms, when the gauge typically cannot catch a representative sample, an average value of the depth of snow or hail on the ground should be measured with a ruler to at least the nearest 0.2 cm.

Sudden Weather Changes during the Afternoon

Account must be taken of the sudden weather changes that frequently occur on summer afternoons; otherwise, the abrupt changes in relative humidity or wind or the occurrence of afternoon showers after calculation of the FWI System components will result in misleading information. Up to 1600 LDT, it is acceptable to create a revised index for the day to reflect more accurately the new weather regime. In this situation, a new set of weather observations should be obtained and the FWI System components recalculated. For the purposes of this supplementary calculation, the values calculated at noon are ignored, and new values of FFMC, DMC, and DC are calculated, using the previous day's values as the starting fuel moisture codes. The amounts of rainfall used in the calculations should include any rain that has fallen since noon. This rainfall must also be included in the 24-h amount at the next regular observation, but it is the noon fuel moisture codes that are carried over to the next day's calculations.

Extended periods of fog or low cloud are reflected in the index calculations only by the associated high relative humidity and low temperature at observation time. As long as the fog is present, the moisture codes may not fully represent the true moisture content of the fuel complex, but after one full drying period, the moisture codes will be correct. If fog is consistently present at the noon observation time but clears within an hour or so, follow the procedure outlined above, but use observations taken after the fog has cleared.

For recording purposes, the value at noon remains the standard observation for the day.

This will normally provide the values from which the next day's codes are calculated.

One basic assumption in the development of the FWI System is that the component weather elements follow a more or less typical diurnal pattern, at least from late morning through late afternoon (Fig. 4). However, in some locations, the regular pattern is distinctly different from the norm. Stations subject to strong sea breezes or valley winds, which pick up after noon, present special problems. Valley bottoms or coastal strips subject to morning fog that persists until noon are best handled by taking additional observations.

If hourly weather observations are available, it is possible to calculate FFMC for every hour around the clock using a computer program such as that described by Van Wagner (1977). Hourly FFMC is recommended to establish diurnal patterns of fire danger for unusual situations created by latitude, elevation, coastal or valley winds, or other factors.

Seasonal Start-up and Shut-down of Calculations

The FWI System tables (Canadian Forest Service 1984) provide the following guidance on starting seasonal recording of weather elements:

Start the daily record as soon as there is measurable fire danger in the spring. The exact date and starting values of FFMC, DMC and DC will normally be provided by the appropriate fire weather authorities. In the absence of such direction, choose the starting date according to the following criteria:

- (a) In regions normally covered by snow during the winter, begin calculations on the third day after snow has essentially left the area to which the fire danger rating applies.
- (b) In regions where snow cover is not a significant feature, begin calculations on the third successive day that noon temperatures of 12 °C or higher have been recorded.

In either case, use the following starting values:

FFMC 85; DMC 6; DC 15

These values should not be applied to late-starting stations. Contact the fire weather authority for instructions.

These instructions take into account the fact that data may be required for supplementary stations that cannot be put into operation at the beginning of the season. In such cases, the regional fire weather authority should be contacted for an estimate of the start-up code values to be used, particularly for DMC and DC. An incorrect guess for the start-up FFMC will correct itself after about three days of recording. Do not assume automatically that the DMC and DC for a particular location will begin at standard start-up values. For late-starting stations, the start-up values of these two codes will generally use the current values of DMC and DC from one or more nearby representative stations.

For stations starting up at the beginning of the fire season or later in the spring or summer, the DC value may have to be adjusted for deficiency in precipitation over the winter. The procedure is complicated (see subsection entitled "Overwintering the Drought Code" within the section "Drought"), but the regional fire weather authority will generally be able to provide the necessary over-winter adjustment for the DC starting value.

The FWI System tables (Canadian Forest Service 1984) also provide guidance on closing down weather element recording for the season:

Closing dates for fire danger calculations will normally be supplied by regional fire weather authorities. In the absence of such direction, it is recommended that observations and calculations be continued until snow covers the ground. Otherwise, the tables provide for the calculation of the components of the FWI System until the end of November.

These instructions for closing down observations do not discuss a situation that may occur in the northern hemisphere, in which snow cover is absent after November 30 and noon temperatures in December remain above 12 °C; under these conditions and in the absence of rain, active drying of fuel may still be occurring. In this case, daily observations and calculations should continue until snow covers the ground or noon temperatures drop below 12 °C for three consecutive days.

Missing Observations

The FWI System tables (Canadian Forest Service 1984) include the following information about dealing with missing observations:

The FWI System requires an unbroken daily weather record. Days when observations are missed cannot be ignored; the best possible estimate of the missing weather observations is necessary to preserve the continuity of the fuel moisture codes. By one means or another, therefore, blank spaces in the daily weather record must be completed.

In the case of days when observations are missed, contact the fire weather authorities for instructions. In the absence of direction, complete the daily record by one of the following methods, and circle the estimated weather observation(s) on the record form.

- (a) use values from recording instruments if available on site;
- (b) use average of values from one or more nearby similar stations;
- (c) use average of values from day before and day after; or
- (d) estimate values from knowledge of recent weather pattern.

These instructions apply to days when observations are unavoidably missed because of equipment breakdown or for some other reason. Given that gaps in the record mean a loss of accuracy in the calculation of FWI System components, these gaps should be minimized. The following procedure represents a consistent method of using available information to minimize the errors caused by missing observations.

1. Measure total rainfall on the day after the day (or period) of missed observations, and do your best to assign reasonable portions of that total to each day for which observations are missing (including the day of measurement). Check the record for relative humidity (using the hygromograph chart or the hourly relative humidity record, if available) to help estimate the timing of rainfall and thus to determine if all of the recorded rainfall fell on one day.
2. Estimate the noon (or 1300 LDT) relative humidity and temperature from the hygromograph chart, if available.
3. Assume the wind to be in the 4–13 km/h class for the FFMC calculation, unless you have good reason to suspect that it should be in one of the other classes.
4. After making the necessary estimates of rainfall, temperature, relative humidity,

and wind speed, calculate the codes and indices for each missing day as you would have done if the observations had been obtained in the regular way.

The following points should be remembered when missing data are generated in this way:

- A common error is to treat days with missing data as if they did not exist, using the moisture code values for the last day before the gap as the starting point for calculations on the next day of observations. This results in misleading (either low or high) values of DMC and DC. To avoid this problem, separate calculations must always be performed for each missing day, based on the best possible estimate for each required weather element.
- If the procedures described above are not feasible, because a hygrothermograph is lacking or because the instrument has had a breakdown, try to get missing observations from the nearest weather station or, even better, average the values from several stations.
- Estimated values for wind and distribution of rain are usually adequate for the bookkeeping required to keep track of the moisture codes. However, the values of ISI and FWI calculated for those days may be subject to large errors and should be treated with caution.

Effect of Surrounding Terrain on Measured Wind Speed

Although applicable to the midafternoon peak fire danger period, the weather elements used to forecast the FWI System components are for noon LST. Of the four key weather elements (rain, temperature, relative humidity, and wind), wind speed is the most difficult to forecast. Moreover, for forestry purposes, the forecasted wind velocity used for predicting fire danger is necessarily lower than what is prepared for public forecasts, as explained below.

The roughness of ground and vegetation surfaces affects wind speed, turbulence, and gustiness to a height of 600 m or so above mean ground level, depending on atmospheric stability. Wind at the top of this friction layer is called the "gradient" or "free-air" wind.

A typical comparison of how surface roughness reduces wind speed near the earth's surface would involve observations from a 10-m mast located in an open grassy field and observations from an opening surrounded by a forest of 15-m pines. The anemometer in the open field is expected to record a wind speed of about 60% of the gradient wind, whereas only about 36% of the gradient wind speed would be measured in the opening surrounded by pine stands. Cities and urban areas in general are associated with an even greater reduction in wind speed. Because of the scale of roughness of houses and commercial buildings, a standard anemometer will show only about 23% of the gradient wind if located in an opening surrounded by such structures.

For a weather station clearing that is surrounded by a 15-m pine stand, these relations mean that the measured wind speed would be only about 60% of that measured 10 m above a large grassy field, assuming the same pressure gradient. Similarly, an anemometer located in an opening in an urban setting would measure only about 40% of the wind speed measured over open fields. These relations are shown in Figure 5 and are illustrated by the following example (from Turner and Lawson 1978):

Gradient wind at 600 m = 64 km/h

Wind at 10 m above extensive open grassland
($0.60 \times 64 \text{ km/h}$) = 38 km/h

Wind at 10 m in opening surrounded by
15-m pine stand
($0.36 \times 64 \text{ km/h}$ or $0.60 \times 38 \text{ km/h}$) = 23 km/h

Wind at 10 m in opening surrounded by city
buildings
($0.23 \times 64 \text{ km/h}$ or $0.40 \times 38 \text{ km/h}$) = 15 km/h

Although the percentage reductions in wind speed owing to surface roughness are subject to wide variations, they can be regarded as typical. Many airport locations give similar wind speed ratios compared to gradient winds as open fields compared to openings surrounded by pine stands, as given here (Simard 1971). A generally acceptable rule of thumb for calculations in the FWI System is to multiply the wind speed measured at an airport by 60% so that they are comparable to winds measured in a forest opening.

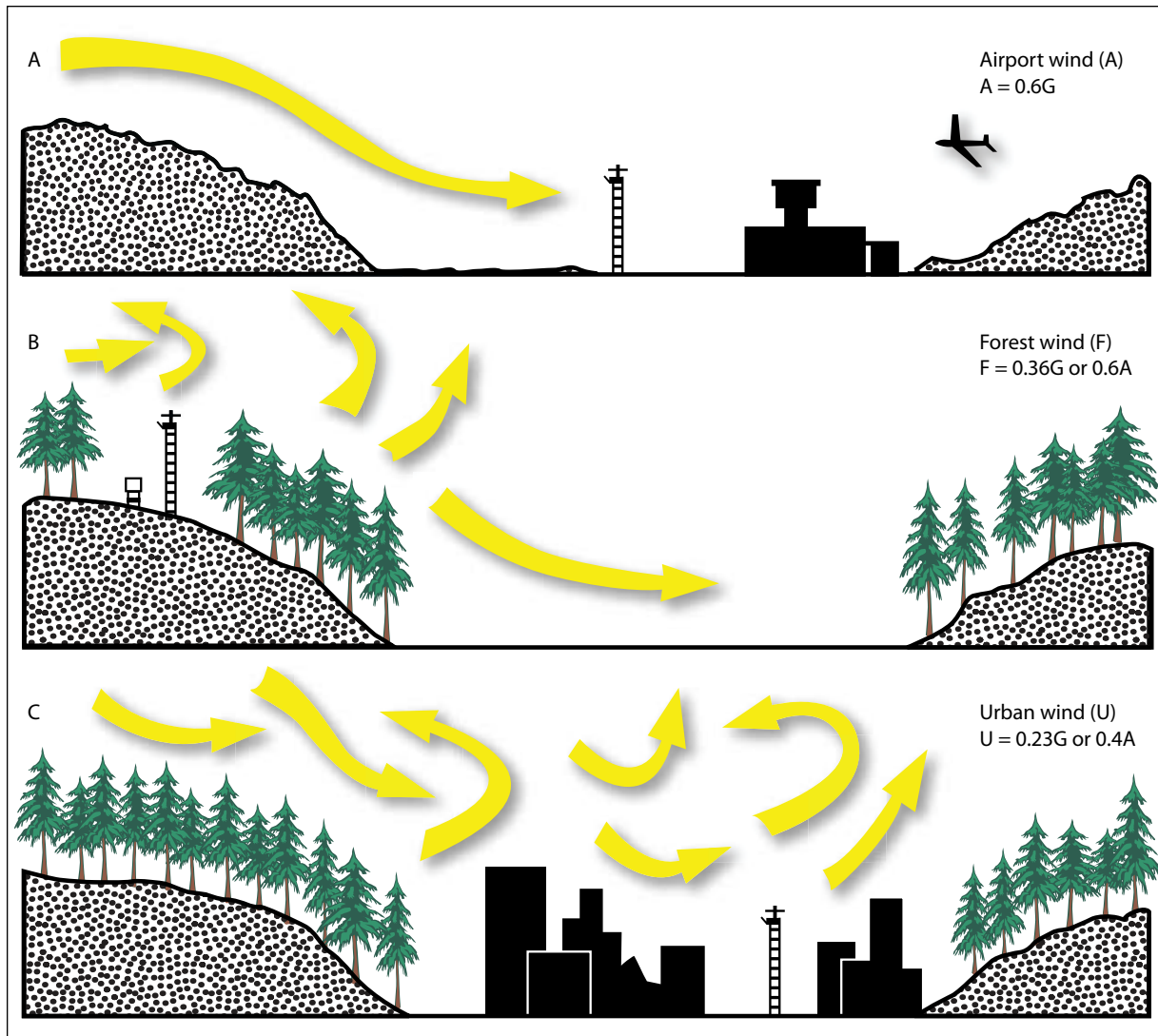


Figure 5. Reduction of surface wind speeds according to roughness of surrounding terrain. (A) Airport wind in relatively smooth open grassland. (B) Typical forest wind, where surrounding timber slows the wind and creates turbulence. (C) Wind in a city opening, which is further reduced by surface roughness. G = gradient wind (adapted from Turner and Lawson [1978].)

FIRE WEATHER STATIONS

Location Standards

In general, the standards for Canadian fire weather stations conform with those recommended by the WMO for agrometeorologic observations in forest areas (WMO 1968). The standards are designed to give representative values of the various weather elements; unfortunately, however, it is not usually possible to meet all of these standards in practice. Nonetheless, every effort should be made to do so, since any major deviation can reduce the accuracy of the FWI System components.

Ideally, the location of the fire weather station should have the following characteristics:

- representative of the general area of concern with respect to topography, vegetative cover, and local weather patterns, with avoidance of sheltered valleys and exposed peaks and ridge tops, a preference for level or nearly level ground (Fig. 6) (or, if slopes must be used, avoidance of shaded and east-facing slopes), and avoidance of concave (dish-shaped) landforms;
- at the center of a forest clearing with diameter no less than 10 times the height of the surrounding timber;
- no closer than 100 m to any major source of moisture, such as a lake, stream, swamp, or irrigated area;

- no closer than 10 m (or, in the case of buildings, no closer than a distance equal to twice the height of the building) from large reflecting or radiating surfaces, such as metal or white-painted buildings, black-topped or graveled parking lots, rock outcrops, and recently burned areas;
- no closer than a distance equal to 1.5 times the height of the obstruction from any large building, tree, or vegetation;
- no closer than 5 m from any road; and
- at least 50 m away from excessively dusty areas (which can usually be avoided by checking dust accumulation on nearby vegetation).

If the prevailing wind direction during fair weather is known for the area, the station should be located on the windward side of any sources of moisture, reflection, radiation, or dust.

It is good practice to arrange the instruments in a fenced enclosure at least 7 m × 7 m. The type of fencing is subject to regional specifications but should be of wire or open-pole construction suitable for safeguarding the equipment and not more than 1.2 m high. The ground area inside the fence should consist of mown grass or cropped natural vegetation. When located in a logged area, the enclosure should be cleared of logs and branches.



Figure 6. Fire weather station in large clearing on open level ground. Photo courtesy of Ember Research Services Ltd.

Instrumentation

This weather guide does not describe the maintenance of specific meteorological instruments used for fire weather observations. Such specifications, which are too detailed for a user's guide of this type, are available in other publications (British Columbia Forest Service 1969; Ontario Ministry of Natural Resources 1974; Environment Canada 1977; Finklin and Fischer 1990; WMO 2006); guidance may also be available from regional fire weather authorities.

Instrument Shelters

Thermometers and recording instruments such as hygrothermographs must be housed in a white-painted, wooden Stevenson-type screen with double-louvered sides and double roof (Fig. 7). The screen should be solidly mounted, with the floor 115 cm above ground level and the door opening to the north in the northern hemisphere or to the south in the southern hemisphere. The shelter should be mounted on a rigid but open framework of posts, not on a solid base such as a stump.



Figure 7. Stevenson screen, on an open framework stand that is staked to the ground. The floor of the unit is 115 cm above ground. The white-painted double-louvered wooden door faces north on this unit, which is located in the northern hemisphere. Photo courtesy of British Columbia Ministry of Forests and Range, Protection Branch.

Instrument screens should be large enough to properly house the equipment they are designed to shelter. Auxiliary equipment not requiring this kind of screen (e.g., data loggers) should be housed in a separate box. It is particularly important that screens be kept painted and in good repair. In particular, they must be kept free of dust and dirt, both inside and outside.

Although it is possible to specify short response times for the thermometers and electronic temperature and relative humidity sensors used in automatic weather stations,

these are usually overridden by the response time of the instrument shelter. Typical response times are about 10 minutes for shelters in forest clearings, which is adequate for fire weather purposes.

Small, white, louvered radiation shields for the temperature and relative humidity sensors used in automatic weather stations generally have response times of a few minutes, suited to the shorter response times of electronic capacitance-type relative humidity sensors.

Equipment for Measuring Temperature and Relative Humidity

The dry- and wet-bulb thermometers used for determining relative humidity should have an accuracy of ± 0.1 °C. They must be adequately

ventilated, preferably by a motor-driven fan with the capacity to deliver air past the two thermometer bulbs with a velocity of at least 3 m/s. One type of an electric fan psychrometer is shown in Figure 8.



Figure 8. Portable electric fan psychrometer, with battery-powered fan and wet-and dry-bulb thermometers. Photo courtesy of British Columbia Ministry of Forests and Range, Protection Branch.

Dry- and wet-bulb readings may be taken with a good portable psychrometer with a battery-operated fan or with a sling psychrometer large enough to provide the necessary precision. The wicking for the wet-bulb thermometer must be clean and should be replaced several times a season. Clean, mineral-free water or distilled water should be used to wet the wick.

The hygrothermograph is an instrument that records temperature and relative humidity on the same chart (Fig. 9). The thermograph component should be capable of an accuracy of ± 0.5 °C and should have a time constant on the order of several minutes or less. The hygrograph component should be accurate to less than 5%

under steady conditions, where the relative humidity is not changing rapidly. The hairs should be arranged to have a short response time at normal operating temperatures. The instrument should not have any significant temperature coefficient or, if it does have one, the correction factor should be known and should be applied to the readings.

In practice, hygrothermographs may be quite inaccurate, especially at low relative humidity, where accuracy is critical. Therefore, it is useful to compare hygrothermograph chart readings with relative humidity determined by a sling or electric fan psychrometer.



Figure 9. Hygrothermograph mounted in separate screen with double-louvered sides and double roof. Photo courtesy of British Columbia Ministry of Forests and Range, Protection Branch.

Equipment for Measuring Wind

To meet the WMO standards on which the FWI System is based, the anemometer should be mounted on a substantial, well-guyed mast, with provision for climbing with safety or for lowering the anemometer head when servicing is required. Provision for lightning protection is highly recommended.

The three-cup anemometer, with its ruggedness and reliability, is well suited to fire danger measurements. It is a simple matter to electronically count the number of meters of wind that pass the cups in the basic 10-min period.

Accuracy depends on proper maintenance of the cups (which should be round, free of dents or holes, and turning freely on the shaft), the counter or recorder, and the power supply.

Wind speed increases rapidly in the layers just above the ground and is strongly influenced by nearby obstructions. The standard height for an anemometer over open, level ground is 10 m, and this height is acceptable in a clearing if the nearest timber edge is more than five times the average height of the trees away from the mast (Fig. 10).

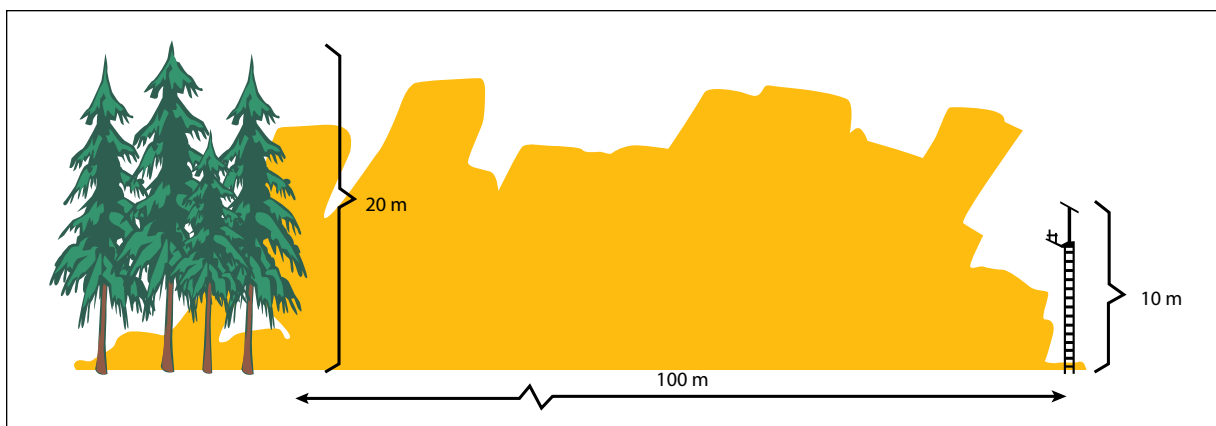


Figure 10. Standard anemometer height: 10 m, if the clearing is large enough that nearest timber edge is a distance of at least 5 times the height of the trees away from the mast (figure not to scale) (adapted from Turner and Lawson [1978]).

Clearings of this size are difficult to find, and an alternative is often required. One possibility is to use a taller mast, but such masts cost more and may not be as safe as 10-m masts. If no clearing is available at all, the correct mast height would be 10 m above the mean treetop level. However, smaller clearings are usually available, and the corresponding anemometer height would be somewhere between the "open ground" value of 10 m and the "closed canopy" requirement of tree height plus 10 m.

Table 7 gives the recommended height of the anemometer on the basis of the average distance from the timber edge and the average

stand height. For example, if the mast could be located 50 m from the edge of a stand of trees 20 m tall, the anemometer should be located 16.5 m above open, level ground.

Table 7 assumes that the clearing is more or less flat. If that is not the case, and the clearing contains many large irregularities, such as hummocks, clumps of brush, or slash piles, the effective ground level must be raised from the actual ground level by an amount equal to three-quarters of the average height of the irregularities. The anemometer height should be measured from this level (Fig. 11).

Table 7. Recommended height of anemometer for small clearings

	Average stand height (m)										
	5	10	15	20	25	30	35	40	45	50	
Average distance from timber edge (m)	5	14.2	Mast height = tree height + 10 m								
	10	12.4	18.4	23.8							
	15	11.0	16.7	22.6	28.1	33.2	38.7	43.8	48.9		
	20	10.3	14.9	20.9	26.7	32.2	37.7	42.9	48.2	53.3	58.5
	25		13.2	19.9	25.1	30.9	36.7	42.1	47.4	52.6	57.8
	50			12.1	16.5	22.2	28.2	34.1	40.2	45.8	51.8
	100					11.4	14.1	18.4	23.0	28.6	34.4
	150		Mast height = 10 m					11.3	13.2	16.2	19.8
	200								11.4	12.8	

Adapted from Turner and Lawson (1978).

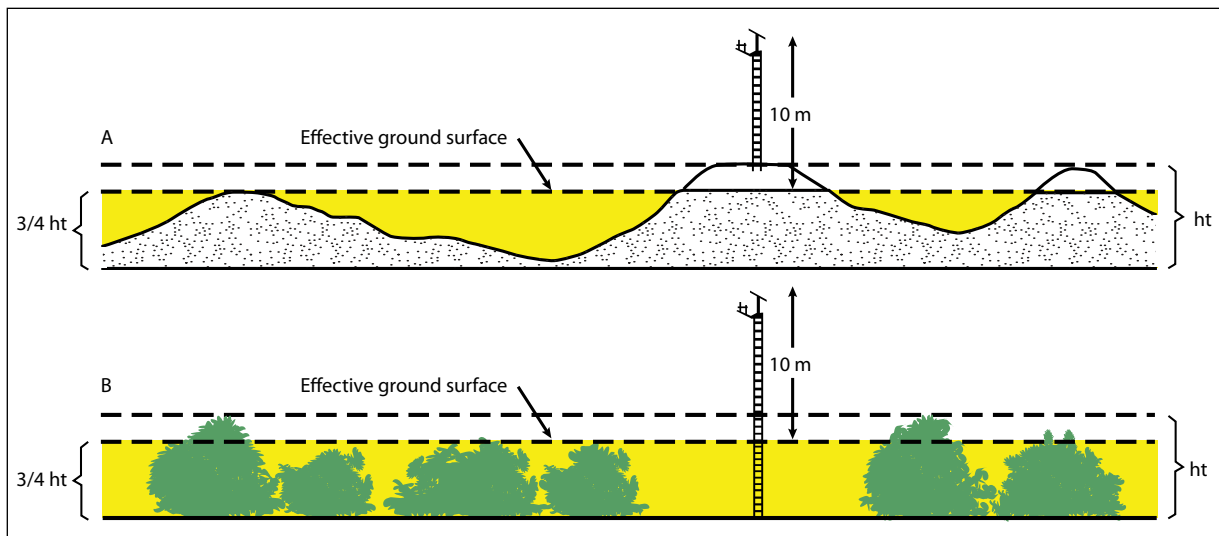


Figure 11. Anemometer height adjusted for uneven ground or brush. (A) clearing with uneven ground, where ht is the height difference in metres between valley bottom and highest ridge in the clearing. (B) clearing with brush clumps, where ht is the height in metres of the tallest brush clump (adapted from Turner and Lawson [1978]).

In Figure 11A, the anemometer is mounted in a clearing in rough terrain. The sensor should be 10 m above a representative high spot, determined by taking three-quarters of the difference in the height between ridges and valleys. If the anemometer is mounted in a clearing covered with clumps of brush 2 m high, as in Figure 11B, the mast should be at 11.5 m, i.e., $10\text{ m} + (3/4 \times 2\text{ m}) = 10\text{ m} + 1.5\text{ m}$.

Equipment for Measuring Rain

Rain may be measured with any suitable gauge, provided the collecting area is rigid enough to be constant and the depth to the funnel is adequate to prevent splashing. The gauge must be rigidly mounted, and the top surface of the collecting funnel must be level. The usual mounting height for a rain gauge positions the orifice above the maximum expected depth of snow cover and above the height of any significant potential inward splashing from the ground. Such criteria generally result in the gauge orifice being positioned between 0.5 and 1.5 m above ground (WMO 2006). Lower mounting could result in errors caused by splashing, whereas higher mounting could result in reductions in the amount of rain collected because of turbulence (unless the gauge is equipped with a properly designed windshield).

The gauge should be located so that no obstruction is closer to it than twice the height of the obstruction. Mast guy wires, which could drip into the gauge, should be avoided.

Rain gauges must have a dent-free collecting surface between 60 and 300 cm². Manual gauges may incorporate a calibrated dipstick or collecting cylinder, but the graduate designed for the particular instrument must be used.

Automatic recording rain gauges, with a tipping bucket, are commonly used in automatic weather stations. To comply with the specified measurement accuracy (0.2 mm), the tipping bucket should tip for at most each 0.2 mm of rain. Routine maintenance should include cleaning the funnel and buckets of dirt and debris as needed and ensuring that the gauge is level.

Automatic Weather Stations

The WMO (2006) defines an automatic weather station as a meteorological station at which observations are made and transmitted automatically. At such weather stations (e.g., Fig. 12), the measurements from each instrument are read out or received by a central data acquisition unit. The data collected from the autonomous measuring devices can be processed locally at the automatic weather station or elsewhere (e.g., by the network's central processor). An automatic weather station may be designed as an integrated complex of measuring devices combined with the data acquisition and processing unit.

Automatic weather stations increase the number and reliability of surface observations in a number of ways (WMO 2006):

- by increasing the density of an existing network through provision of data from new sites and from sites that are difficult to access;
- by supplying, for manned stations, data outside normal working hours;
- by increasing the reliability of measurements through sophisticated technology and modern digital measurement techniques;
- by ensuring homogeneity of networks through standardization of measuring techniques;
- by satisfying the need for new types of observations;
- by reducing human error;
- by lowering operational costs through a reduction in the number of observers; and
- by measuring and reporting with high frequency or continuously.

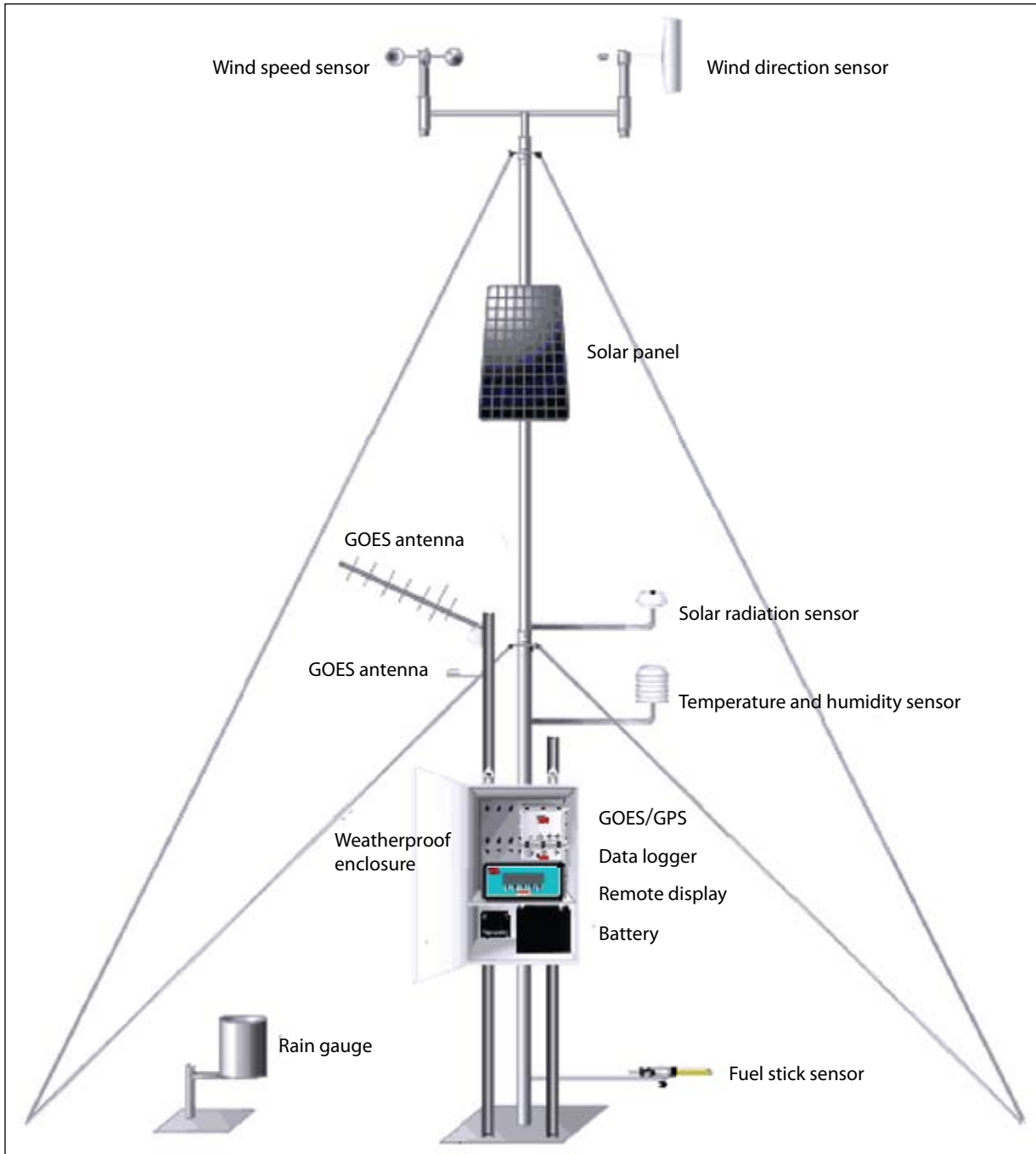


Figure 12. Automatic fire weather station showing typical configuration of sensors, power supply, data storage, and communication. Solar radiation and fuel stick sensors collect data not required by the Canadian Forest Fire Danger Rating System. Standard height for wind speed and wind direction sensors is 10 m. GOES = Geostationary Operational Environmental Satellite, GPS = global positioning system. (Diagram courtesy of Forest Technology Systems Ltd.)

Any automatic weather stations that are to be used in generating the FWI System components for fire danger rating and the fire behavior prediction components of the CFFDRS must meet the measurement accuracy standards specified in this weather guide. When considering the introduction of new automated instrument systems, the managers of forest fire weather networks should introduce into service only those systems that are sufficiently well documented to provide adequate assurance of their capabilities, characteristics, and algorithms. It is equally important to develop or subscribe to adequate programs for maintenance and calibration support for such weather stations (WMO 2006). Furthermore, automatic weather stations usually form part of a network of meteorological stations (see the subsection entitled "Fire Weather Station Networks," immediately below), each transmitting its processed data to a central system by various means; because the central processing tasks are strongly related and complementary to the tasks of the automatic weather stations, the technical requirements of both the central system and the automated station must be well coordinated.

The hardware and software for automatic weather stations has been described in detail by the WMO (2006), so only a few highlights are discussed here.

Sensors

The meteorological requirements for sensors at automatic weather stations are not very different from those required at manual observation stations. The sensors must be robust, require little or no maintenance, and be without bias or uncertainty in the way in which they sample the weather variables. In general, any sensor with an electrical output is a suitable candidate, whether analog, digital, or "intelligent" (i.e., including a microprocessor that provides output in serial digital or parallel form).

Temperature: The most common type of thermometers used in automatic weather stations are pure metal resistance thermometers or thermistors; platinum is preferred. Proper radiation shielding of thermistors is critical. At an automatic weather station, radiation shields adjusted to the size of the sensor typically replace the naturally ventilated Stevenson screen. Air temperature should be reported as 1-min averages. For the calculation of FWI System components, air temperature should be calculated as a 10-min average of instantaneous readings taken immediately before the hourly reporting time.

Relative humidity: Relatively low-cost resistance and capacitance sensors for direct measurement of relative humidity are widely used in automatic weather stations, but they are subject to poor performance in the presence of pollutants and require special protection filters. Additional corrections must be applied for measurements below 0°C (even if the sensors incorporate temperature compensation circuits) and if hysteresis problems occur when the sensor is exposed to saturated conditions. The problems associated with the short time constant of many humidity sensors are more critical than is the case for temperature sensors. As for temperature sensors, relative humidity sensors must be installed within proper radiation shields. Although the WMO (2006) recommends artificial ventilation or aspiration for radiation shields, the problems associated with aspiration shields may outweigh the small improvement in accuracy. Radiation shields in automatic weather stations are not usually aspirated, but rather are naturally ventilated. For the calculation of FWI System components, relative humidity should be reported as 10-min averages from 600 samples (assuming a sampling rate of once per second).

Wind: The use of conventional cup or propeller anemometers with pulse or frequency output is widespread. The WMO (2006) has defined "response length" as (approximately) the passage of wind (in meters) required for the output of a wind-speed sensor to indicate about 63% of a step-function change of the input speed. For new cup and propeller anemometers, the response length (which is called the "distance constant" by some manufacturers) should be smaller than 5 m. Wind speed measurements should be recorded by a sensor that is accurate to ± 0.4 km/h or 1.5% and should be recorded to the nearest whole number. Wind vanes with an undamped natural response length (or "delay distance") smaller than 10 m and a damping ratio between 0.3 and 0.7 are recommended. Wind vanes should have a specified accuracy of $\pm 5^\circ$ or better. Wind direction should be recorded to the nearest degree. Intelligent wind sensors with a serial digital output and digital displays of the operational variables (peak gust, 2-min and 10-min average wind speed, and wind direction) are now common. For the calculation of FWI System components, wind speed should be calculated as a 10-min average of 600 samples (assuming a sampling rate of once per second) taken immediately before the hourly reporting time. Wind direction should be calculated as a 10-min vector average from 600 samples taken once per second immediately before the hourly reporting time.

Precipitation: Most automatic weather stations use a tipping-bucket rain gauge. Such gauges are rapidly clogged by debris such as leaves, sand, and bird droppings, so problems can arise if the station is left for long periods without maintenance. Power is required to properly heat the gauge for measurements of rain and snow at temperatures below 0 °C, and this requirement can be a problem for battery-operated automatic weather stations. Also, heated gauges introduce errors through evaporation losses. Tipping-bucket rain gauges should achieve an accuracy of 5%. Accuracy can be improved by adding a proper windshield around the gauge. For the calculation of FWI System components, the rain gauge should cumulate continuously, recording both hourly totals and 24-h totals to noon LST.

Fuel temperature and fuel moisture: Some automatic weather stations have optional sensors that measure such variables as the temperature and humidity inside a 1-inch (2.54-cm) diameter ponderosa pine, *Pinus ponderosa* Dougl. ex P. & C. Laws., dowel or the derived moisture content of a 0.5-inch (1.27 cm) diameter ponderosa pine dowel, based on the current between two electrodes attached to the wood surface. Various manufacturers offer these products for automatic measurement of the US NFDRS 10-h time lag fuel moisture. Traditional weighed fuel moisture sticks (100-g oven-dry) have been manufactured for decades from 0.5-inch diameter kiln-dried Douglas-fir, *Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco, and ponderosa pine doweling and have been used widely in western Canada and the United States in wildfire and prescribed fire operations and planning; studies continue to determine their correlation with predicted (from FFMC) and actual litter and fine fuel moisture content (Whitehead et al. 2006).

However, neither fuel temperature nor the weight of a fuel moisture stick is required as input to the CFFDRS, so technical specifications and guidance for the use of these electronic sensors are not provided here.

Central Processing Unit

The core of an automatic weather station is its central processing unit (CPU), which functions as an interface for data acquisition, processing, storage, and transmission. In most automatic weather stations, all of these functions are carried out by one microprocessor-based system installed in a weatherproof enclosure located as close as possible to the sensors. One or more sensors (the data acquisition units) may be connected

to a data processing and/or data transmission unit of the CPU by means of telephone lines that allow digital data transmission.

The data acquisition function consists of scanning sensor output at a predetermined rate and translating the signals into computer-readable format. Parallel digital input and output are generally used for such sensors as wind vanes with Gray code¹ output. Pulse and frequency counters are used for wind speed sensors and tipping-bucket rain gauges. Serial digital ports are used for intelligent sensors.

Data processing within the CPU depends on microprocessors and random access memory (RAM) chips capable of performing complex computations. Programs are entered by way of such devices as nonvolatile, erasable read-only memories, particularly for the storage of constants that can be modified directly by the software. Most automatic weather stations have battery backup to avoid loss of RAM data after power failures. Data are stored in external memories such as RAM cards.

The data may be transmitted from the CPU to the central network processing system or to the direct end user of the weather data or the CFFDRS components through one or more methods, including telephone lines, digital broadband, or radio and satellite telemetry.

Calibration

Sensors with electrical outputs show drifts in accuracy over time, so regular inspection and calibration are needed. Initial calibration is required to ensure that the sensors and the station overall are meeting the manufacturer's specifications and that transportation has not affected the measuring characteristics of the equipment.

In the field, periodic comparison of data recorded by the automatic weather station's sensors with "traveling standards" is essential to control sensor performance. Traveling standards with similar characteristics to those of the sensors in use at the station are preferred.

Maintenance

Any complex system requires maintenance support, and the cost of servicing a network of automatic weather stations can greatly exceed the cost of their purchase. Hardware components

¹ Gray code is a binary coding system in which successive values differ in just one digit.

may fail for many reasons, and computer programs may fail because of design errors that may go undetected for a long time. A well-organized preventive maintenance program, including service and calibration of sensors, is recommended. In general, it is not advisable to repair sensors or other modules in the field. Centrally located technical personnel should be available to repair, replace, calibrate, and service modules and sensors.

Fire Weather Station Networks

Distribution of Stations

There is no hard-and-fast rule for how large an area can be reliably represented by any given FWI System component calculated from data obtained at a single station. In early studies (from the 1940s), the results of which would still apply for eastern and central Canada, index values were highly reliable within a radius of about 40 km, but at distances greater than 160 km, weather conditions were generally so different from the index values as to make calculations based on those values unreliable.

In the Canadian west (British Columbia, Yukon Territory, western Northwest Territories, and the east slopes of Alberta), weather patterns tend to vary from one valley to the next and from one elevation zone to the next. As such, the area accurately represented by a given station is best determined by local knowledge of the terrain and climate. A 10-year study of index values and fire statistics in British Columbia indicated that index values provided useful information on fire activity for fires occurring up to 100 km away.

Stephens and Stitt (1970) provided an equation for the optimum radius of influence (R):

$$R = 1.6(a/n)^{1/2} \quad (1)$$

where a is the area of the region and n is the number of stations in the region. In a study of one Ontario fire region, Flannigan and Wotton (1989) calculated the radius of influence of 145 km using this equation; when they tried different values for the constant (ranging from 1.0 to 2.0), they

found that the station network was insensitive to changes in the radius of influence from 90 to 180 km. Furthermore, Flannigan and Wotton (1989) regarded as unworkable the number of stations that had been identified in early studies as being required to achieve the 40-km radius of influence: in the region they studied, 340 weather stations would have been required.

Weather stations in Canada tend to be unevenly distributed, with fewer stations in northern regions and in the northern parts of regions. This northerly shortage of weather stations reduces the success of interpolation techniques, especially with respect to precipitation. As Flannigan and Wotton (1989) pointed out, the spatial variability of summer precipitation is the largest unknown in interpolating FWI components between weather stations. The current density of fire weather stations does not allow detailed knowledge of precipitation. It may be more cost effective to explore remote sensing options (e.g., by satellite or radar) for quantifying the distribution of precipitation at a regional scale rather than relying on dense networks of complete fire weather stations.

There is also no simple rule for choosing the locations of fire weather stations. Automatic weather stations have eliminated the earlier constraint that stations had to be located where people could attend them daily at a fixed time. Even so, each station should be located where it can best represent the area it is intended to cover, whether that area is tens of thousands of square kilometers for a regional network or a few square kilometers for a particular operating area. Distance may not be the sole factor determining the representativeness of a particular station. In mountainous terrain, differences in topography and elevation can be far more significant in limiting the area represented by a given station. In particular, it is often difficult to relate information from stations in the valley bottom to nearby ridges only a few kilometers away. As such, it may be more appropriate to locate weather stations on midslope benches, rather than on ridge tops or in valley bottoms, particularly if the terrain at the mid-elevations represents critical fire danger situations (Fig. 13).

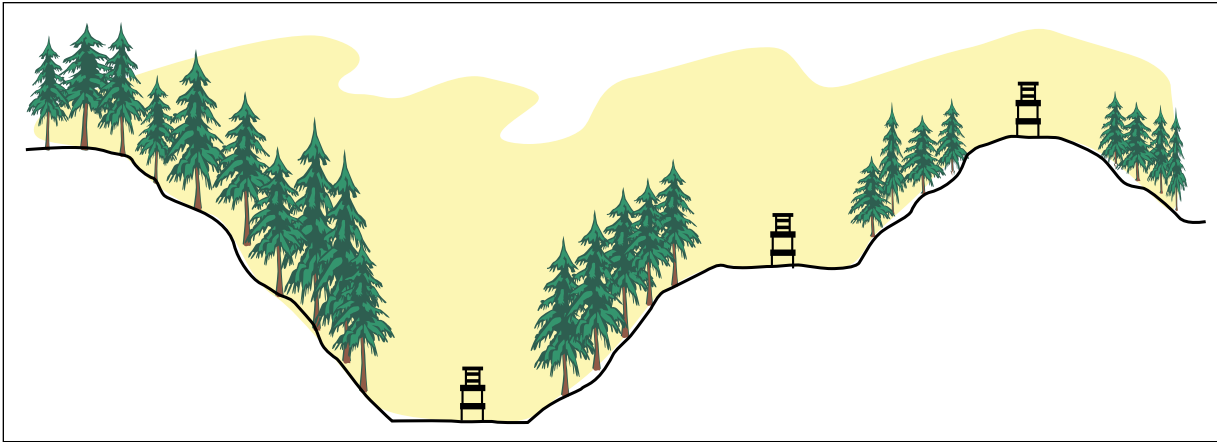


Figure 13. Placement of fire weather stations in hilly or mountainous terrain. Such networks of fire weather stations must take account of the need to represent midslope forests, which may be a problem with valley-bottom or ridge-top stations (adapted from Turner and Lawson [1978]).

Interpolation of Fire Weather Observations

Flannigan and Wotton (1989) investigated interpolation methods applied to fire danger rating in Canada, noting that some agencies divide their areas of responsibility into regions and then into a large number of cells. These cells are described with geographic coordinate systems such as latitude and longitude or the Universal Transverse Mercator (UTM) system. Most cells are squares or rectangles 10–20 km on a side. Each cell is assigned to the most appropriate weather station and given the index values of that weather station. Flannigan and Wotton (1989) regarded such cell assignment as a crude means of interpolating between stations, one that often leads to spurious sharp discontinuities in index values. More sophisticated methods blend information from many locations to estimate FWI component values between stations.

Flannigan and Wotton (1989) evaluated several of these interpolation methods, including second-order least-square polynomial, smoothed cubic spline, and weighted interpolation, for applicability to a region within Ontario. They tried two approaches to the second-order interpolation method: first, simply interpolating the FWI values from the observing stations and second, interpolating 24-h precipitation, temperature, relative humidity, and wind, and then computing the FWI components from existing equations. The authors found that the second-order polynomial, the smoothed cubic spline, and the weighted interpolations were consistently better than the replacement method, in which cells within a region are assigned the FWI value from the nearest appropriate weather station, based on site, topography, proximity to water, and experience. For the second-order method, the

interpolated FWI approach was better than the interpolated weather inputs approach, mainly because of the highly variable nature of the spatial distribution of rainfall amount.

Interpolation of summer rainfall amounts presents a special challenge, because of summer showers, which typically lead to substantial differences in rainfall between nearby stations (e.g., > 15 mm versus none). Generally, the network density of fire weather stations is inadequate for confident interpolation of rainfall amounts. In some regions, radar-interpreted rainfall is available to help in determining the spatial variability of summer rains. Widespread precipitation is associated with well-defined synoptic systems (e.g., lows and troughs), whereas spotty precipitation is associated with isolated showers and thunderstorms. Radar or even satellite data could be used to determine the nature and occurrence of precipitation (Flannigan and Wotton 1989).

Flannigan et al. (1998) compared three methods of interpolating fire danger between weather stations, using radar precipitation estimates from a C-band radar station located at Upsala, Ontario. The first method was the standard practice of interpolating components of the FWI System from a weather station to any specified location. The second method involved interpolating the weather variables (precipitation, temperature, relative humidity, and wind speed) from the weather station to any specified site and then calculating the FWI System components. The third method was the same as the second, except that precipitation was estimated from radar before calculation of the FWI System components for a specified site.

For all three interpolation methods, the cubic spline technique was used.

Overall, the standard method of interpolating FWI System components performed best. However, FFMC and FWI were best determined using the radar precipitation method. For the FFMC, this may have been due to the strong influence of 24-h precipitation amounts greater than 0.5 mm on FFMC, whereas the DMC and DC are affected only when 24-h rainfall exceeds 1.5 and 2.8 mm, respectively. Radar precipitation estimates were significantly lower than actual values, especially at sites farther away from the radar site, which resulted in larger errors for DMC and DC than for FFMC. The authors concluded that this type of radar could be used to best advantage in discriminating between areas with and without precipitation. High errors in ISI from the second and third methods, even though FFMC was predicted well, indicated that wind speed was difficult to interpolate accurately. The authors noted that local factors, such as topography and siting of the anemometer, can strongly influence the observation of local wind speed.

Flannigan et al. (1998) noted that as the density of weather stations increases, the various interpolation methods should work better in estimating fire danger across a region. Conversely, as the density of weather stations decreases, interpolation will yield poorer estimates of fire danger, and the radar-estimated precipitation method for predicting fire danger will perform better than straightforward interpolation.

Flannigan et al. (1998) recommended that fire management agencies continue to interpolate FWI system components for locations between weather stations, noting that radar-based calculations of FFMC and FWI and radar-based estimates of precipitation coverage will both be useful for fire management applications. The newer Doppler radar units, which replaced the C-band radar units, currently installed across Canada should provide better estimates of precipitation amounts and should be examined for their potential usefulness in interpolation of fire danger.

Abbot et al. (2007b) investigated the potential use of RADARSAT-1 images to assess daily variations in dead fuel moisture over a northern boreal forest area, relating radar backscatter to rainfall and finding strong relations with DMC and DC. RADARSAT-1 is a satellite-based synthetic aperture radar system that operates at

frequencies near 5.3 GHz (in the C-band), which is ideal for estimating the near-surface moisture of bare soil and agricultural canopy-cover surfaces. However, mapping fire danger with the C-band requires that radar signals interact with the ground surface beneath the forest canopy, which presents a problem in many forest cover situations, although it is potentially feasible in boreal forests dominated by large burn scars and open canopies.

Abbott et al. (2007b) found strong correlations between calculated DMC and DC values and sampled forest floor moisture contents at a depth of 0–4 cm in both burned and mature boreal forests and, in turn, strong dependence of backscatter on the moisture content of the 0–4 cm fuel layer, as represented by calculated DMC, DC, and BUI values. Stronger correlations were observed for burned forest, which has high backscatter contributions from the ground surface. Backscatter variations related better to 10-day cumulative rainfall amounts than to 1-day accumulations, which indicates that backscatter better detected the moisture of fuels that dried more slowly. Abbott et al. (2007b) concluded that although RADARSAT-1 provides limited information on fuel moisture content and fire danger, the potential of using synthetic aperture radar images for fire danger monitoring will improve when a new generation of radar sensors, such as RADARSAT-2, becomes available; these units will provide multipolarization data with better spatial resolution (up to 3 m).

Interpolation of temperature between weather stations at different elevations can be done in various ways:

- direct interpolation, in which two or more observations are averaged;
- inverse distance weighting, in which station observations are weighted according to the inverse of the distance between the stations and the point of interest;
- use of an environmental lapse rate (see the subsection entitled “Vertical Structure of the Atmosphere” within the section “Weather Not Directly Observable”) to normalize the observed temperatures for the effect of elevation and then averaging or applying inverse distance weighting.

A “virtual weather station” can be created by applying an appropriate lapse rate to an observed temperature, which results in an adjusted value for the elevation difference of interest.

However, it is important to reiterate the recommendations of Flannigan and Wotton (1989) and Flannigan et al. (1998) that, for the spatial estimation of FWI system components, the components must be calculated at the weather stations and then interpolated onto the spatial grid, rather than interpolating the weather variables and then calculating the FWI components at the grid resolution. This preferred method has also been recently recommended for New Zealand (Tait and Zhen 2005), a country that uses the CFFDRS.

Supplementary Fire Weather Stations

In addition to regular fire weather network stations, which should have a real expectation of permanence, temporary special-purpose stations are frequently needed.

Campaign wildfires may require quick-deploy automatic stations to be set up near the fire operations center for the duration of fire suppression and mop-up activities. Prescribed fires generally require monitoring of weather from a temporary station immediately off site, from the date of recommended start-up in spring until the burn takes place or, at a minimum, 3 weeks before the burn (Alexander 2006). Such stations (Fig. 14) may have anemometer masts shorter than 10 m, in which case, wind speed observations may require adjustment for the nonstandard mast height (see Table 8 and description below in this section).

Such stations may be complete automatic weather stations or some variant thereof, ranging from a rain gauge and hygrothermograph to a portable psychrometer and hand-held wind gauge. At a bare minimum, rain should be recorded on site before the burn, unless a permanent fire weather station is located a short distance away. Alexander (2006) stated that the need to meet this minimum requirement would depend, to some extent, on whether the site of the prescribed burn had a substantial organic layer; under normal circumstances, it should not be necessary to monitor preburn rainfall amounts for more than a few days if only fine fuels are present (e.g., cured annual grasses). On the burning day, temperature, relative humidity, and 10-m open wind speed or its equivalent (Table 8) should be measured at least every hour. If automatic recording equipment is available, the hourly weather 24 h in advance of burning should be documented, which will also permit hourly calculation of the

FWI System components, especially FFMCI and ISI. Prescription, monitoring, and evaluation of prescribed fires involve many variables; however, for a given fuel type and topographic situation, any variations in fire behavior and impact or short-term fire effects are wholly a reflection of past and present weather conditions (Alexander 2006). Accurate weather records and accurate calculation of FWI System components for a prescribed fire will allow the burning conditions to be duplicated or understood by others (Hawkes and Lawson 1983). In addition, on-site or immediately off-site meteorological observations are needed for spot fire weather forecasts and for assessing hold-over potential or subsurface fire persistence (Alexander 2006).

Table 8 can be used to correct wind measurements obtained from anemometer at nonstandard heights in standard-sized clearings; two options are available, depending on the surface roughness of the particular clearing. Values from the "rough" column in Table 8 should be used for forest clearings covered in low brush or slash (with roughness length 0.1–0.3 m in meteorological terms), whereas values from the "smooth" column should be used for clearings where the ground is smooth or covered in mowed grass or cropped brush (roughness length 0.03 m).

Recent field calibration studies in large, smooth clearings in Saskatchewan (Emmett and Poirier 2005) and Montana (Bradshaw et al. 2003) confirmed the logarithmic wind profile reduction from 10 m to 1.8 m (eye level) and also confirmed that reductions in wind speed are much less over smooth-surfaced clearings than over rough-surfaced clearings, as indicated in Table 8.

To make adjustments for mast height less than 10 m, the observed wind speed is multiplied by the appropriate factor (selected from Table 8) for the surface roughness of the opening. For example, for wind speed of 12 km/h measured at the top of a 6-m mast, the adjusted wind speed would be 14 km/h ($12 \text{ km/h} \times 1.18 = 14.2 \text{ km/h}$) for a standard 10-m mast in a clearing with a rough surface or 13 km/h ($12 \text{ km/h} \times 1.11 = 13.3 \text{ km/h}$) for a 10-m mast in a clearing with a smooth surface.

Estimates of wind speed using such guides as the Beaufort scale (Appendix 1), rather than instruments, are generally representative of the 10-m standard height.

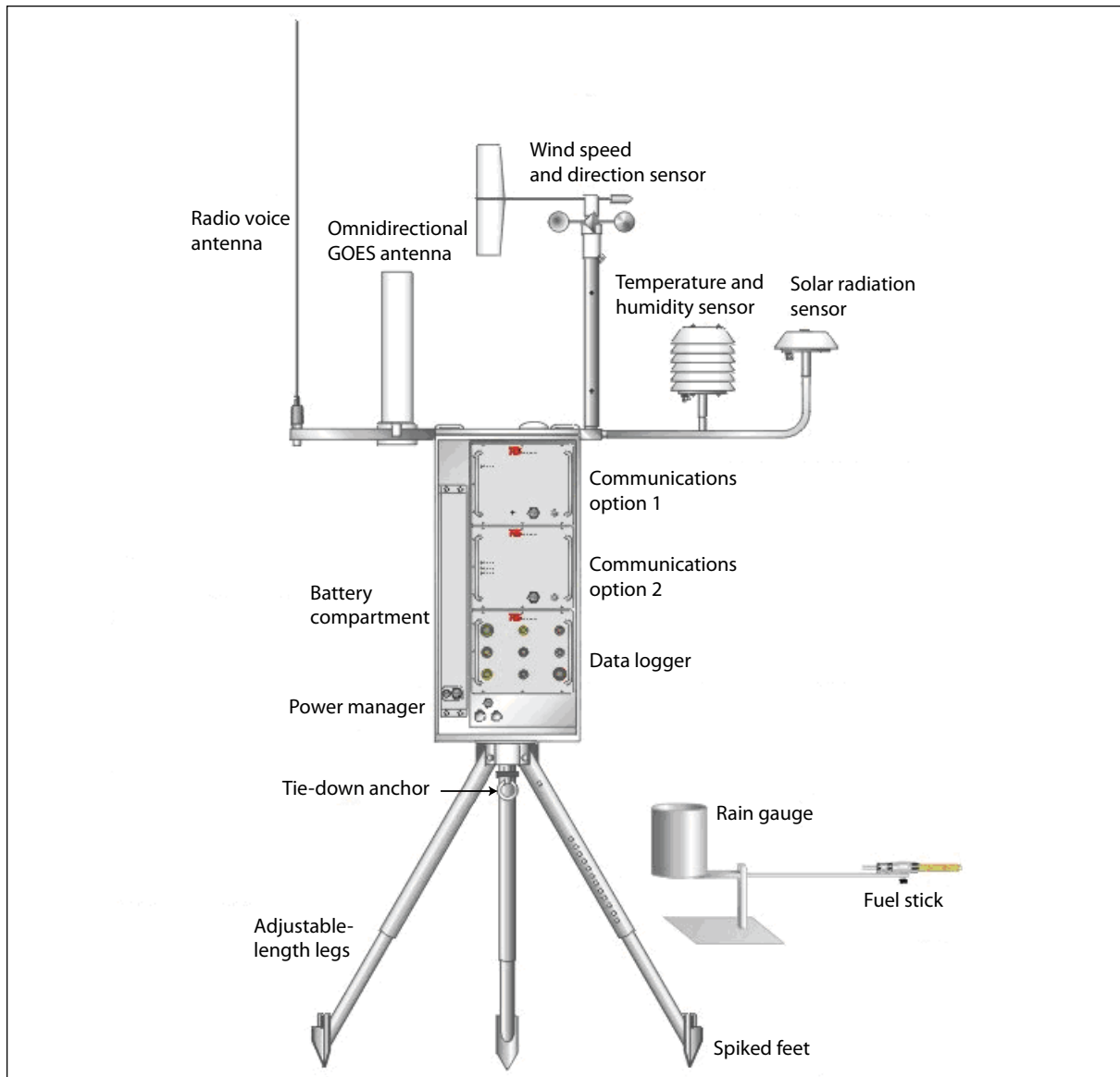


Figure 14. Quick-deploy automatic weather station with nonstandard-height anemometer requiring wind speed adjustments. This station collects data on solar radiation and electronically simulated fuel moisture stick readings, neither of which are required by the Canadian Forest Fire Danger Rating System. GOES = Geostationary Operational Environmental Satellite. (Diagram courtesy of Forest Technology Systems Ltd.)

Table 8. Wind speed adjustment factors for anemometer mast height less than 12 m

Mast height (m)	Adjustment factor	
	Rough surface	Smooth surface
1.5	1.94	1.48
2.0–2.9	1.54	1.31
3.0–3.9	1.37	1.22
4.0–4.9	1.26	1.16
5.0–6.9	1.18	1.11
7.0–8.9	1.06	1.03
9.0–11.9	1.00	1.00

DROUGHT

Drought over a Summer

The direct effects of a seasonal drought on the moisture content of the forest floor are accounted for in the FWI System by the DC, which has a 53-day time lag in standard moderate weather conditions. The DC was first developed (Turner 1972) to serve as an index of cumulative drying, based on the water stored in the soil, rather than to follow the moisture content of a particular slow-drying forest fuel. However, it has been assigned a nominal fuel depth (thickness) of 18 cm, a nominal fuel load of 25 kg/m², and a maximum theoretical moisture content of the fuel represented by DC of 400% (Van Wagner 1987). With these specifications, the DC fuel layer has a water capacity of 100 mm, rather than the 200-mm (8-inch) water reservoir described by Turner (1972). (A forest floor layer weighing 25 kg/m² on an oven-dry basis, if saturated at 400% moisture content, would hold 100 kg/m² of water, equivalent to 100 mm depth of water).

DC is a suitable predictor of moisture variations at depth in the forest floor and is a warning indicator of moisture reversals with depth, whereby lower layers of deep duff may be drier than upper layers (Muraro and Lawson 1970). The latter phenomenon results in persistent deep smoldering even though fire behavior at the surface may not be severe. Moisture reversals tend to be associated with DC greater than 300, which occurs late in the season, and are an important consideration for the safe conduct of prescribed burns.

Other seasonal drought effects that may be tracked by DC include the availability of water in streams and swamps, which may reduce the availability of water for fire suppression and for containment of fire spread (Turner 1972).

One important factor that can affect the moisture content of the boreal forest floor over the summer is the presence of permafrost. Lawson et al. (1997) presented equations for predicting the probability of sustained smoldering ignition in some boreal forest duff types, based on moisture content derived from the DC. They noted that one equation was recommended for predicting the moisture content of deep organic layers on mesic, well-drained boreal forest sites from DC values, whereas sites affected by permafrost or a permanent ice layer that restricts moisture drainage may be better represented by another equation (the national standard equation for predicting the DC moisture equivalent).

Overwintering the Drought Code

Of the three fuel moisture codes making up the FWI System, only the DC must be overwintered. As Van Wagner (1985) explained, any moisture index can be overwintered, but whether the effect of doing so projects far enough into the new season for it to be worthwhile depends on the time lag. This principle is governed by the time lag theory for negative exponential systems, whereby the proportion of any effect remaining after one time lag period is 36.8%, after two periods is 13.5%, after three periods is 5.0%, and after 4 periods is 1.8%. Taking 5% as the practical point of no further concern, time lags between 32 and 64 days were shown to cover the range of effects between disappearing during the current season and extending into the next fire season. Thus, with a time lag of 53 days in standard weather, DC may carry forward the effect of winter precipitation into the new fire season's starting value.

In some regions and in some years, the degree of fire danger may be modified by abnormally dry conditions during the previous fall and winter. This carry-over effect is handled by a calculated adjustment to the spring start-up value for DC to allow for drier-than-normal duff and soil moisture conditions. The following procedure now constitutes an integral aspect of the DC and its computation for northern hemisphere locations (Van Wagner 1987):

$$Q_s = aQ_f + b(3.94r_w) \quad (2)$$

where Q_s is the starting spring moisture equivalent of the DC value, Q_f is the final fall moisture equivalent of the DC value, r_w is winter precipitation (mm), and a and b are user-selected values accounting for carry-over fraction and wetting efficiency fraction, respectively (Table 9).

Q_f is calculated from the following equation:

$$Q_f = 800 \exp(-DC_f/400) \quad (3)$$

where DC_f is the final fall DC value.

The spring start-up value for the DC can then be calculated from the conversion equation:

$$DC_s = 400 \ln(800/Q_s) \quad (4)$$

The values for a and b in equation 2 are set by regional fire weather authorities using

the guidelines presented in Table 9. Computer applications are generally used to calculate spring start-up values for DC, but look-up tables are also available (Alexander 1982a, 1983b). A calculator for over-winter adjustments to spring start-up values for DC is available in a training course available in CD-ROM format ("Understanding the Fire Weather Index [FWI] System," Environmental Training Centre, Hinton,

Alta., and Canadian Forest Service, Northern Forestry Centre, Edmonton, Alta.).

In areas where normal winter precipitation exceeds 200 mm, the DC overwintering exercise tends to be unnecessary. However, adjustments to DC start-up values are generally required in the normally dry western and northern regions of Canada, excluding the west coast.

Table 9. User-selected values and criteria for equation 2 constants a and b, overwintering the Drought Code

Constant	Value	Criteria
Carry-over fraction of last fall's moisture (<i>a</i>)	1.0	Daily DC ^a calculated up to 1 November, continuous snow cover, or freeze-up, whichever comes first
	0.75	Daily DC calculations stopped before any of the above conditions met or the area is subject to occasional winter chinook conditions, leaving the ground bare and subject to moisture depletion
	0.5	Forested areas subject to long periods in fall or winter that favor depletion of soil moisture
Effectiveness of winter precipitation in recharging moisture reserves in spring (<i>b</i>)	0.9	Poorly drained, boggy sites with deep organic layers
	0.75	Deep ground frost does not occur until late fall, if at all; moderately drained sites that allow infiltration of most of the melting snowpack
	0.5	Chinook-prone areas and areas subject to early and deep ground frost; well-drained soils favoring rapid percolation or topography favoring rapid runoff before melting of ground frost

Sources: Turner and Lawson (1978); Alexander 1983b.
^aDC = Drought Code.

Ground-truthing the Drought Code

Lawson and Dalrymple (1996) described a "standard" methodology for and study of ground-truthing the over-winter recharge of DC fuel moisture in several areas of western and northern Canada. The recommended methodology involves field sampling of organic layers of the forest floor on mesic sites. The samples consist of 2-cm thick strata of the forest floor cut to a consistent size (0.1 m² is recommended). The samples are oven-dried and the oven-dry moisture content determined. Moisture content by depth can then be compared to various site-specific "ground-truthing" models and to the national standard DC calibration equation.

Before a discussion of the site-specific calibration equations presented by previous authors, a misleading graph, Figure 1 in Lawson and Dalrymple (1996), must be corrected. In that

earlier publication, the only standard equation for DC was the moisture equivalence equation (equation 3 above). However, because their Figure 1 presents equations for moisture content (%) as a function of DC, the moisture content (%) version of the national standard equation should have been plotted for comparison with site-specific calibration equations.

The DC has been assigned a maximum theoretical moisture content of 400%, so the appropriate standard equation linking moisture content (MC) and DC is as follows:

$$MC = 400 \exp(-DC/400) \quad (5)$$

where MC is moisture content, on an oven-dry basis.

Equation 5 is plotted in Figure 15, for comparison with site-specific calibration equations.

Lawson and Dalrymple (1996) also presented an equation for the 9–10 cm depth in coastal cedar-hemlock (CWH) forests near Mission, B.C., that is representative of deep, compact forest floors exhibiting DC properties of depth and bulk density. That equation used a saturated value of 351% at zero DC, similar to the theoretical saturation value of 400% for a forest floor of “standard” DC properties (Fig. 15):

$$MC = 351/e^{(DC/390)} \quad (6)$$

Lawson and Dalrymple (1996) also presented empirically based equations for various forest types and geographic areas, along with cautions related to study robustness, shallowness of duff depth, and presence of transient ice layers north of 60° latitude. These equations are reproduced here, with the cautions repeated and a revision to the equation for southern interior British Columbia, to correct an error in the earlier publication.

For forests in the southern interior of British Columbia:

$$MC = 285.8/e^{(DC/304.5)} \quad (7)$$

Derived from “one-shot” sampling in 1988 of a range of sites across several biogeoclimatic zones and subzones, equation 7 lies below the CWH curve because of shallower duff depths and lower bulk densities and because the moisture contents were calculated for the entire organic layer rather than for a particular depth stratum. In addition, most of the forest floors sampled in the southern interior British Columbia study were less than 10 cm (average depth of litter, fermentation, and humus layers 5.0 cm) and thus did not meet the standard DC properties for depth and bulk density. Caution is advised when applying this equation as a predictor of moisture content. It is, however, a useful relative indicator,

suggesting that the DC correlates generally with moisture content in the forest floor, at least for the range of June values sampled (69–480) over 20 different ecosystems ($R^2 = 0.59$, coefficient of variation [CV] = 45.3%) and a variety of moisture regimes (ranging from submesic interior Douglas-fir, *Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco, at the dry end to subhygric interior cedar-hemlock, *Thuja plicata* Donn ex. D. Don – *Tsuga heterophylla* (Raf.) Sarg., and mesic Engelmann spruce-subalpine fir, *Picea engelmannii* Parry ex. Engelm. – *Abies lasiocarpa* (Hook.) Nutt., at the wet end of the range).

For white spruce, *Picea glauca* (Moench) Voss, forests in the Yukon Territory:

$$MC = 488.4/e^{(DC/267.9)} \quad (8)$$

Equation 8 was based on 43 observations, each the average of at least two samples taken weekly throughout the summer near Whitehorse, Yukon. The best correlation of sampled moisture content with DC was obtained from the 6–10 cm depth stratum ($R^2 = 0.74$, CV = 56.9%, DC range 144–606, average duff depth 7.2 cm). Equation 8 crosses the CWH curve (Fig. 15), which suggests that some other factor may be causing higher saturated moisture content at low DC values in spring, perhaps restricted drainage because of frozen ground that persists well into June north of 60° latitude, even on nonpermafrost sites. In contrast, for the CWH saturation values, restricted site drainage due to ice or permafrost was not a factor. An ice layer below the duff was observed at the Whitehorse sites from early May to mid-June. The crossover at DC of approximately 300 may indicate that the longer summer day lengths in the north tend to produce slightly lower forest floor moisture content than is the case for forest floors in southern British Columbia, such as those found in CWH ecosystems.

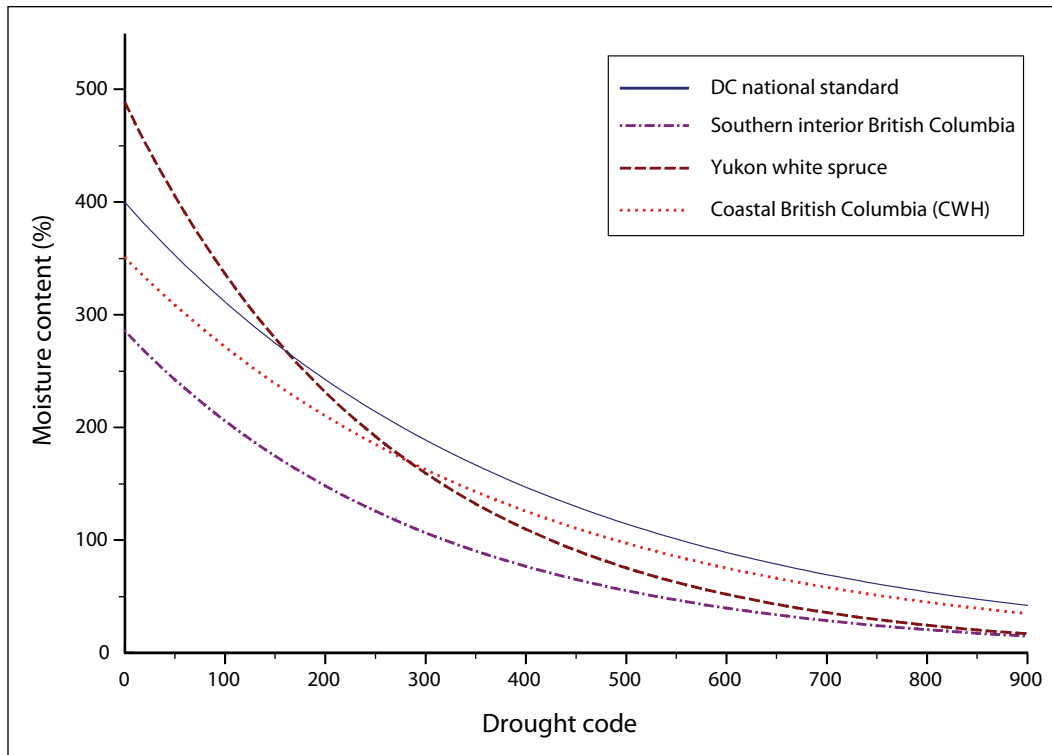


Figure 15. Calibration curves for forest floor moisture content as a function of Drought Code (DC): national standard, coastal British Columbia cedar–hemlock (CWH) forests, southern interior British Columbia forests, and southern Yukon white spruce forests.

The most appropriate of equations 6, 7, and 8 or other equations for calibrating regional moisture content as a function of DC that are available in the literature (e.g., Anderson and Otway 2003; Abbott et al. 2007a; Otway et al. 2007) can be used to compare local “ground-truth” field sampling of moisture content to the standard spring start-up model for DC and can be used to override the standard model, if warranted.

As Lawson and Dalrymple (1996) concluded, the results of the wide-ranging empirical field studies discussed here generally support the theoretical need (based on time lag) to overwinter the DC. The simple overwintering model presented here, combined with one of the regression equations from Figure 15 or the national standard DC equation (equation 4 above), is adequate for broad-area DC calibration and inferences of forest floor moisture for the purposes of fire danger rating.

Of the three calibration equations included here, Lawson and Dalrymple (1996) regarded

only equation 6 as “final,” in the sense that it is based on sufficient sampling from several benchmark sites with typical DC forest floor characteristics over more than one season. However, equations 7 and 8 have been used in various ground-truthing studies in Yukon and Alberta and are now regarded as sufficiently robust for use where appropriate.

Another application of ground-truth sampling of duff moisture content arises when fire weather stations are established later in the season for some special purpose, such as servicing a campaign wildfire or prescribed burn. Normally, the fuel moisture codes from the nearest representative weather station will be applied as start-up values for the late-starting station. However, in critical situations, ground-truth sampling results can be compared with the predicted results for one of the above equations, and the DC from the nearest weather station can be adjusted up or down, as appropriate.

WEATHER NOT DIRECTLY OBSERVABLE

A number of complex meteorological conditions that are not readily recognized or easily measured have significant effects on fire behavior. Schroeder and Buck (1970) discussed the following topics in greater detail, but their key points are presented here from a fire danger perspective. It should be noted, however, that this section is not intended to cover comprehensively the range of topics linking fire weather with firefighter safety.

For example, temperature inversions, in which temperature increases with elevation, instead of decreasing as it does in an unstable or naturally stable atmosphere, may result in surprising variations in fire danger with small changes in elevation. Strong instability may also result in unexpected fire activity. Foehn winds (e.g., chinooks) that flow down mountain slopes or blow out coastal inlets have the potential to cause extreme drying of fuels because of the accompanying low humidities.

Brotak and Reifsnyder (1977b) described the frontal weather patterns, local wind profiles, and temperature profiles occurring in the lower 5550 m of the atmosphere that are associated with extreme fire behavior. No provision can be made in the FWI System or the FBP System to account directly for these atmospheric profiles, but a fire weather forecaster can often recognize dangerous warning signs in the upper air balloon soundings taken daily at a network of weather stations across the country. Such soundings may also be taken at special fire weather stations established to service campaign wildfires.

Flannigan and Wotton (2001) described in detail synoptic surface weather features and upper air features that have been correlated with severe fire weather and burned area events in Canada. The most important surface weather features with respect to area burned are passage of cold fronts, dry spells, and low relative humidities. The latter two weather elements influence fuel moisture and associated fire danger rating components, and passage of a cold front was associated with nearly 80% of the large fires in the eastern United States over a 10-year period studied by Brotak and Reifsnyder (1977a). Flannigan and Wotton (2001) noted the importance of the shift in surface winds from southwest to northwest that occurs with the passage of a cold front in the northern

hemisphere; as this occurs, the flank of a fire burning with a southwest wind becomes the head of a fire burning with a northwest wind, which in turn causes rapid and significant growth in the fire.

Flannigan and Wotton (2001) also noted that the breakdown of an upper atmospheric ridge is critical in accounting for the area of burning. Newark (1975) and Nimchuck (1983) described significant wildfire episodes in 1974 in northwestern Ontario and in 1981 in Alberta, respectively, that were associated with the breakdown of upper (500 mbar) long-wave ridges. Such breakdowns are often accompanied by an increase in lightning activity, as upper disturbances (with short waves) move along the west side of the ridge, and by strong and gusty surface winds. Breakdown of an upper ridge is preceded, possibly for several weeks, by the warm, dry conditions associated with the upper ridge, which produce very dry fuels.

Vertical Structure of the Atmosphere

Vertical temperature profiles reveal a great deal about the dynamic processes that occur in the atmosphere, and Schroeder and Buck (1970) have discussed in detail how atmospheric stability and instability affect fire behavior. However, temperature inversions can have strong effects on fire behavior, without necessarily showing up in advance in the weather observations collected for calculation of fire danger rating indices, particularly once-a-day observations from weather stations confined mostly to valley bottoms.

The degree of stability or instability of an atmospheric layer is determined by comparing its temperature lapse rate, as shown by a sounding, with the appropriate adiabatic lapse rate. The lapse rate of the atmosphere is defined as the rate at which temperature decreases with increasing height. If the temperature is increasing with height, the lapse rate is negative, indicating an inversion.

The atmospheric stability of any layer is determined by the way in which temperature varies through the layer and by whether air in the layer is saturated. A measured temperature lapse rate less than the dry-adiabatic rate of

9.8 °C/km (5.5 °F/1000 ft) for an unsaturated parcel is considered “stable,” because vertical motion is damped (Schroeder and Buck 1970). By contrast, a lapse rate greater than the dry-adiabatic rate favors vertical motion and is “unstable.” If the lapse rate of an unsaturated parcel equals the dry-adiabatic rate, the layer is considered “neutrally stable,” and any vertical motion is neither damped nor accelerated.

In the case of a saturated parcel of air, the same stability terms apply; however, the comparative atmospheric lapse rate is the saturated-adiabatic rate of 4.9 °C/km (3 °F/1000 ft) on average. Unlike the dry-adiabatic rate, which is constant, the saturated-adiabatic lapse rate is variable. To facilitate stability determinations, the meteorologist plots the measured temperature and moisture structure of the atmosphere on a gridded adiabatic chart of height versus temperature. The moisture is plotted as a dew-point temperature. Also printed on the chart is a set of dry-adiabatic and a set of moist-adiabatic lines or adiabats. By referring to these adiabatic charts, the meteorologist can compare the lapse rates of the various layers of the atmosphere with the dry- and saturated-adiabatic rates. The atmosphere at various heights may be stable, unstable, or “conditionally unstable,” the latter referring to an environmental lapse rate that falls between the dry- and saturated-adiabatic lapse rates (Schroeder and Buck 1970). A conditionally unstable atmosphere will support active convection until the environmental lapse rate becomes less than the saturated lapse rate, at which time convection stops and the atmosphere becomes stable.

The vertical structure of the atmosphere influences fire behavior in various ways. Flannigan and Wotton (2001) observed that dry and unstable air enhances forest fire growth in two ways: first, in the absence of strong winds, it promotes a well-developed convection column, which may produce spotting and other erratic fire behavior such as fire whirls; second, when wind speeds are strong near the earth’s surface, the instability allows the high winds to be mixed down to the surface, where they enhance fire spread and erratic fire behavior such as horizontal roll vortices (Haines 1982).

To address the role of the atmosphere’s vertical structure on fire activity, Haines (1988) developed a lower atmosphere severity index for wildland fires, which accounts for the influence of temperature stability and moisture content

in the lower atmosphere. Haines found that although only 6% of fire season days fell into the high-index class in the western United States, 45% of days with large or erratic fires occurred on those days.

Although a dry, unstable atmospheric profile may contribute to a persistent convection column above a fire, convection columns above wildland fires may also occur under inversion conditions, eventually “punching through” the inversion (Alberta Forest Service 1985).

Inversions form in various ways. Maritime inversions commonly occur during the warm season, when cool, moist air from an ocean or a large lake spreads over low-lying land. Although maritime inversions may persist during the day, they are strongest and most noticeable at night, when fog may form in the cool moist air. Nocturnal inversions form in mountain valleys as cool air drains down slopes, leaving warmer air above an inversion layer, in what is known as a thermal belt below the main ridges (Schroeder and Buck 1970). The highest minimum temperatures occur within this midslope thermal belt, as do the lowest nighttime relative humidity and fuel moisture, which may help fires to remain active during the night. Such nighttime fire activity can cause the fire’s intensity to build up to the extent that a convection column develops above the fire, punching through the inversion layer at the top of the thermal belt and further increasing fire intensity.

Subsidence, another mechanism that contributes to the formation of inversions, can also contribute to erratic, high-intensity fire behavior. Subsiding air warms and dries as it sinks to the surface, which leads to extremely low relative humidities. Large-scale subsidence inversions are usually associated with warm upper-atmosphere high pressure ridges that may extend all the way from the surface to the troposphere (Schroeder and Buck 1970), but relatively weak high pressure conditions at the surface. As the upper ridge develops or advances (usually from the west), the subsidence of air on the east side of the ridge is accompanied by warming and drying of the air that is aloft; that warmer, drier air may eventually approach ground level, resulting in a subsidence inversion (B. Janz, Fire Weather Supervisor, Alberta Forest Service, Edmonton, Alberta [retired], December 11, 2006, personal communication). If it reaches the surface, the effect on fuel moisture and fire behavior can be dramatic, and a potentially critical

fire weather situation often results (Schroeder and Buck 1970). The dry subsiding air usually does not reach the surface as a broad layer; rather, because of convection currents, it comes down to the surface in patches, which cause the subsiding air to mix with the air in the layer below the subsidence inversion. The resulting air is not as dry as the pure subsiding air, but it still has a very low relative humidity, often in the range of 10% to 20%, with temperatures in the mid-30s (Alberta Forest Service 1985).

Dangerous, erratic fire behavior can result when subsiding air overlies a layer of cool, shallow marine air, particular in coastal areas. Humidity is high in the marine air, the top of which is usually marked by low stratus clouds. Above the marine layer lies very dry air, which creates high potential for fire behavior. In this situation, an existing low-intensity fire burning in the cool marine air can “explode” in intensity as it burns up the slope into the dry subsiding air.

In all, four types of subsidence have been identified (Alberta Forest Service 1985):

1. down-valley or down-slope winds, which result from radiational cooling;
2. thunderstorm downdrafts, which can be quite strong, especially when combined with normal down-valley winds, and which can create a threat to safety if personnel are caught on the side of the fire opposite the thunderstorm;
3. large-scale subsidence of an air mass, as discussed above, in the context of upper ridges (i.e., high pressure in the middle or upper troposphere); and
4. subsidence to the lee of mountain ranges, which is caused by the slight pressure drop as wind blows across a mountain barrier and which usually results in downward flow or descent of the air (this form of subsidence, which produces the chinooks east of the Rockies and warm, dry outflow conditions along the south, central, and north coasts of British Columbia and the east and west coasts of Vancouver Island, often

occurs in sunny weather, when there are few visual indicators that it is present, and may drive fires downhill, instead of allowing them to stop at the ridges, as would be expected).

Low-Level Jet

In addition to identifying highly unstable atmosphere as a criterion for severe (“blow-up”) fire behavior, Byram (1959) listed additional criteria, including abundant dry fuel and the presence of a “low-level jet,” with wind speed decreasing above that level. Byram (1959) regarded 500 m as a working value for this critical height above the fire but suggested that the “jet,” or maximum wind speed, would be lower in the case of light fuels or light surface winds. Byram found that the most intense fires occurred when the wind speed at the jet exceeded 30 km/h, but blow-up fires do occur with winds between 20 and 30 km/h at the jet, especially where topography contributes to fire behavior. The decrease in wind with height above the jet is required to maintain a strong convection column above the fire, while the jet contributes to strengthening the wind at the surface, as the fire increases in intensity (Alberta Forest Service 1985). Increasing wind speed with height would tend to shear off the fire’s convection column, thus removing energy from the vicinity of the fire. A fire weather forecaster must pay particular attention to a low-level jet in the presence of other criteria for extreme fire behavior. Of course, height-related wind speed profiles constitute special meteorological information that would usually be available only to weather specialists working with a fire weather forecasting unit or a campaign fire overhead team.

Crossover

Widely used rules of thumb warning of potentially severe fire weather include “crossover,” a concept that has been discussed for decades (Alberta Forest Service 1985). Crossover refers to an hourly pattern of temperature and relative humidity in which a rising temperature trend is intersected or crossed by a falling relative humidity trend, which may indicate potentially severe fire behavior (Fig. 16).

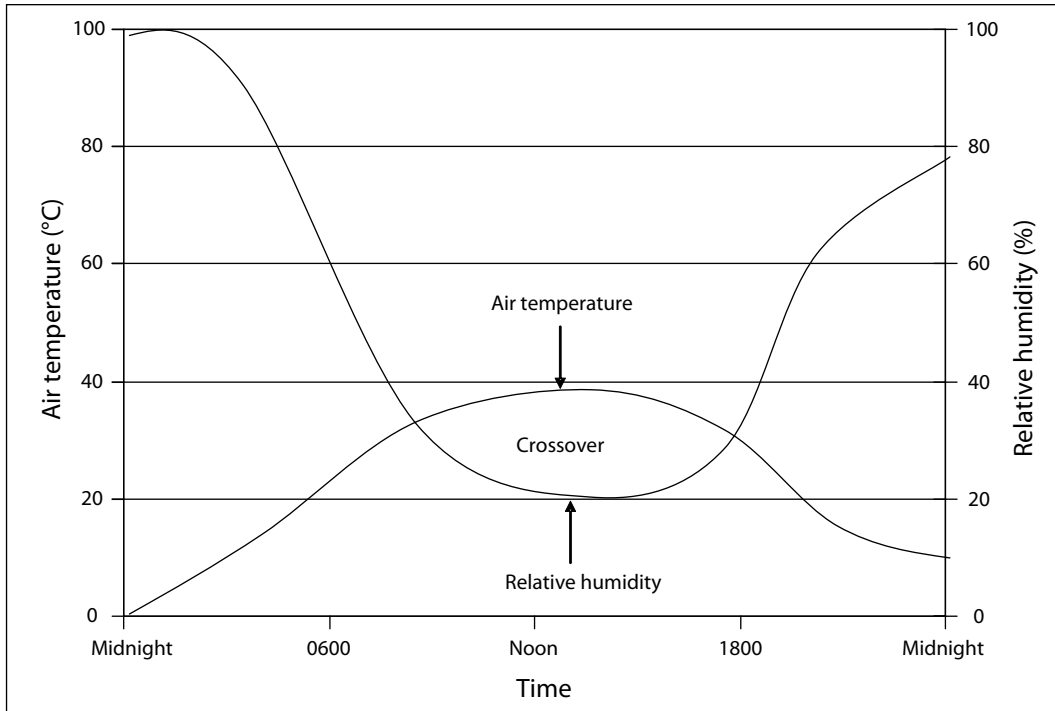


Figure 16. Diurnal trends of temperature and relative humidity in which for a portion of the day the relative humidity is equal to or less than the air temperature, termed “crossover” (sources: M.E. Alexander, Forest Fire Research Officer, Canadian Forest Service, Edmonton, Alberta, November 3, 2003, personal communication; Thorburn et al. [2000]).

However, some researchers have been cautious of the crossover rule of thumb, saying that it has some value but may be overused and misinterpreted (M.E. Alexander, Forest Fire Research Officer, Canadian Forest Service, Edmonton, Alberta, November 3, 2003, personal communication). One of the problems, according to Alexander, is the tendency of fire managers to prepare for severe fire behavior circumstances only when crossover conditions occur. However, severe fires can occur in the absence of crossover. For example, the 1968 Lesser Slave Lake Fire in Alberta ran 64 km in 10 h, with significant crown fire behavior and consumption of heavy fuels (Alexander 1983a); yet the temperature was only 21°C and relative humidity 30% at the start of the run, nowhere near crossover conditions (although such conditions had prevailed on the four consecutive days leading up to the run). Obviously, fires may exhibit extreme behavior because of other factors, including wind speed and profile, steepness of the slope, and dryness of medium and heavy fuels. In the interactive training course titled “Wildland Fire-Safety on the Fireline,” Alexander has stated, “Cross-over

can be a useful reminder that the potential for blowup or extreme fire behavior exists. However, do not rely on cross-over as your only indicator of such situations. Many fires can exhibit blowup or extreme fire behavior characteristics without cross-over conditions.” (Thorburn et al. 2000).

In the context of the CFFDRS, when air temperature is greater than or equal to relative humidity, then FFMC is always 92 or higher (assuming that the previous day’s FFMC was 89 or higher). FFMC values of 92 or above correspond to a fine fuel moisture content of less than 9%, which correlates with significant potential for spot fire ignition. Furthermore, the FBP System indicates that continuous crown fire with rates of spread exceeding 15 m/min and fire intensities exceeding 10 000 kW/m for most boreal forest fuel types will occur when FFMC is at least 92, wind speed is in the range 15–20 km/h, and medium and heavy fuels have a moderate level of dryness (M.E. Alexander, Forest Fire Research Officer, Canadian Forest Service, Edmonton, Alberta, November 3, 2003, personal communication).

Therefore, forecasters must be mindful that there is more to extreme fire behavior potential than just crossover or wind speeds greater than 30 km/h. Crown fire behavior can occur in the absence of crossover conditions and with only moderate wind speeds (about 15 km/h) if other criteria are met, such as dry medium or heavy fuels or steep slopes. Nonetheless, even

though crossover is not a sure-fire method of predicting extreme fire behavior, it is at least a useful indicator that can be determined with nothing more sophisticated than a belt weather kit (Fig. 17); access to a permanent fire weather station or danger rating calculations is not required.



Figure 17. Sling psychrometer from belt-mounted weather kit used for local measurements of wet-bulb and dry-bulb temperatures and calculation of relative humidity (photo courtesy of Ember Research Services Ltd.).

Dew and Frost

Dew and frost are two forms of moisture that are deposited on fuels directly from the atmosphere. Unlike rain, snow, and other forms of precipitation, dew and frost do not fall but instead are deposited when water vapor condenses or sublimates on the ground or on objects near the ground. Dew forms when air next to the ground or to cold objects is chilled to the dew point of the air but remains above freezing. Frost forms by sublimation when the air is chilled to its dew point, and the dew point is below freezing (Schroeder and Buck 1970). When the air temperature drops to its dew point value, the relative humidity is 100%.

Dew and frost can affect the moisture content of fine fuels, even though they are not measured directly in standard fire weather observations (Pech 1991). However, their effects are usually of short duration and dissipate by noon. Dew point temperatures may be reached overnight in clearings or open forests, which increases the moisture content of open fine fuels during the morning hours; in contrast, adjacent closed-canopy forests may stay warmer, above the dew point temperature, and may therefore present drier fine fuels during the morning hours.

In a study of the effects of dew on 1.2-cm diameter, 100-g fuel moisture sticks kept in the open, Haines (1979) found that the amount of

dew was generally in the range of 0.1 to 0.2 mm, with heavy dews (0.15 to 0.25 mm) occurring mostly during nights in August and September. Heavy dew produced average increases in the weight of the fuel sticks of about 10 g overnight (compared with sticks sheltered from dew formation). The dew effect decreased rapidly after sunrise; 75% of the moisture increase was lost within 4 h, and the extra moisture was almost completely gone by 1300, the time when fire weather observations are recorded for the day. Under windy conditions with clear skies, the dew deposited on fuels was less than half what was deposited on nights with low wind, and half of the dew was lost within 4 h after sunrise under these conditions.

Haines (1979) concluded that awareness of the effects of dew on fuel moisture content can aid fire managers in predicting fire activity. For example, if a prescribed burn is planned for 1300 following a clear night with heavy dew forecast, the manager can carry on with the prescribed burn, knowing that the effects of overnight dew should have passed by the time of the burn. However, after a clear but windy night with little or no dew, a fire may continue to spread through the night.

SENSITIVITY OF CFFDRS COMPONENTS TO WEATHER CHANGES

Users of the CFFDRS should have an idea of the sensitivity of key components of the FWI System and FBP System to changes in key weather elements and hence their sensitivity to the ability to observe and measure these weather elements accurately. This section explores in particular the relations between wind speed and the fire danger and fire behavior prediction outputs that flow from wind speed observations. Wind is the weather element that is most difficult to measure representatively and the one to which fire behavior is most sensitive. For completeness, the sensitivity of FFMC, DMC, and DC to their respective weather inputs (temperature, relative humidity, and wind speed) are also illustrated.

Sensitivity of Fuel Moisture Codes to Weather Elements

Fine Fuel Moisture Code

Detailed descriptions of the mathematical relations between FFMC drying rates and the

input weather elements of temperature, relative humidity, and wind are available in Van Wagner (1987) and are not repeated here. However, Figures 18, 19, and 20 illustrate the effects of a particular day's noon temperature, relative humidity, and wind, respectively, on that day's FFMC for three selected levels of the previous day's FFMC: 30 (wet), 70 (drying), and 90 (dry).

The effect of noon temperature on FFMC is approximately linear across the entire range of temperatures and has a decreasing influence on FFMC as the fine fuels dry (Fig. 18). The effects of relative humidity on FFMC are nonlinear (Fig. 19), such that even if the previous day's FFMC was 90, relative humidity has a significant effect on day-to-day changes in FFMC. The effect of wind speed on drying rate is proportionally greater at lower wind speeds (Fig. 20), and any effect of wind on fine fuel drying is effectively constant by the time FFMC has reached 90.

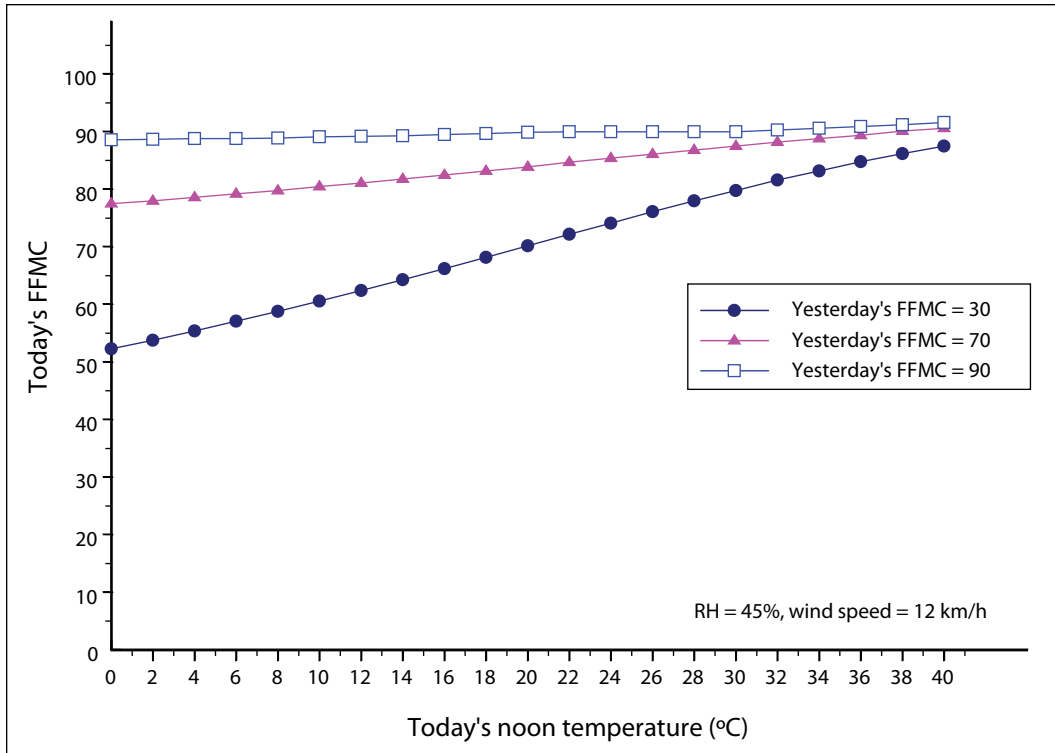


Figure 18. Effects of today's noon temperature on Fine Fuel Moisture Code (FFMC) for three levels of yesterday's FFMC. RH = relative humidity.

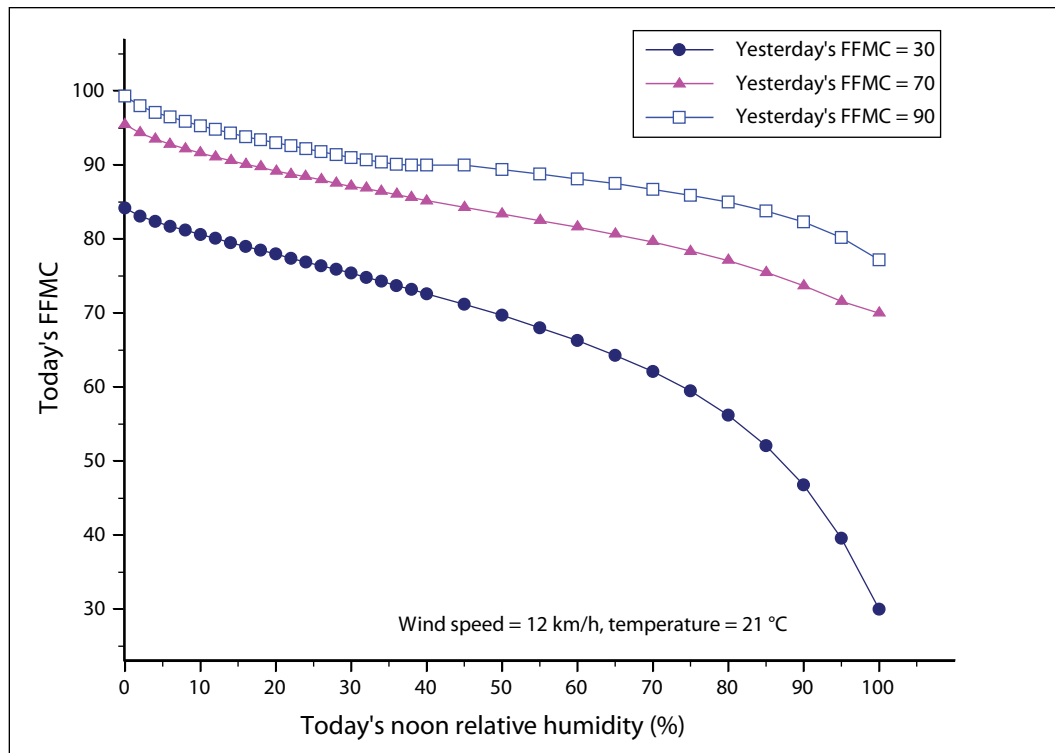


Figure 19. Effects of today's noon relative humidity on Fine Fuel Moisture Code (FFMC) for three levels of yesterday's FFMC.

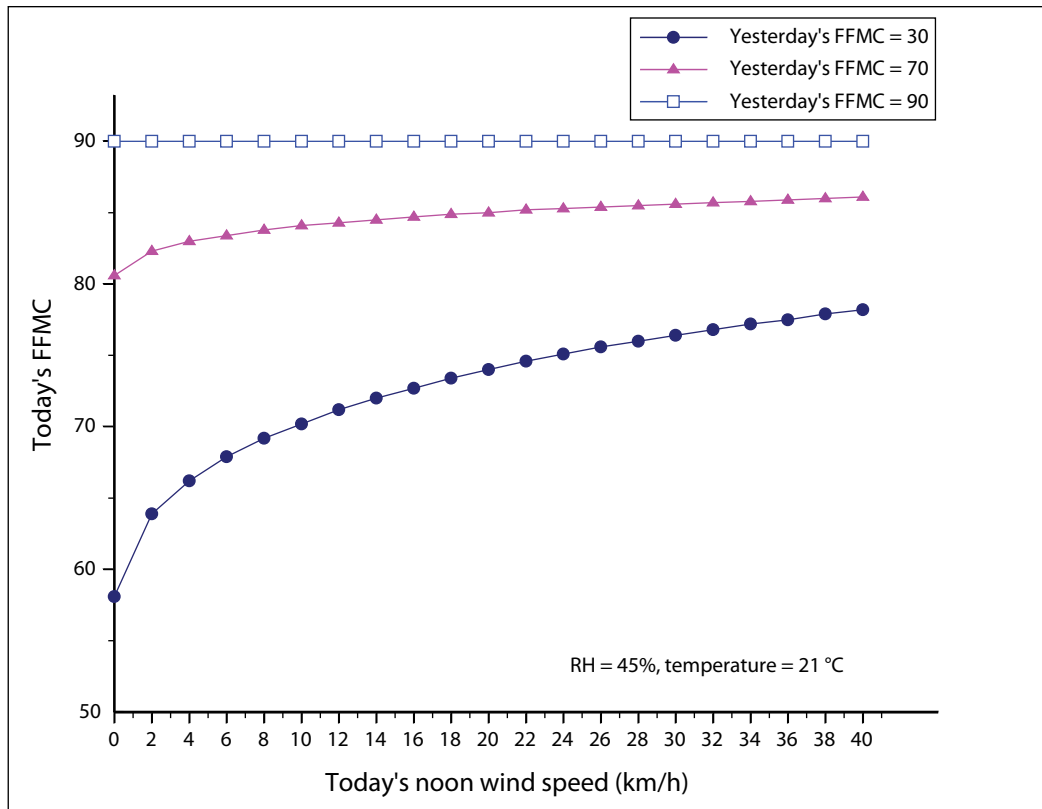


Figure 20. Effects of today's noon wind speed on Fine Fuel Moisture Code (FFMC) for three levels of yesterday's FFMC. RH = relative humidity.

Duff Moisture Code and Drought Code

When the effects of weather elements on any of the three fuel moisture codes are considered, it is important to bear in mind that the scales (equations) used to convert calculated fuel moisture content into FFMC, DMC, or DC are logarithmic (i.e., nonlinear transformations), reflecting the logarithmic drying rates of forest fuels. Thus, although the relations between temperature and DMC (Fig. 21), between relative humidity and DMC (Fig. 22), and between temperature and DC (Fig. 23) are linear, day-to-day drying in constant weather is exponential.

The DMC was designed as a logarithmic function of actual moisture content that rises with dryness; its scale has the advantage of daily

drying increments (ranging from 0 to 9) that are independent of the current value of the code.

The DC is unlike a real fuel code, in that it was designed to serve as an index of the water stored in the soil, rather than following the moisture content of a particular forest floor layer. However, because soil also loses moisture exponentially, such an index is suitable for representing certain heavy fuels, as discussed in the subsection entitled "Ground-truthing the Drought Code" (within the section "Drought"). The DC has a logarithmic scale analogous to that of the DMC, which permits the addition of daily drying increments that are independent of the daily value of DC (Fig. 23).

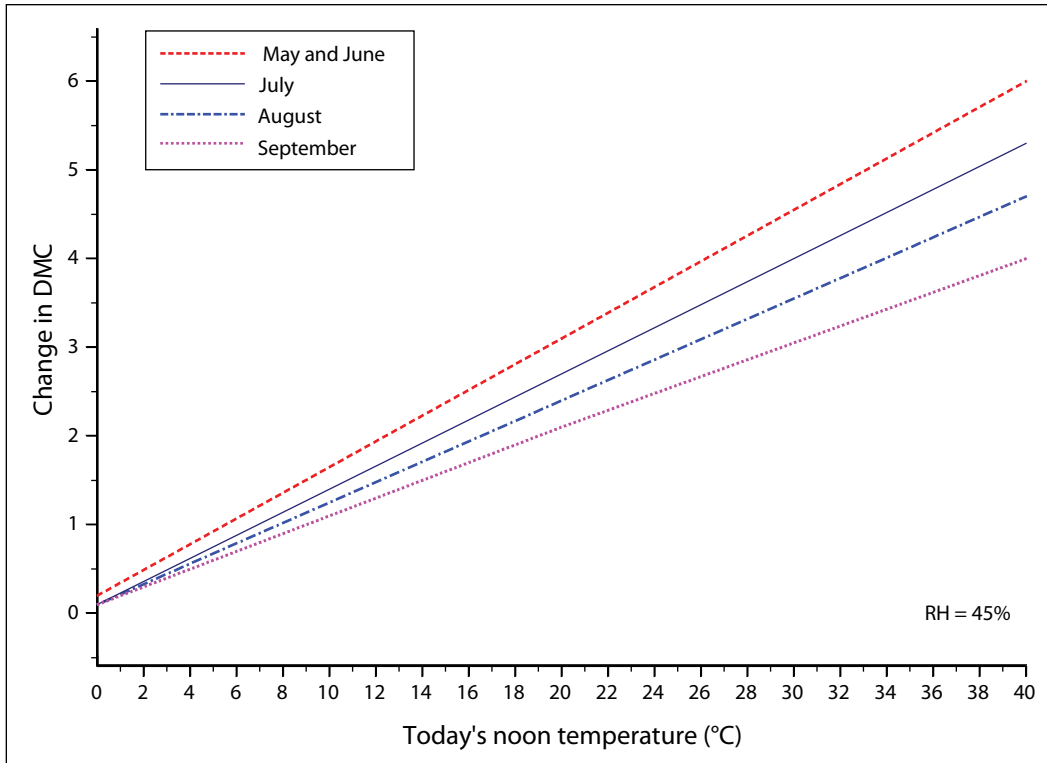


Figure 21. Change in yesterday's Duff Moisture Code (DMC), given today's noon temperature. RH = relative humidity.

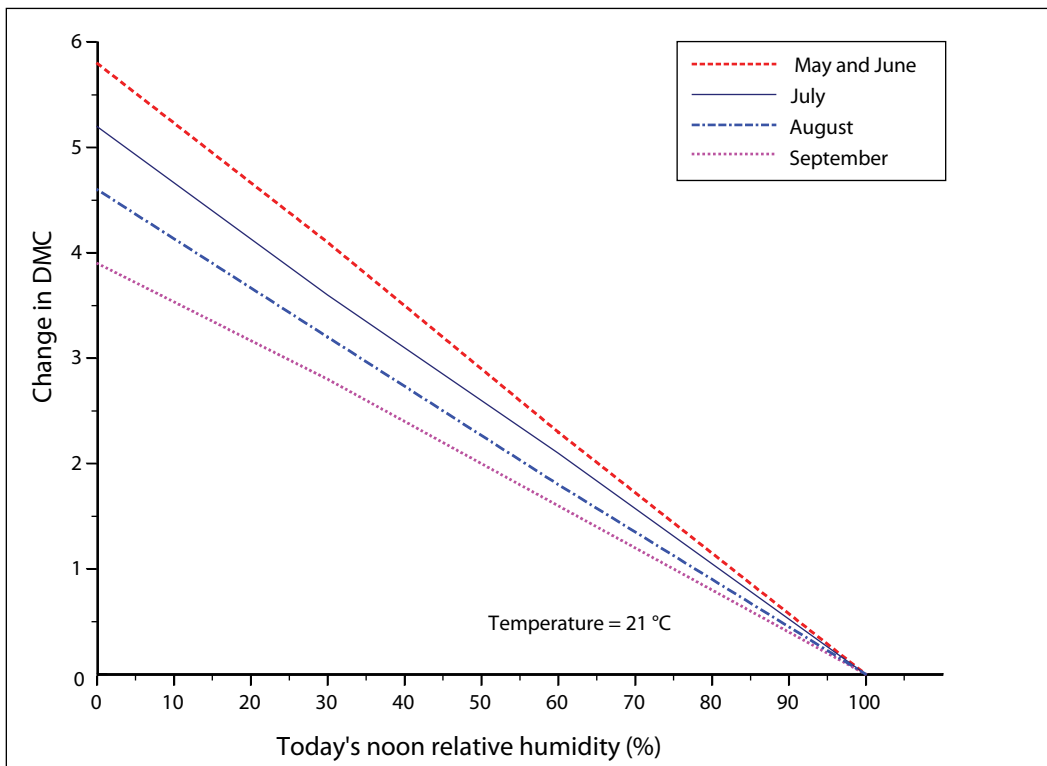


Figure 22. Change in yesterday's Duff Moisture Code (DMC), given today's noon relative humidity.

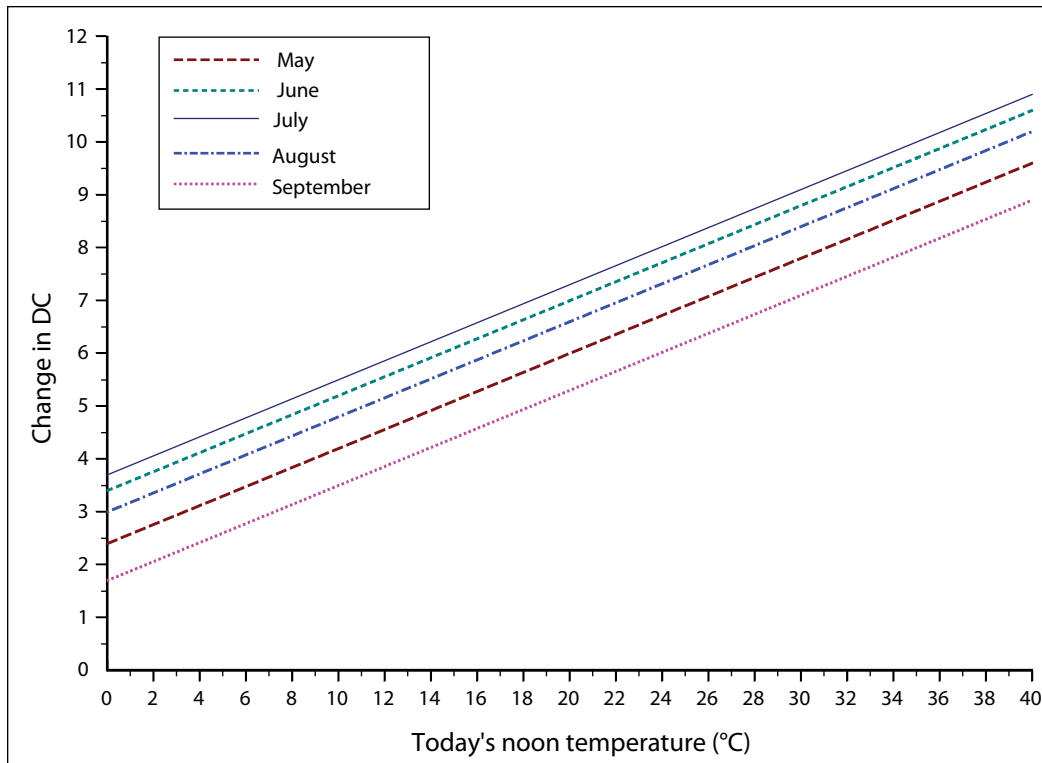


Figure 23. Change in yesterday's Drought Code (DC), given today's noon temperature.

Sensitivity of Initial Spread Index and Predicted Rate of Spread to Wind Speed

Before consideration of the sensitivity of the ISI to wind speed and changes in wind speed, it is important to note that the CFFDRS calculates ISI in two ways, using one equation for the FWI System and a different equation for the FBP System (to predict the rate of spread and fire intensity for specific fuel types). The two equations (numbered 53 and 53a in Forestry Canada Fire Danger Group [1992]) are identical for wind speeds up to 40 km/h but differ significantly at wind speeds above 40 km/h.

In particular, the FWI ISI (the "standard" ISI) rises steeply at wind speeds above 40 km/h, whereas the FBP ISI rises at a lower rate and levels off at wind speeds above 40 km/h (Fig. 24). Because the two ISI models diverge at high wind speeds, the sensitivity of ISI to incremental changes at high wind speeds is far greater for the standard ISI than for the FBP ISI (Fig. 24). By contrast, at low wind speeds (less than about 12 km/h), the two ISI models are relatively insensitive to incremental changes in wind speed.

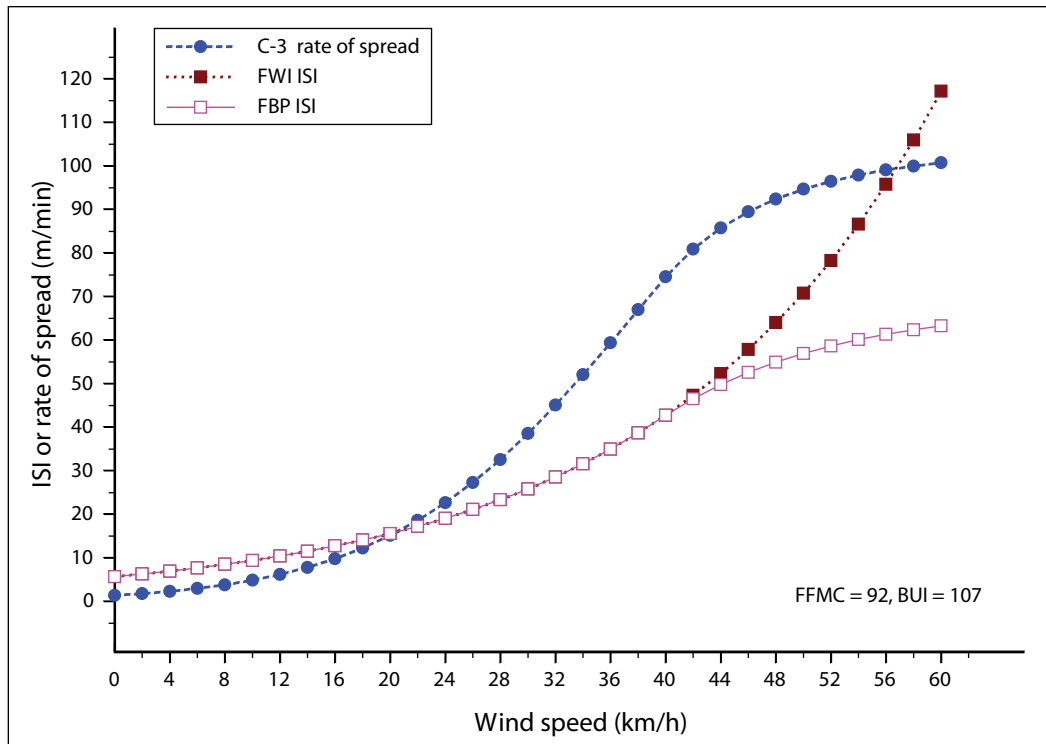


Figure 24. Fire Weather Index (FWI) Initial Spread Index (ISI), Fire Behavior Prediction (FBP) ISI, and rate of spread for fuel type C-3 (mature jack or lodgepole pine) as a function of wind speed. FFMC = Fine Fuel Moisture Code, BUI = Buildup Index.

As discussed in the subsection on wind within the section “Elements of Fire Weather,” the ISI, which reflects the joint influence of wind and fine fuel moisture on fire spread, is calculated with a simple exponential equation whereby ISI doubles for every 14 km/h increase in wind speed, with FFMC held constant (Table 5). The exponential relation of standard ISI plotted against wind speed rises steeply, at an increasing rate, as wind speed increases beyond 12 km/h, and ISI continues to double for every increase in wind speed of 14 km/h, even beyond 60 km/h. Van Wagner (1987) noted that the effect of wind on ISI was similar to the effect of wind on forest fire spread and matched fairly well the local experimental field evidence. However, Van Wagner pointed out that the relation is essentially empirical, and at very high wind speeds its validity is uncertain.

This uncertainty about the exponential effect of wind on ISI at high wind speeds continued as the FBP System was developed to predict

quantitative rates of spread in specific fuel types. As reported by the Forestry Canada Fire Danger Group (1992), for all rate-of-spread equations derived from the FBP System database of experimental fires and well-documented wildfires, the independent variable was the standard ISI. No advantage was found to using FFMC and wind speed separately to predict the rate of spread. However, the fires in the database that were associated with high winds were primarily wildfires that had burned through several fuel types; as such, they were included in more than one fuel-type subset. Also, crowning and spotting ahead, features of fire behavior under conditions of high wind, were automatically accounted for, in terms of their influence on overall rate of spread. The high-wind wildfires in the FBP fire database contributed uncertainty to the high ends of the predictive rate-of-spread equations. Therefore, as the authors of the FBP System described, the principle that rate of spread levels off at very high ISI values was adopted as an appropriate

conservative approach in the absence of concrete knowledge (Forestry Canada Fire Danger Group 1992).

Wotton et al. (n.d.) have discussed the assumption of leveling-off in the context of documented grass fires and forest fires that have exceeded the maximum spread rates predicted by existing equations in the FBP System. These case studies are not discussed in detail here, but for the first formal update of the 1992 FBP System (Wotton et al. n.d.), the assumption that rate of spread levels off at very high ISI values is retained.

The form of equation chosen for all fuel types was an S-shaped asymptotic curve with parameters for each fuel type estimated with nonlinear techniques (see Forestry Canada Fire Danger Group [1992]). Figure 24, which illustrates the rate of spread as a function of wind speed for fuel type C-3 (mature jack or lodgepole pine), clearly shows the conservative leveling-off of predicted spread rate above wind speeds of 40 km/h.

The leveling-off of rate-of-spread equations for all FBP System fuel types required a modified ISI (i.e., an ISI that also leveled off at wind speeds greater than 40 km/h), rather than the standard ISI used in the FWI System, which rises exponentially as wind speed increases (Fig. 24). The Forestry Canada Fire Danger Group (1992, p. 32 [footnote]) explained that the modified ISI was required to prevent anomalous measurable ISI and predicted spread rates at very low values of FFMC, but in fact the modified ISI is used in the FBP System for all conditions where wind speeds exceed 40 km/h.

The exponential relation whereby standard ISI doubles for every 14 km/h increase in wind speed does not hold for the modified ISI used in the FBP System. Because it levels off, the modified ISI is less sensitive to variation in wind speed above 40 km/h. Furthermore, the sensitivity of predicted rate of spread to changes in wind speed is greatest in the middle range of wind speeds (Fig. 24) and less at low and at very high wind speeds.

Sensitivity of Fire Weather Index and Predicted Fire Intensity to Wind Speed

Predicted fire intensity is an important output of the FBP System that is directly proportional to rate of spread and wind speed (through the ISI). The degree of sensitivity over the range of wind speeds is subject to the same factors as discussed in the previous subsection. The plot of FWI as a function of wind speed for low and high BUI (Fig. 25) shows that, like the standard ISI (Fig. 24), FWI is also an exponential function that rises continually with wind speed. By contrast, because predicted fire intensity by fuel type in the FBP System is derived from the rate of spread and fuel consumption, it reflects the same S-shaped curve (with leveling off) as occurs for the underlying rate of spread and modified ISI, as discussed in the previous subsection.

Also shown in Figure 25 are fire intensity classes 4, 5, and 6 (from a 6-class scheme), which encompass the fire intensity values at which surface fire transitions to intermittent crown fire and continuous crown fire. These fire intensity classes have been standardized (Alexander and Cole 1995) into the following ranges of fire intensities:

Fire intensity class	Fire intensity (kW/m)
1	< 10
2	10–500
3	500–2000
4	2000–4000
5	4000–10 000
6	> 10 000

Fire suppression interpretations based on head fire intensity classes are available for several fuel types (Alexander and de Groot 1988; Alexander and Lanoville 1989; Cole and Alexander 1995). Hirsch (1996, 1998) has presented a generalization of the above fuel-type specific fire intensity descriptions for standing conifer forest fuel types.

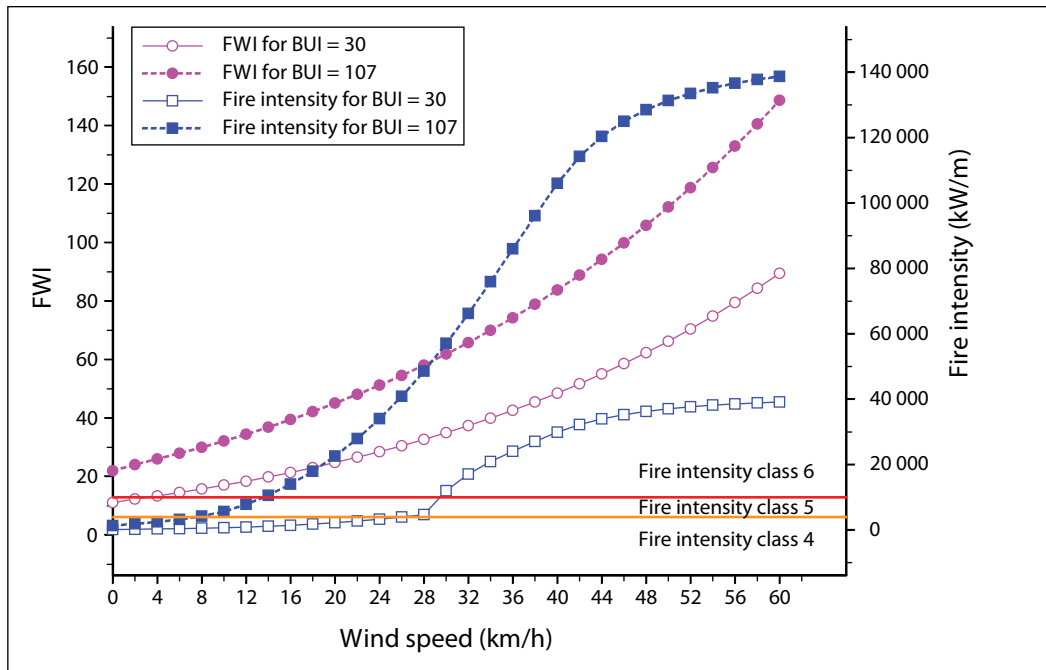


Figure 25. Fire Weather Index (FWI) and fire intensity for fuel type C-3 (mature jack or lodgepole pine) as a function of wind speed. BUI = Buildup Index.

From the standpoint of sensitivity of fire intensity class to measurements of wind speed, it is clear from Figures 24 and 25 that an error of 8 km/h in measuring, estimating, or forecasting wind speed would underestimate (or overestimate) predicted rate of spread by 100% in the steep portions of the S-curves for fuel type C-3. Similarly, an error of just 2 km/h in wind

speed would produce a difference of 4 m/min in the basic rate of spread for C-3 fuel. Coupled with a low BUI of 30, this small change in rate of spread would cover most of the range of intensity class 5 (Fig. 25) and, significantly, the transition from surface fire to crown fire, an important fire behavior threshold for suppression effectiveness and crew safety.

FIRE WEATHER FORECASTING

In Canada, general weather services are provided to the general public by the Meteorological Service of Canada (MSC), Environment Canada. Weather forecasting services in support of fire management agencies are produced at several levels, as described below.

The MSC performs a comprehensive program of meteorological data acquisition across Canada. These data, consisting of observations of weather elements from the earth's surface into the stratosphere, are used to prepare public forecasts and warnings and to provide information to meet the general requirements

of all users. Processed information is distributed from the Canadian Meteorological Centre (located in Montréal) to the five storm prediction centers across the country.

Forecasters at the five MSC regional storm prediction centers (Atlantic Region, Quebec Region, Ontario Region, Prairie and Northern Region, and Pacific and Yukon Region) provide detail on the behavior of global and medium-sized weather systems for their respective areas. In this way, the forecasters can be much more specific as to the timing and occurrence of local weather features.

Fire weather forecasts are provided by contractors or employees of the fire management agency. The organization providing the service varies from agency to agency, and these organizations are flexible enough to serve the specific needs of the user agencies.

Fire Weather Forecasts

A desirable method of providing a specialized fire weather forecasting service is to have meteorological personnel functioning as an integral part of the fire management agency. This approach allows appropriate emphasis on the weather factors that are significant to the user agency (e.g., duration of dry spells, frontal passage, local wind patterns, lightning activity). Direct, one-to-one contact between meteorologist and fire management officer ensures that the former is kept informed of changing weather requirements as they develop and the latter is able to request specific details and get some feel for the reliability of forecast information.

It is not possible to measure more than a small sample of weather. The MSC, in cooperation with other national weather services, operates a synoptic network of weather stations that is adequate for sampling on a global or continental scale. These stations are, of necessity, located in well-exposed sites and are usually representative of nonforested areas.

A much larger network of fire weather stations is needed if reliable fire weather forecasts are to be prepared at a scale suitable for efficient and effective fire management. These additional specialized stations are necessary to fill the gaps between synoptic stations and to enable individual fire weather forecasters to provide the amount of detail and the precision required for spot forecasts for specific locations, for interpretation in terms of fire behavior.

Fire Danger Forecasts

Routine calculation of the six standard components of the FWI System, usually performed daily for the regional fire weather network with a computer program (Van Wagner and Pickett 1985), results in an estimate of fire potential for the current afternoon period. Because the FWI System is designed entirely as a function of weather, forecast values for the codes and indices can be produced readily from the forecast values of the necessary weather elements.

One of the problems in calculating and using forecasted fire danger indices is the inherent difficulty in forecasting two of the fire weather elements to which the FWI is most sensitive: rain and wind. This challenge is offset somewhat by the fact that the need for precise danger forecasts is reduced with the occurrence of any appreciable rainfall.

Forecasts of numeric values have traditionally been presented as single figures, sometimes rounded to the nearest 5 or 10 units. This presentation implies that the forecasted value is expected to occur, and that all other values are not expected. In reality, the forecast value is usually the most probable value, and there may be a number of other values with an expectation only slightly less than the one indicated. Forecasters can improve on single-value forecasts by assigning the probabilities of occurrence to each range of values for each forecast element. This approach goes beyond simply forecasting the probability of precipitation, to assigning the probability in several rainfall amount classes.

Two basic approaches to fire danger forecasting are in current use: area averaging and point forecasting. These approaches are described briefly here.

In regions where the scale of significant fire weather patterns is large enough to be represented by several observing stations over the area, the weather observations from these stations are averaged together before the day's fire danger indices are calculated. The forecasted fire danger indices for the next day use the current day's fire danger calculation for the area, together with the next day's forecast weather observations for the area, such that the numbers issued by the forecaster represent an average index for the area as a whole. This technique minimizes some of the difficulties associated with variability in rain and wind from station to station.

The point forecasting approach is used in mountainous regions, such as British Columbia, where topography forces the fire weather pattern into a fine-scale mosaic. A number of areas or weather zones with fixed boundaries are selected, and one or more reference weather-observing stations are chosen to represent at least some part of each zone. Indices are calculated for the observed and forecasted weather for these specific station locations. This approach recognizes that index values at certain locations

within each zone will be markedly different from those at the selected station. These differences can be allowed for, at least qualitatively, on the basis of recognized features of the landscape.

Various agencies are investigating the application of meso-scale weather models to fire danger and fire behavior prediction. Similarly, the USDA Forest Service has been evaluating its MM5 meteorological I model at hourly time scales and at spatial resolutions that may be useful for producing NFDRS predictions for both fire danger rating and fire behavior prediction. Hoadley et al. (2006) simulated an extreme fire event by applying MM5 model predictions of weather elements to compute gridded predictions of NFDRS indices in a case study of the 2000 fire season in northern Idaho and western Montana. They found that the model's predictions of fire danger indices were consistently lower than the observed indices; however, the results indicated that the MM5 weather model had captured trends and extreme changes in the NFDRS indices reasonably well. Of the three spatial resolutions tested (36, 12, and 4 km), the best results were consistently obtained for the 4-km domain.

As in many Canadian fire management jurisdictions, once-daily manual observations in the United States have, for the most part, been replaced by remote automatic weather stations that collect weather data hourly. However, as in the CFFDRS, the NFDRS rating is calculated (as a regulated requirement) only once a day, at 1300 LST, to represent the midafternoon peak of fire danger conditions. Now, the advent of operationally accessible, high-resolution meso-scale models to produce regional weather predictions in near-real time has opened the door for US fire managers to obtain fire danger predictions at finer temporal and spatial resolutions than have previously been available (Hoadley et al. 2006).

Nonetheless, in their case study, Hoadley et al. (2006) found that the US meso-scale weather model (the MM5 model) contained systemic bias toward overprediction of relative humidity and overestimation of predicted rainfall, which in turn led to errors in hourly predictions of the energy release component and the burning index that may be too large for practical application in fire operations. Those authors noted that improvements in MM5 real-time predictions for the Pacific Northwest are planned as a way to mitigate the modeled bias in relative humidity and temperature. Similarly, Canadian applications of meso-scale weather models to operational

predictions of CFFDRS components should be carefully evaluated for systemic bias before the new modeling technology is implemented by fire management agencies.

Meso-scale weather models have been evaluated for their potential application in forecasting fire behavior conditions over complex terrain in Canada since at least 1998 (Anderson et al. 1998). In a study geared to Jasper National Park, Alberta, Anderson et al. (1998) defined the meso-scale (after Huschke 1959) as the state of the atmosphere as it exists between meteorological stations, denoting a range of atmospheric scales from 200 to 2 km and the scale at which forest fires occur and interact with the atmosphere. Accurate weather-prediction models at the meso-scale would enhance the ability to model fire growth and micro-site fuel moisture conditions, especially in complex terrain.

Anderson et al. (1998) tested two meso-scale weather models, the Regional Atmospheric Modelling System (RAMS, University of Colorado, Denver, and *ASTER division of Mission Research Corp.) and the Meso-scale Comprehensive Community (MC2, Cooperative Centre for Research in Meteorology, Environment Canada, Montréal, PQ), for their ability to forecast fire weather and fire behavior conditions in the mountainous terrain of Jasper National Park, which is located in the Rocky Mountains just east of the continental divide. RAMS was run at spatial-resolution grids of 64, 16, 4, and 1 km and at 21 atmospheric levels to a height of 17 km. MC2 was set up on three different grids (35, 10, and 2 km resolution). Model validations were run against a network of five automatic fire weather stations collecting hourly observations of precipitation, temperature, relative humidity, and wind speed and direction. The RAMS model predicted humidity well, but its predictions of wind in rugged terrain were poor. The MC2 model was better for wind but was still not usable at an operational fire management level, explaining at best 36% of the variation. The authors attributed the poor performance of the models to the complexity of the topography.

Fire Behavior Forecasts

Current applications of the two main subsystems of the CFFDRS have extended well beyond traditional fire prevention and the setting of preparedness levels. Now, fire-weather-based information systems include quantitative predictions of fire behavior on an hourly basis

across landscapes, geared to work-site safety issues, the setting of evacuation strategies, and many other uses (Alexander and Thomas 2004).

Beck et al. (2002) described one such operational fire management methodology which coupled three-day fire weather forecasts with local information on fire environment, including fuel types, fuel moisture, and slope steepness, to forecast diurnal variations in fire intensity, based on outputs from the FWI and FBP systems. For situations in which forecasted weather lacks sufficient diurnal resolution, climatologically based models of air temperature, wind speed, and relative humidity (given daily maximum and minimum values, latitude, and date) have been developed (Beck and Trevitt 1989).

Fire management agencies must anticipate wind events and extreme fire behavior and must communicate this information to workers who may be at risk, particularly with respect to fire suppression strategies and tactics. Fire behavior advisories may be issued at various levels, as is the case in British Columbia (Beck et al. 2002), where the provincial headquarters issues wind warnings for broad areas, regional fire centers issue wind warnings and fire behavior warnings by fuel type for broad areas, and a fire behavior officer issues fire behavior warnings for specific sections or fuel types of specific fires.

Although the federal MSC has the legal mandate to issue public weather warnings, the responsibility for issuing fire weather advisories and warnings rests largely with provincial and territorial fire management agencies.

Implications of Fire Weather: Fire Management Information Systems

Lee et al. (2002) described four national forest fire management information systems currently used in Canada, and detailed some of their implications for the management and manipulation of fire weather data.

The first information system is the CFFDRS, a nonspatial system that is the main subject of this weather guide. The second system is the sFMS, a GIS-based fire management information system that uses the two core subsystems of the CFFDRS, the FWI System and the FBP System. The sFMS is the spatial engine used to implement both of Canada's national forest fire management information systems, the Canadian Wildland Fire Information System (CWFIS) and

the fire monitoring, mapping, and modeling system (Fire M3).

The CWFIS presents daily information on fire weather, fire behavior potential, and selected upper atmospheric conditions. Fire M3 uses satellite technology to monitor and map the occurrence of large fires in Canada. Fire M3 also incorporates information from CWFIS to model the impacts of large forest fires on the basis of fire weather conditions and potential fire behavior.

The sFMS has been designed to support a range of fire management functions, from the formulation of policy to fire-suppression decision support (Lee et al. 2002). The system is used primarily with current weather data and short-term forecasts to provide daily or hourly maps of fire weather, fire behavior, ignition probability, and attack time. It is also used with long-term climate forecasts to predict the impacts of climate change on fire danger, area burned, fuel consumption, and greenhouse gas emissions.

The CWFIS, in operational use since 1994, was developed to provide a national overview of daily wildland fire conditions for national reporting (Lee 1995); as such, it is used daily by the Canadian Interagency Forest Fire Centre. The CWFIS employs sFMS as its underlying software and operates automatically from the Northern Forestry Centre of the CFS in Edmonton, Alta.

The CWFIS collects hourly weather data from about 1500 weather stations across Canada, of which about half are operated by the federal government and about half by provincial and territorial fire management agencies. Data are also gathered from about 15 weather stations in the United States, along the international borders. The data from all of these stations are processed by sFMS to produce daily maps of the various components of the FWI and FBP systems within the CFFDRS. Lee et al. (2002) noted that weather data are interpolated between weather stations to produce surfaces for each FWI System input (24-h precipitation, temperature, relative humidity, and wind speed) and for wind direction. Interpolation procedures include adjustments of temperature and relative humidity for elevation. Cartographic modeling is then performed on these weather data surfaces to compute values for both the FWI System and the FBP System at 2-km cell resolution.

The Fire M3 system for monitoring, mapping, and modeling active large fires also

has implications for the underlying system for collecting fire weather data across Canada. As Lee et al. (2002) explained, Fire M3 integrates data from CWFIS to provide point estimates of fire weather conditions, FWI System component values, and potential fire behavior (i.e., values for selected FBP System components) at hot-spot locations.

A new fire growth model called Prometheus is now being developed. This deterministic fire growth simulation model uses spatial fire behavior

input data on topography (slope, aspect, and elevation) and FBP fuel types, along with weather streams, which are sequential observations or forecasts, currently at a temporal resolution of 1 h, becoming variable in temporal resolution as development proceeds. The development of Prometheus (<http://www.firegrowthmodel.com>) is a national interagency project led by Alberta Sustainable Resource Development and endorsed by the Canadian Interagency Forest Fire Centre and its members.

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APPENDIX 1

THE BEAUFORT SCALE FOR ESTIMATING 10-m OPEN WIND SPEEDS

Appendix 1. Beaufort scale for estimating 10-m open wind speeds

Force or number	Wind speed (km/h)		Description	Observed wind effects
	Range	Mean		
0	< 1	0	Calm	Smoke rises vertically
1	1-5	3	Light air	Direction of drift shown by smoke drift but not by wind vanes
2	6-11	9	Light breeze	Wind felt on face; leaves rustle; vanes moved by wind
3	12-19	16	Gentle breeze	Leaves and twigs in constant motion; wind extends light flag
4	20-28	24	Moderate breeze	Raises dust and loose paper; small branches are moved
5	29-38	34	Fresh breeze	Small trees in leaf begin to sway; crested wavelets on inland waters
6	39-49	44	Strong breeze	Large branches in motion, whistling in telephone wires, umbrellas used with difficulty
7	50-61	55	Moderate gale	Whole trees in motion; resistance felt when walking against wind
8	62-74	68	Fresh gale	Breaks twigs off trees, generally impedes progress
9	75-88	82	Strong gale	Slight structural damage occurs
10	89-102	96	Whole gale	Seldom experienced inland; trees uprooted; considerable structural damage
11	103-117	110	Storm	Very rarely experienced; wide-spread damage
12 or above	118+	> 125	Hurricane	

Note: Beaufort scale is adapted from List, R.J. 1951. Smithsonian meteorological tables. 6th rev. Ed. Smithsonian Inst. Press, Washington, D.C.

Source: Taylor, S.W.; Pike, R.G.; Alexander, M.E. 1997. Field guide to the Canadian Forest Fire Behavior Prediction (FBP) System. Nat. Resour. Can., Can. For. Serv., North. For. Cent., Edmonton, AB. Spec. Rep. 11. Reprinted with permission.

APPENDIX 2

COMPARISON OF HOURLY AND DIURNAL MODELS FOR THE FINE FUEL MOISTURE CODE

The Fine Fuel Moisture Code (FFMC) is the component of the Canadian Forest Fire Weather Index (FWI) System that tracks, in code form, the moisture content of fine dead forest fuels on the surface of the forest floor. One of three methods (algorithms) can be used to calculate an FFMC value:

- Standard daily FFMC, calculated from weather observations taken at “noon” local standard time (LST) according to specifications of the FWI System (Canadian Forest Service 1984; Van Wagner and Pickett 1985), describes the midafternoon (1600 LST) state of fine fuels, forecasted from noon weather conditions.
- Diurnal FFMC is calculated for each hour around the clock without the need to input hourly weather data. Typical (midlatitude) diurnal weather trends, with no rain, are assumed. The original tabular versions of diurnal FFMC (Muraro et al. 1969; Van Wagner 1972; Alexander 1982a), which did not extend around the clock, have now been computerized and updated to allow calculation of FFMC for every hour around the clock (Lawson et al. 1996). A tabular version of the computerized diurnal FFMC developed by Lawson et al. (1996) was included in the field guide to the Canadian Forest Fire Behavior Prediction (FBP) System (Taylor et al. 1997). Diurnal FFMC is applicable to latitudes from 48° N to 60° N, and an input of relative humidity class is required to calculate diurnal FFMC for the period from 0600 to 1159 LST.

The current version of the program `Diurffmc.c` (C source code created by B. Armitage for Lawson et al. [1996]) is available from the Canadian Forest Service, along with an explanatory description of the code and its executable program (`Diurnal Ccode.doc`, in MS Word).

- Hourly FFMC (Van Wagner 1977) is calculated by an hourly FFMC program that uses continuous hourly weather inputs (temperature, relative humidity, wind speed, and rainfall). The current version of program `HFFMC.c` (the program for hourly FFMC, written in C code) is also available from the Canadian Forest Service, along with an explanatory description of the code and its executable program (`Hourly Ccode.doc`, in MS Word).

Although once-daily calculation of FFMC (i.e., the standard daily FFMC) is usually adequate for fire prevention and preparedness planning, finer

resolution of the predicted moisture content of fine fuels has been recommended for quantitative predictions of fire behavior using the FBP System (Forestry Canada Fire Danger Group 1992). The Forestry Canada Fire Danger Group described the same three options for calculating FFMC values, noting that hourly FFMC yields the most representative FFMC and Initial Spread Index (ISI) but also demands the most weather data.

In the context of operational application of the FBP System for quantitative fire behavior prediction, all three options for calculating FFMC use actual or forecasted wind speed for the time and area of interest to calculate the ISI. With Option 1, the standard daily FFMC can be used with an updated afternoon wind speed to compute a wind-adjusted ISI for any time of the afternoon up to the typical peak of 1600 h LST. Option 2, Diurnal FFMC extends the time period from 1200 to 2000 h LST for which an adjusted FFMC (and ISI, if an updated wind speed is available) can be calculated; however, the assumed diurnal weather curve is a restriction (Forestry Canada Fire Danger Group 1992).

Differences will exist between the standard daily FFMC (calculated from noon LST weather observations) and the midafternoon FFMC values computed from hourly weather data with the hourly FFMC program. According to the Forestry Canada Fire Danger Group (1992), the hourly FFMC should be regarded as the “true” value and should be archived as the reference FFMC on which any future fire behavior analysis would be based. However, the next day’s codes are derived from the standard daily FFMC, rather than from the diurnal or hourly FFMC. The user must be aware of the differences in the FFMC models underlying the various computational schemes, so that a knowledgeable decision can be made about which method of computing FFMC is most appropriate in a given situation.

For example, diurnal FFMC can be used only in the absence of rain, since it simply extrapolates the standard daily FFMC for 24 h into the future. The effect of any rain event will not be incorporated into the calculation of diurnal FFMC until after the next noon readings are taken. By contrast, hourly FFMC responds immediately to each hourly rainfall amount, and the calculated hourly FFMC value is reduced accordingly. The responses of diurnal FFMC and hourly FFMC to an afternoon rain event of 12.2 mm are widely divergent during the hours following the rainfall but converge again the following afternoon (Fig A2.1).

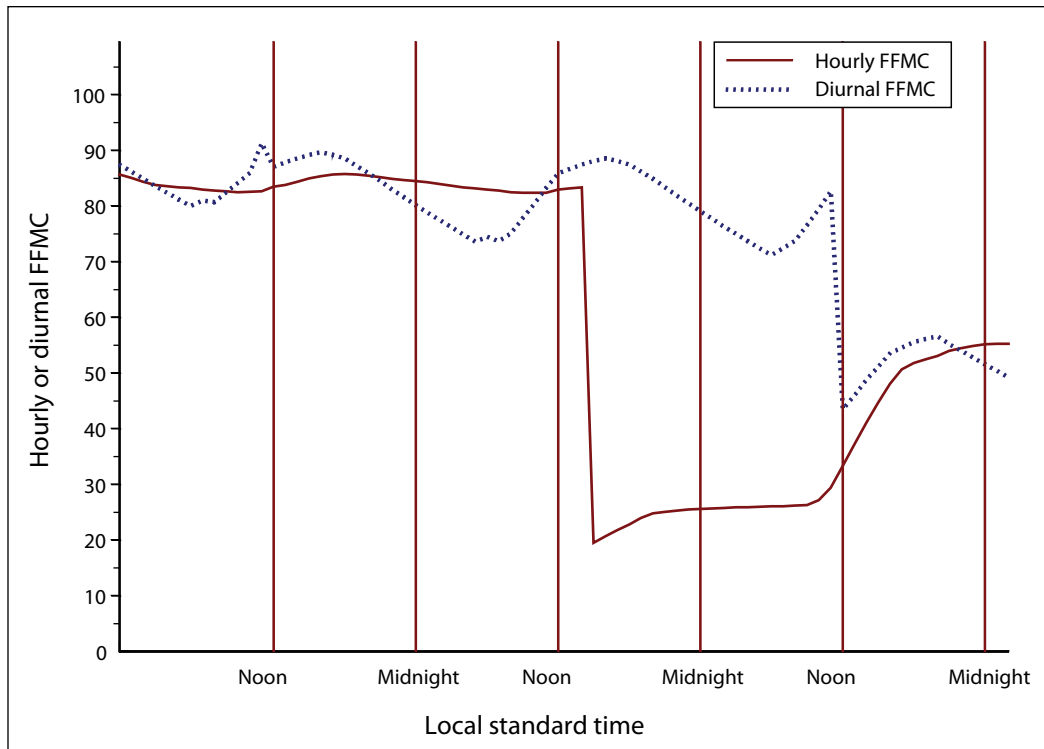


Figure A2.1 Responses of hourly (VanWagner 1977) and diurnal (Lawson et al. 1996) models of Fine Fuel Moisture Code (FFMC) to a rain event in the early afternoon hours.

Users should be aware of a problem with the hourly FFMC algorithm that occurs in the absence of rain. In this situation, the diurnal amplitude of the hourly FFMC curve is unrealistically restricted during the nighttime hours. The consequence of using hourly FFMC during extended dry periods is that predictions of fire spread generated through the FBP System (or simulations of fire growth generated by a fire growth model such as Prometheus) will predict fire growth at night in excess of what would be expected in nature. In such excessively dry situations, the diurnal FFMC provides a more realistic indication of the diurnal variation in FFMC between daytime and nighttime (Fig. A2.2).

Furthermore, the restricted amplitude of the hourly FFMC leaves it significantly lower than

diurnal FFMC during the peak fire danger hours in the afternoon (Fig. A2.2). In the example shown, the FFMC curves generated by the two algorithms diverge in the morning hours, then converge to the same value at noon, because at that point the diurnal FFMC picks up the day's noon weather readings; the curves diverge again toward the midafternoon peak, such that diurnal FFMC is 1 or 2 FFMC units above the hourly FFMC. This difference between the two FFMC algorithms means that hourly ISI values calculated from the diurnal FFMC are higher (typically by 2 to 5 units) than those calculated with the hourly FFMC; this difference in turn results in significantly higher predicted rates of spread and fire growth projections.

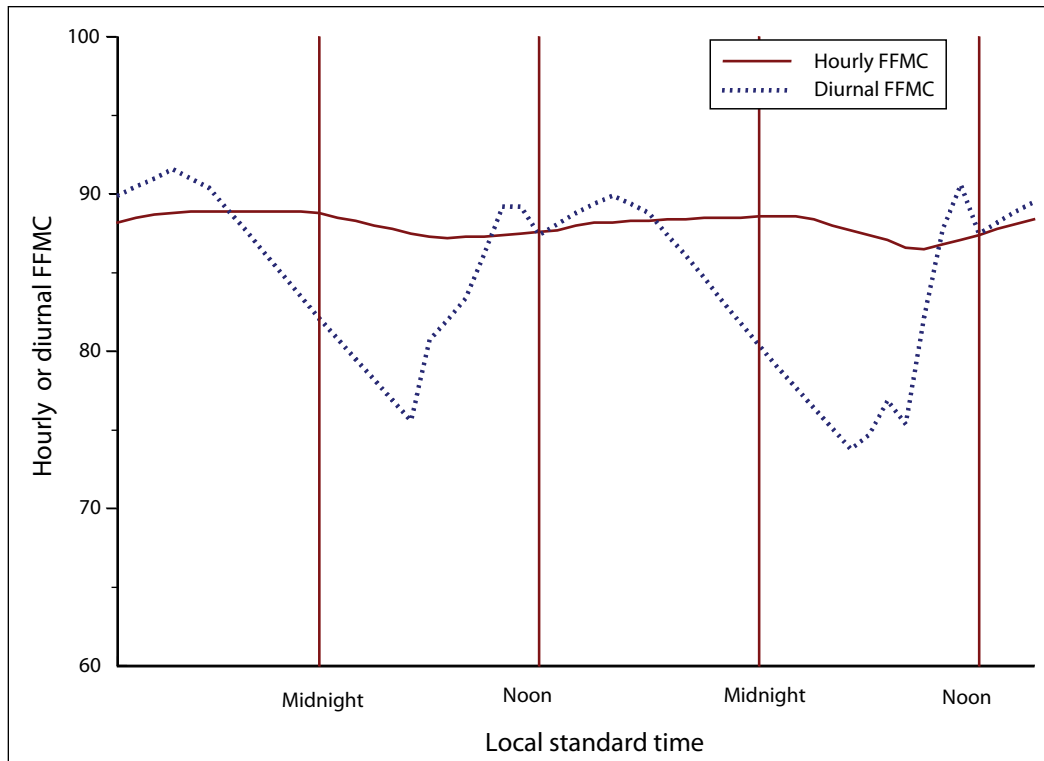


Figure A2.2 Typical trends for the hourly (Van Wagner 1977) and diurnal (Lawson et al. 1996) models of Fine Fuel Moisture Code (FFMC) in the absence of rain.

Beck and Armitage (2004) documented these differences between the two FFMC algorithms in the context of predicting in-stand fine fuel moisture content at latitudes north of 60°. They found that, for dry days, diurnal FFMC best described the amplitude of the moisture content of feathermoss, *Pleurozium schreberi* (Brid.) Mitt., fuels throughout the day, whereas the amplitude of the moisture content of jack pine, *Pinus banksiana*, needles was better described by hourly FFMC. The algorithms for both hourly FFMC and diurnal FFMC overestimated the minimum moisture content of feather moss and jack pine needles on dry days, and both models overestimated needle moisture content and underestimated feathermoss moisture content after rain.

The diurnal FFMC model has certain limitations related to where and how it was developed. The algorithm was derived from midlatitude field experiments, so it is not recommended for use north of 60° latitude. The diurnal trends in FFMC were developed for a site at 54°22' N, 60 km north of Prince George, B.C., and are typical of midlatitude trends in Canada. However, these

relations may not be applicable for latitudes north of 60°, where litter moisture can remain at midafternoon levels throughout the early evening hours (Beck and Armitage 2004).

Furthermore, the diurnal FFMC model was developed using litter that consisted of lodgepole pine (*Pinus contorta*) needles, and the tips of both feather moss and reindeer lichen (*Cladonia* sp.); the litter was destructively sampled in situ. While such a mixture of litter fuels, sampled as they rest naturally on the forest floor, may be the most representative of real-world moisture conditions, it may be difficult to calibrate the resulting moisture model to other litter types, weather regimes, or latitudes.

Although both the diurnal and the hourly FFMC models have advantages and disadvantages, overall the hourly FFMC is preferable, because actual or forecasted hourly weather data can be used to compute the hourly FFMC values. This feature avoids the problem of any particular weather cycle deviating considerably from the standard diurnal trend, depending on latitude, season or day length, and terrain (Beck and

Armitage 2004). As mentioned, north of 60° N latitude, day length may have a significant impact on the timing and duration of the minimum fine fuel moisture content (Lawson et al. 1996), because maximum overnight humidities are significantly lower, and maximum overnight temperatures higher, than at lower latitudes.

Beck and Armitage (2004) summarized the development of the hourly FFMC as follows:

Van Wagner developed the Hourly FFMC model (Van Wagner 1977) via simple modifications to the daily FFMC model, under the assumption that the fine fuels represented by the FFMC dry quickly enough to undergo a substantial diurnal trend in moisture content that can be superimposed on the larger day-to-day trend. In the derivation of the daily FFMC in the absence of rain, a log wetting or drying rate in units of log moisture content per day, or per 24 hour period, was assumed. For practical purposes, wetting and drying rates are actually described mathematically using exponential functions and the moisture content of the fine fuels increases or decreases towards its equilibrium.

By trial and error, hourly drying and wetting rates were chosen to yield the desired day-to-day trend while producing realistic hourly trends. Rates of change equal to 1/8 of the standard daily rates appeared to yield the best results when evaluated ocularly against typical trends for jack pine needle litter at selected sites near the Petawawa National Forest Institute in Ontario. These litter samples were exposed in trays under plastic shelters that were weighed periodically rather than having been collected by destructive sampling.

The effect of rainfall on the moisture content of fine fuels is similar in both the daily and hourly FFMC models, except the first 0.5 mm of rain over a 24 hour period is ignored in the daily FFMC, whereas the first 0.5 mm of rain is not excluded in the hourly FFMC. However, the effects of hourly rainfall were not studied in detail and have yet to be field validated. Moreover, Van Wagner (1977) acknowledged that a complete verification of the hourly and daily FFMC models would require a great deal of field work. [As discussed earlier in

this Weather Guide] Pech (1989) produced a variation on the FFMC that improved day-to-day prediction of the moisture content of the top 3–4 cm layer of reindeer lichen (*Cladonia rangiferina*).

Beck and Armitage (2004) concluded that their field study results were unsurprising, given that the performance of the theoretical hourly FFMC model had been calibrated against data from trays of jack pine needle litter, whereas the diurnal FFMC model had been developed for litter composed of lodgepole pine needles and the tips of both feathermoss and reindeer lichen. They explained that the differences in moisture content between the needle fuels sampled by Van Wagner (1977) and those collected in their field study north of 60° latitude may be attributed to the fact that Van Wagner (1977) worked with a needle litter bed in sample trays and plastic shelters. By contrast, both the northern field study and the field study that led to the diurnal FFMC (Lawson et al. 1996) used destructive fuel sampling methods and natural wetting and drying.

Beck and Armitage (2004) also pointed out that the standard daily FFMC scale equation ($FFMC = 59.5[250 - m]/[147.2 + m]$) relating FFMC to litter moisture content (m) (Van Wagner 1987) is a theoretical curve developed specifically for pine needle litter. Van Wagner (1987) explained the rationale for the revised equation as follows: "1) The real moisture content of pine litter ranges up to about 250%; 2) A realistic moisture scale was desired to render the standard FFMC compatible with future developments in fine fuel prediction."

Van Wagner (1987) pointed out that the original Tracer Index, a precursor of the FFMC, was presented in the simple code form of 150 minus moisture content. This led to the first FFMC ("old") scale equation ($FFMC = 101 - m$), which was used in the first three editions of the FWI System but was revised in 1984 for the reasons given above. As Van Wagner (1987) summarized:

This [fine fuels (FF)] scale [$FFMC = 59.5 (250 - m) / (147.2 + m)$] permits realistic conversions from code to moisture content, allows the internal operation of the FFMC to be carried out on moisture content value, and retains the traditional code scale for quoting the FFMC itself. Furthermore, the formal artificial 2% minimum limit on moisture content is no longer deemed necessary in computing practice. The potential code scale length is now 101.

Van Wagner (1987) went on to describe in detail his analysis of the drying and wetting phases of the original Tracer Index, including the determination of log drying rates, hysteresis effects as equilibrium values are approached after drying or wetting, temperature effects, and wind effects, all of which resulted in the new algorithm for standard daily FFMC. Rather than describing the standard daily FFMC now in use and its moisture content conversion (FF) equation as “theoretical,” it is probably more correct to describe them as a blend of empirical field study (based on the original Tracer Index from the 1930s), modern physics theory, and laboratory evidence (such as the effect of wind on drying and the effect of atmospheric wetting at high humidity described by Van Wagner [1979]).

Lawson et al. (1996) further elaborated on the various historical FFMC scale equations and their derivations, with respect to how they relate to the current hourly and diurnal FFMC models. These authors noted that the *F*-scale equation ($F = 82.90[250 - m]/(205.20 + m)$), developed by Van Wagner (1972) to better link actual fine fuel moisture content to the FFMC, was based on the diurnal FFMC field data sets from Prince George, B.C., and another data set from jack pine litter at Petawawa, Ont. The *F*-scale curve lies slightly above the curve for the standard daily FFMC equation (i.e., the FF-scale) but coincides at both dry and wet end points.

This same *F*-scale equation was adopted by Van Wagner for his 1977 hourly FFMC model. However, in 1984, Van Wagner revised the hourly FFMC, converting it to the same FF-scale equation that is used for standard daily FFMC.

Lawson et al. (1996) also replaced the *F*-scale and adopted the FF-scale for the computerized version of the diurnal FFMC. Thus, all three of the current FFMC models (standard daily FFMC, diurnal FFMC, and hourly FFMC) use the same scale equation linking FFMC to moisture content. The effects of computerizing the diurnal FFMC and changing the scale equation were reported by Lawson et al. (1996) to be approximately a 1% difference in predicted moisture content across the entire range of possible inputs, with a maximum absolute difference of 4.6 at

the wet end in terms of FFMC, when the scale equation change was also factored in. The “new” diurnal FFMC values trend lower than the “old” Van Wagner (1972) diurnal FFMC values.

Finally, it is essential to note the results of Wotton and Beverly (2007), who analyzed a large dataset of litter moisture measurements collected by CFS at several sites across Canada over the period 1939 to 1961. They found a significant influence on the relations between FFMC and litter moisture content of the upper duff layer. While these authors presented a model that adjusts the standard FFMC value for these influences, they do emphasize that as surface fuels become very dry, differences between stand types (deciduous compared with pine), season (spring, summer, fall), and across stand densities tend to disappear. Only samples above standard FFMC 75 were analyzed for the model, and diurnal FFMC was used to estimate FFMC value for the time of collection of each litter sample.

A validation dataset was collected by the authors during the summer of 2004 near Sault Ste. Marie, Ontario. Observed litter moisture contents from a range of forest fuel types were correlated against moisture contents converted from Standard FFMC (“raw”), diurnal FFMC, and hourly FFMC, as well as the predicted moisture contents from their “stand-adjusted” model. For this dataset, stand-adjusted moisture content estimates from each of standard FFMC, diurnal FFMC and hourly FFMC were more strongly correlated with the observed moisture content than raw moisture content values calculated from standard FFMC using the standard formula. The improvement in correlation was strongest for deciduous and mixedwood types, while jack pine forests showed little difference. This is because there is little difference between the standard formula and the development model for pine-moderate (stand density)-summer. However, litter moisture estimates for red pine were not improved by the stand type model, and in fact, had a lower correlation than using diurnal FFMC, because red pine litter tends to be drier than litter that sits more directly on the wet forest floor.

Conclusions

The three FFMC models in current use were derived in different ways and have undergone revision since their original development. Each model has pros and cons, but it should be remembered that the standard daily FFMC has proven a robust model of fine fuel moisture content. In their study conducted north of 60° latitude, Beck and Armitage (2004) found that although FFMC slightly overestimated the moisture content of jack pine needles and greatly overestimated the moisture content of feathermoss, these differences were small for both litter types for FFMC values within the range of flammability (FFMC > 77). FFMC and litter moisture content correlated very well in spite of the documented differences in litter fuels, sampling methods, stand characteristics, and latitude between the study conditions and those for the original model.

Five of Beck and Armitage's (2004) conclusion are worth repeating here:

- Differences in understory and overstory stand densities measured at the two study sites north of 60° did not have a significant effect on the moisture content of fine fuels such as feathermoss and needle litter, which are described by FFMC. Care should be taken before pooling such data in the development of moisture models however, since a high moisture content of the partially decomposed lower horizons of the duff may slow the drying rate of the top layer of duff or litter.
- Moisture content data for feathermoss and needle litter were used to assess performance of Diurnal FFMC and Hourly FFMC models. Diurnal FFMC best described the amplitude of feathermoss moisture content variations throughout the day, while Hourly FFMC best described the amplitude of jack pine needle litter.
- Hourly FFMC and Diurnal FFMC models were not in synchrony, even on typical dry days, because they were based on slightly different fuel types with different amplitudes in moisture content throughout the day.
- Discontinuities in the Diurnal FFMC model occur at transition phases (0700h and 1300h DST [daylight saving time]), and these are especially noticeable when rainfall occurs. Once a rain event begins, outputs from Diurnal FFMC should not to be considered applicable until the rain stops, and all rainfall effects have been applied to reset the current day's FFMC.
- Fixed stand characteristics and a common standard fuel should be used for the models that support standard daily FFMC and hourly FFMC and moisture predictions within the CFFDRS. Given an appropriate model to predict fuel moisture content from FFMC, the Hourly FFMC model needs to be studied in more detail and possibly re-parameterized to correctly describe the wetting and drying rates of jack pine needles or feathermoss.

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APPENDIX 3

LATITUDE CONSIDERATIONS IN ADAPTING THE CANADIAN FOREST FIRE WEATHER INDEX SYSTEM FOR USE IN OTHER COUNTRIES

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Introduction

Latitude, along with season or time of year, influences the effective day length (Fig. A3.1) and thereby the amount of drying that occurs

on any given day. For example, a day in June in British Columbia at 54° latitude has almost twice the drying power as a day in September with the same weather conditions (Lawson 1977).

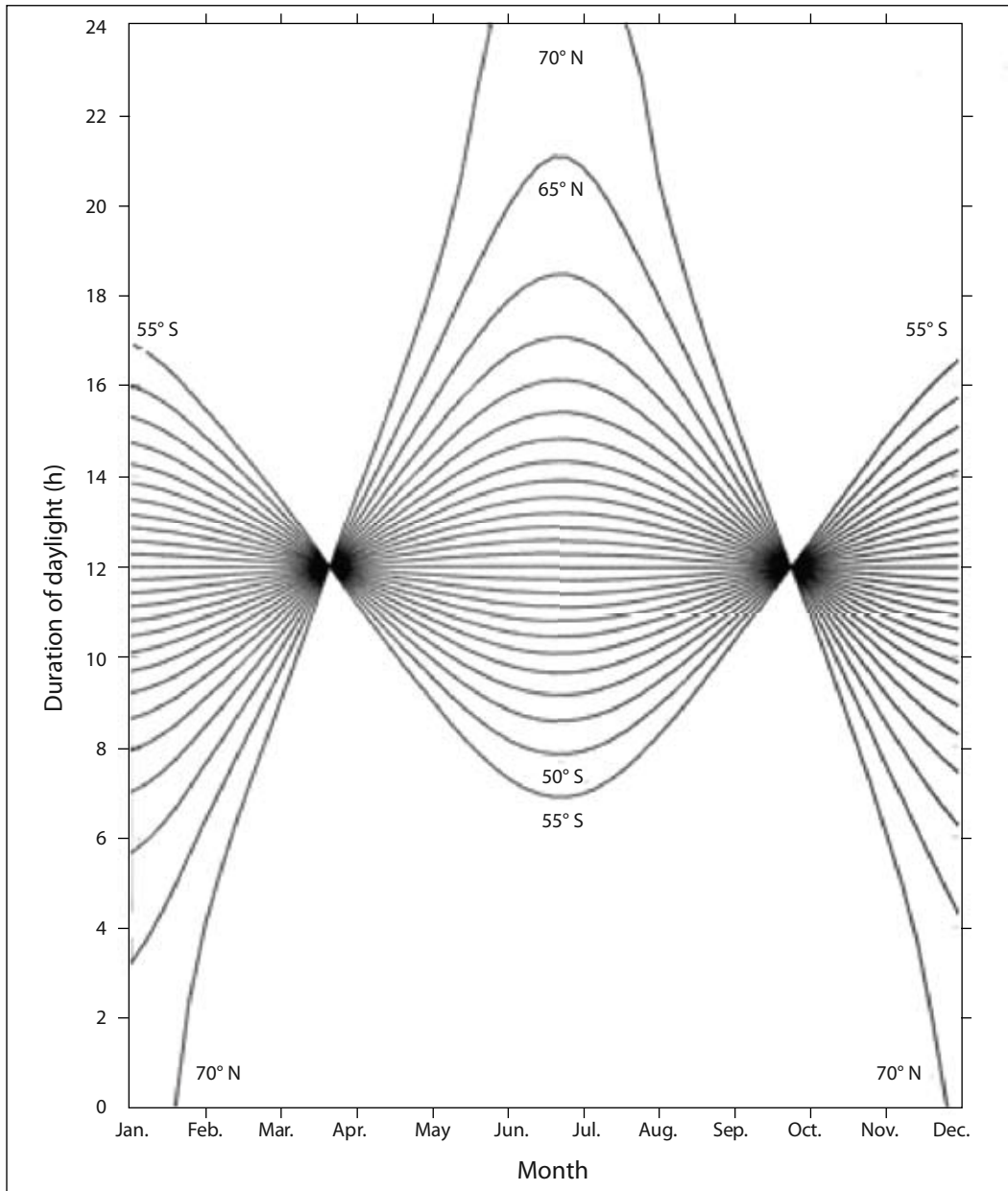


Figure A3.1 Duration of daylight as a function of time of year and latitude for the wildland fire-prone regions of the world, based on equations given in Whiteman and Allwine (1986).

In the development of the Canadian Forest Fire Weather Index (FWI) System, these seasonal effects were accounted for in the Duff Moisture Code (DMC) by an effective day length factor (L_e) and in the Drought Code (DC) by a seasonal day length adjustment factor (L_f). Details regarding the derivation of L_e and L_f were presented by Van Wagner (1970) and Turner (1972), respectively, and will not be covered here, except to say that the derivation of both factors was largely empirical, although for the DMC, “The daylength, varying with season, has an effect roughly proportional to three less than the number of hours between sunrise and sunset” (Van Wagner 1987).

The FWI System was originally designed for the range of fuel and weather conditions found in Canada. However, increasing foreign use of the FWI System and the Canadian Forest Fire Danger Rating System (CFFDRS) has dictated that certain international standards be established. The purpose of this appendix is to discuss how day length considerations in the calculation of the DMC and the DC should be handled for locations outside of Canada.

Canadian Standards and Latitude Effects

The effective range of latitude for lands prone to wildfire within Canada is over 25° (i.e., from about 42° N to about 68° N). As presented by Van Wagner and Pickett (1985) and Van Wagner (1987), a single set of monthly values for L_e and L_f have been assigned for Canada as a whole (see first row of Table A3.1 and Table A3.2, respectively). These quantities are referred to collectively as the “Canadian standard” (Van Wagner 1987) and are, strictly speaking, valid for only one latitude. This has generally come to be considered as 46° N because the fieldwork associated with the development of the DMC and in turn the L_e values was undertaken at the Petawawa Forest Experiment Station in eastern Ontario, (Van Wagner 1970), although Valentine (1978) considered the reference latitude to be 45° N. However, the L_f values associated with the DC were based on data from 32 climatic stations in British Columbia (Turner 1972), which effectively cover a latitude range from about 49° N to about 60° N.

Table A3.1 Monthly day length adjustment factors for Duff Moisture Code (L_e) in relation to reference latitudes, exclusive of the equatorial region^a

Reference latitude	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
~46° N ^b	6.5	7.5	9.0	12.8	13.9	13.9	12.4	10.9	9.4	8.0	7.0	6.0
20° N	7.9	8.4	8.9	9.5	9.9	10.2	10.1	9.7	9.1	8.6	8.1	7.8
20° S	10.1	9.6	9.1	8.5	8.1	7.8	7.9	8.3	8.9	9.4	9.9	10.2
40° S	11.5	10.5	9.2	7.9	6.8	6.2	6.5	7.4	8.7	10.0	11.2	11.8

^a $L_e = 9.0$ for all months for areas lying between 10° N and 10° S latitude.

^bCanadian standard (Van Wagner and Pickett 1985; Van Wagner 1987).

Table A3.2 Monthly day length adjustment factors for Drought Code (L_f) for northern and southern hemispheres, exclusive of the equatorial region^a

Reference hemisphere	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Northern ^b	-1.6	-1.6	-1.6	0.9	3.8	5.8	6.4	5.0	2.4	0.4	-1.6	-1.6
Southern	6.4	5.0	2.4	0.4	-1.6	-1.6	-1.6	-1.6	-1.6	0.9	3.8	5.8

^a $L_f = 1.4$ for all months for areas lying between 10° N and 10° S latitude.

^bCanadian standard (Van Wagner and Pickett 1985; Van Wagner 1987).

Van Wagner (1970) initially addressed the issue of latitude effects on the DMC in his publication documenting the development of the DMC. He concluded that no correction for latitude was necessary given what is known about the total dose of solar energy varying with latitude and date, although he acknowledged that “some tests ... would be desirable.” His reasoning went as follows:

Consider, for example, the difference in this quantity between latitudes 45 and 55. On June 22, the longest day of the year, the respective energy doses are within 1% of one another, since the longer day length at 55° just compensates for the lower angle of the sun.

By September 22, when all latitudes have a 12-hour day, the energy received at 55° is still 80% of that received at 45°. The difference by then becomes unimportant, since the daily drying factors are much diminished by lower temperatures.

Later on, Van Wagner (1987) examined latitudinal effects on the DMC and DC at 45° N, 55° N, and 65° N using theoretical day lengths and daily weather data. He found that the effect of latitude was fairly gradual, and the resultant differences in season average and maximum values (Table A3.3) were not judged serious or great enough to warrant special DMCs or DCs for different latitudes.

Table A3.3 Results of latitude testing of modified Duff Moisture Code (DMC) and Drought Code (DC) values based on theoretical day lengths for three different locations versus the standard values for a single season of fire weather data (April–October 1967, Lac La Biche, Alberta) (adapted from Van Wagner 1987)

Statistic	45° N	55° N	65° N	Canadian standard
DMC season average	34.5	32.4	30.0	31.9
DMC maximum value	85	83	78	88
DC season average	312	302	274	293
DC maximum value	523	497	436	495

DMC Effective Day Length Factors and DC Seasonal Adjustments for More Southerly Latitudes

Valentine (1978) was the first to derive a specific set of DMC L_e values for a geographic location quite different from Canada, namely New Zealand. Using Nelson as the central point in the country (at about 41° S), Valentine (1978) computed monthly L_e values by subtracting 3 h from the number of hours of sunshine reported in the New Zealand almanac. These values were in turn used in computer and manual calculations of the DMC. Later on, New Zealand adopted a set of L_e values proposed by Alexander (1993) for 40° S latitude (Table A3.1), on the basis of the theoretical mean day length for each month (less 3 h), as computed from formulas presented by Whiteman and Allwine (1986). These were used to produce the DMC and DC drying factor tables found in the FWI System tables now used in New Zealand (NRFA and NZFRI 1993).

In 1992, the author of this appendix, as a member of the Forestry Canada Fire Danger Group, made a proposal (subsequently accepted by the group as a whole) that the L_e and L_f values for latitudes other than Canada be standardized. On the basis of an earlier suggestion by Van Wagner (1988) and the fact that Canada uses a single set of L_e values over a range of latitude of about 25°, reference latitudes of 20° N and 20° S were selected as representing the ranges from 10° N to 30° N and from 10° S to 30° S, respectively. Latitude 40° S, as originally selected by the author for New Zealand (Alexander 1993), was adopted as the other reference point in the southern hemisphere, on the grounds that the need to apply the associated L_e values to any land mass of interest would not extend beyond 55° S. L_e values were computed as per Whiteman and Allwine (1986), using the theoretical mean day length for each month less 3 h (Table A3.1). de Groot and Field (2004) reproduced these values in their documentation of the Southeast Asia Fire Danger Rating System.

Thus, the reference values for L_e (Table A3.1) would be used as follows:

- For areas at the same latitude as Canada and further north, use the Canadian standard values.
- For areas south of Canada to latitude 30° N, use the Canadian standard values.
- For areas between 10° N and 30° N, use the values for 20° N.
- For areas between latitude 10° S and 30° S, use the values for 20° S.
- For areas between latitude 30° S and 55° S, use the values for 40° S.

To give a few practical examples, countries in Europe, including Turkey and all of Russia, as well as the state of Alaska in the United States, would use the Canadian standard values. Honduras, Fiji, and New Zealand would use the values for reference latitudes 20° N, 20° S, and 40° S, respectively.

Inherent in the 1992 proposal but not explicitly stated was the intention that for areas near the equator (i.e., 10° N to 10° S), which experience nearly equal hours of daylight and night, L_e would be simply 9.0 (i.e., 12 h – 3 h [Van Wagner 1970, 1987]). Indeed, de Groot et al. (2007) set $L_e = 9.0$ in their adaptation of the FWI System for Indonesia and Malaysia by taking the average of the mean L_e values for reference latitudes 20° N and 20° S (de Groot and Field 2004).

The author's 1992 proposal included a very simplistic approach with regard to the L_f values for the DC. Because of their highly empirical nature, the decision was made to simply reverse the standard values used in Canada for seasons in the southern hemisphere (cf. List 1951, p. 506), the sole exception being the equatorial region. In other words, the L_f used in Canada in July was deemed applicable for January in the southern hemisphere, Canada's August values would be used for February in the southern hemisphere, and so forth (Table A3.2). There was no consideration for any intermediate reference latitudes as there was for the L_e values for DMC. For areas near the equator (i.e., from 10° N to 10° S), the simplest solution was deemed to be using the mean DC day length adjustment value (i.e., $L_f = 1.4$) year-round, similar to what de Groot et al. (2007) did in their adaptation of the FWI System for Indonesia and Malaysia; the value of 1.4 was based on the annual average value for the northern and southern hemispheres (de Groot and Field 2004).

Discussion and Conclusions

The concepts outlined here have been implemented in the global FWI System calculator contained in the CD-ROM-based training course "Understanding the Fire Weather Index System" (Alexander et al. 2002; St. John and Alexander 2004).

The following question naturally arises: Why retain a tabular approach, as suggested here, when in fact it is quite possible in this modern digital world to make point-based calculations for L_e (as frequently as daily)? There are at least three reasons for continuing to do so:

- In Canada, one set of values has been used over a relatively large range in latitude for nearly 40 years. Furthermore, Van Wagner's (1987) analyses suggest that the latitude effect is quite gradual.
- Should a change be made in the way day length is entered in calculations of DMC and DC, any past calibrations between fire danger ratings and fire activity (e.g., Viegas et al. 1999; Dymond et al. 2005) would be rendered invalid. This would be especially significant in Canada, given the number of calibration studies of various sorts that have been undertaken. It would also negate the validity of any fire management guidelines (e.g., preparedness system levels), decision aids and guides, or heuristic rules of thumb.
- The difference in the DMC values between tabular and point-based calculations of L_e (using either daily or mean monthly day lengths) are, in all likelihood, small.

Although there may be an overriding desire to present fire danger rating information on a broad regional or global basis, in the form of the FWI System components (Camia et al. 2006; de Groot et al. 2006), and even though it would be feasible to display the information spatially, the fact of the matter is that in a good many instances it would not be desirable or even relevant to do so (e.g., in an extremely arid country with limited accumulation of organic matter). This is because many regions of the globe simply do not have a forest floor layer or the forest floor layer that is present does not necessarily warrant assessment by the DMC, let alone the DC.

At the outset, it seems conceivable that the tabular approach recommended here could lead to discontinuities in countries that span an area north and south of latitudes 30° N, 10° N, 10° S,

or 30° S. However, a close look at a world map indicates that, with a bit of common sense, there should be very few problems in implementing the recommendations outlined here. For example, the L_e values for 20° N should be used for all of Mexico, even though the very northern parts of the country extend just above 30° N latitude. Conversely, Florida and southern Texas lie below 30° N but would be best served by the Canadian standard values used in the remainder of the continental United States. The very northern portion of South America, which extends to about 12° N should use the equatorial values of L_e . Similarly, all of South Africa would use the 20° S values of L_e , even though the most southerly portion of the country extends to 35° S. Argentina extends from about 22° S to about 55° S, but since the bulk of the country lies below 30° S, it makes sense to use the reference L_e values for 40° S latitude throughout the country.

Australia, which spans a latitudinal range from about 10° S to about 43° S, effectively straddles both the 20° S and 40° S reference latitudes. The simplest solution is to apply the 40° S L_e values to Tasmania and the forested regions of Western Australia, South Australia, Victoria, the Australian Capital Territory, New South Wales, including its northeastern coastal region (which lies north of latitude 30° S), and southeastern Queensland (which also lies north of 30° S). For the remainder of country, the 20° S L_e values would apply.

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