Natural Resources Canada | Ressources naturelles Canada
Canadian Forest Service | Service canadien des forêts

Development and Structure of the Canadian Forest Fire Emissions Prediction System

Kerry Anderson
and a cast of thousands

Canada

Draft document - June 7, 2018

Introduction

The Canadian Forest Fire Emissions Prediction System, or CFFEPS, is a model to predict smoke plume development for Canada. Currently, the system consists of a fire-growth model, an emissions model and a model to predict the penetration height of a smoke plume, based on thermodynamic principles.

As a Canadian model, CFFEPS uses the Canadian Forest Fire Danger Rating System (CFFDRS), including the Canadian Fire Weather Index (FWI) System (Van Wagner 1987) and the Canadian Forest Fire Behaviour Prediction (FBP) System (Forestry Canada Fire Danger Group 1992). The model also follows techniques used in the Fire Emission Production Simulator (FEPS) and CONSUME 3.0, both developed by the US Forest Service (Anderson *et al.* 2004; Prichard *et al.* 2006).

Theory

Smoke emissions and the energy generated from wildland fires is a problem in estimating the amount of forest fuel consumed by fire, which, in turn, is ejected into the atmosphere. Estimating the amount of fuel consumed involves estimating the mass of fuel consumed, which is a product of density and volume. Rearranged, this can be described as the product of fuel consumed per area (kg/m^2 or tonnes/ha)[1] and area burned (m^2 or ha).

Fuel Consumed

Bulk density (gm/cm^3) is a measure of the density of forest fuel. Given the structure of forests, it is customary to break this down vertically, distinguishing the crown (the aboveground branches and foliage) from the forest floor, with the latter further broken down by depth into the litter, fermentation and humus layers (L, F and H). Fuel load is measured as the mass of available fuel per unit area (kg/m^2 or tonnes/ha).

Forest fires spread first as surface fires (Fig 4). A surface fire burns from the top down and is measured as the depth of burn (cm). Also, the bulk density of the forest floor increases with depth. Together, they determine the surface fuel consumed. As the intensity of a surface fire increases, the likelihood of the fire jumping from the surface into the crown increases. As it does, the fire turns into a crown fire. A new source of fuel is accessed and the fire will increase in intensity.

The FBP system of the CFFDRS provides predictions of the surface fuel consumption (SFC), the

[1]Given the frequent conversions, it is worth noting that 10 kg/m^2 equals one tonnes/ha.

crown fuel consumption (CFC) and the sum of the two as the total fuel consumption (TFC) in kg/m^2 or tonnes/ha.

Fuel moisture is a controlling factor in fire behaviour and is tracked by the FWI system as the Fire fuel moisture code (FFMC), duff moisture code (DMC) and drought code (DC). These are numeric ratings, or indices, of the moisture content of the litter and other fine fuels, of the loosely compacted organic layers of moderate depth, and of the deep, compact organic layers respectively. Their values rise as moisture content decreases.

The thin fuels of the litter layer exhibit a diurnal variation in fuel moisture. Typically, FFMC reaches a peak (minimum fuel moisture) at 5:00 PM LST. This affects the velocity, or rate of spread (ROS), of a fire. In turn, this increases the intensity and area growth of a fire. Under these conditions, the likelihood of crown fire increases and thus the CFC typically exhibits a diurnal trend. On the other hand, the SFC is generally driven by moisture in the deeper layers

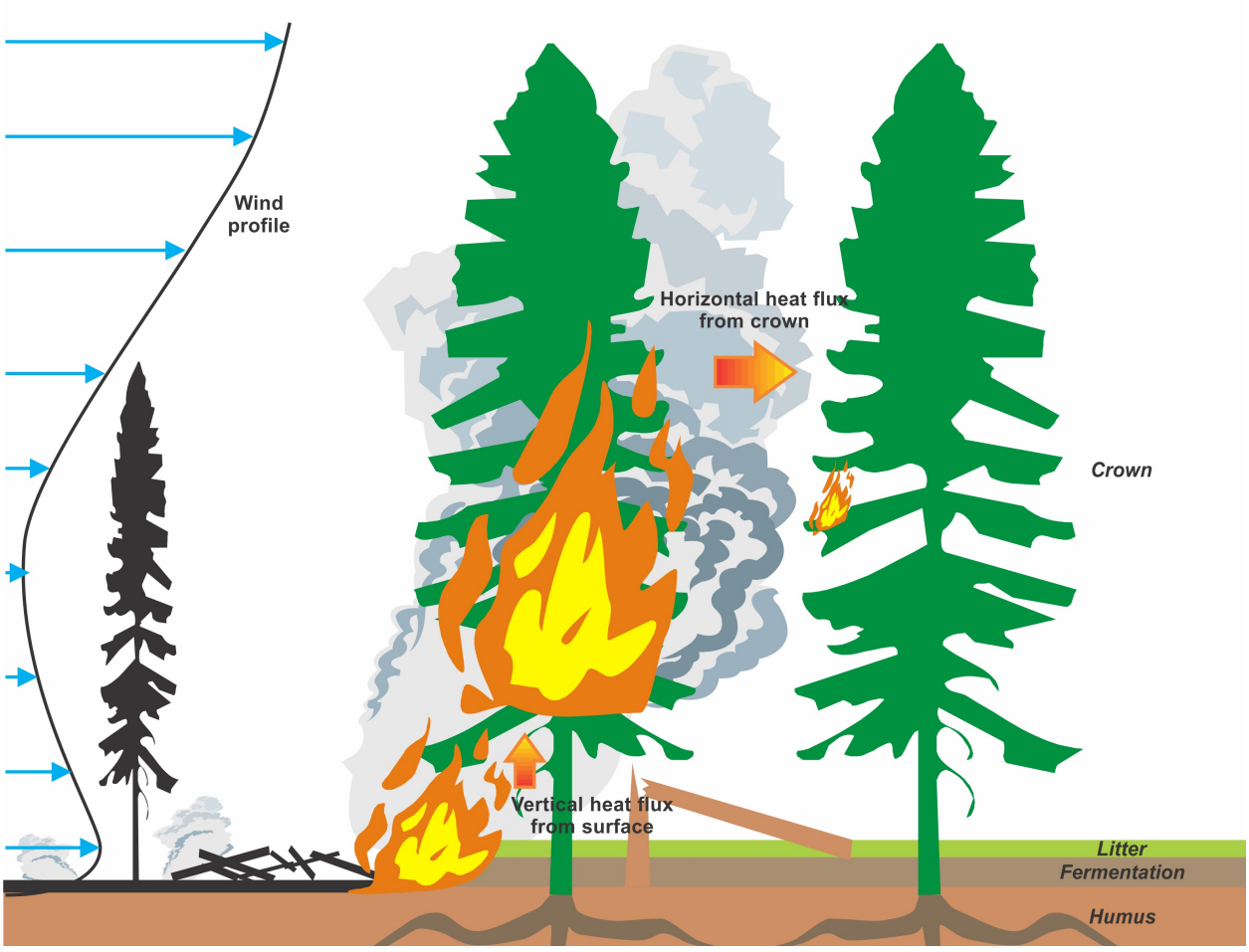

Figure 4. Fire dynamics within a forest stand. A typical wind profile associated with in-canopy flow is shown on the left with a low-level wind maximum (jet) below the principal canopy. When the surface fire reaches an intensity such that branches within the forest canopy are ignited, a crown fire may occur. Smoldering combustion can continue for hours after the principal fire front has passed.

and does not exhibit any diurnal variation. Since TFC is the sum of SFC and CFC, it reflects the diurnal variation of the CFC.

Area Burned

The area burned by a fire is dependent on fire size, which increases geometrically over time. The rate and process of this evolution of fire size are referred to as fire growth.

Many of the calculations in the CFFEPS model depend on fire size. To determine this, the model uses a simple elliptical fire growth model to predict the area burned similarly to that used in Anderson *et al.* 2001.[2] As shown in Figure 5, the model assumes that a fire grows in an elliptical shape: the stronger the driving wind, the higher the ellipticity. Fuel type and wind direction are held constant.

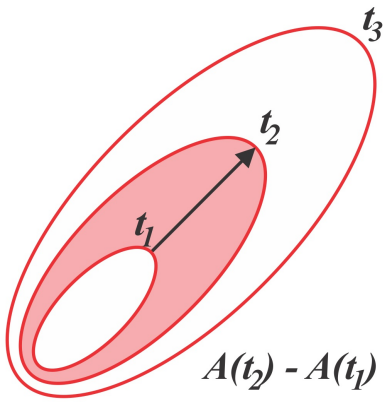

Figure 5. Elliptical fire-growth used in the CFFEPS model, The rate of spread from time t_1 to t_2 is used to calculate the forward spread distance. The grey area represents the area burned between times t_1 to t_2.

The fire-growth model uses components of the CFFDRS to drive it. The fine fuel moisture code (FFMC) is diurnally adjusted over time using the technique developed by Lawson *et al.* (1996). The rate of spread (ROS) is calculated over the course of the day and from this the area growth.

While a number of sophisticated fire-growth models exist that calculate fire spread over a heterogeneous field of fuels and terrain, this model does not go that far. The data needs of models such as Prometheus and FARSITE are extensive and outside the approach presented in this manual. Future attempts may be conducted to incorporate CFFEPS with these models, but for now are outside of the present scope of the model.

Emissions Rates

The CFFEPS model uses fuel consumption as calculated by the FBP system. This includes surface fuel consumption (SFC), crown fuel consumption (CFC) and total fuel consumption (TFC).

Surface fuel consumption (SFC) represents fuel consumption as the fire burns into the forest

[2]Because of the potential for overlapping fire growth, elliptical growth is not used in the FIREWORK implementation of CFFEPS; instead, daily persistence of detected fire size is used.

floor. The bulk density of the forest floor increases with depth, which have an impact on emissions. Table 1 shows the bulk densities used per fuel type. These values are based on the original bulk densities documented in the FBP literature and summarized in Anderson *et al.* 2000.

Table 1. Bulk densities (gm/cm^3) of surface fuels per fuel type.

Fuel	0-2 cm	2-4 cm	4-6 cm	6-8 cm
C1		0.045		
C2	0.019	0.034	0.051	0.056
C3	0.015	0.020	0.032	0.066
C4	0.022	0.029	0.045	0.059
C5		0.093		
C6	0.030	0.050	0.050	0.050
C7	0.100	0.100	0.050	0
D1		0.061		
M1/2	0.0265	0.071	0.0795	0.082
M3/4	0.041	0.061	0.084	0.112

Following the technique used by CONSUME, CFFEPS divides combustion into three stages: flaming, smoldering and residual combustion. Table 2 summarizes the reduction factors used by CFFEPS to convert fuel consumption to these stages. As shown on the table, ground fuel is broken down into three layers. The litter, the upper duff and the lower duff layers. To estimate the amount of each layer consumed, the depth of burn must be calculated – first by burning off the litter layer, then the upper duff and finally the lower duff. This is determined from the fuel type, the surface fuel consumption and the bulk densities from Table 1. It is assumed that the first 1.2 cm describe the litter layer, the upper duff is represented by the 1.2-7 cm depth and the lower duff by 7-18 cm. Crown fraction burned is used for canopy consumption. Slash consumption equals the grass fuel load.

Table 2. Reduction factors per fuel type

Fuel		Flaming	Smoldering	Residual
Ground	Litter	0.90	0.10	0
	Upper duff	0.10	0.70	0.20
	Lower duff	0	0.20	0.80
Canopy		0.94	0.06	0
Slash		0.70	0.15	0.15
Grass		0.95	0.05	0

The three combustion stages are considered to have three duration periods. Flaming combustion is considered to occur within the first 15 minutes with all consumption immediately released into the atmosphere. Smoldering and residual combustion last for several hours. Assuming the forest floor smolders at a rate of 1 cm/h, one can calculate the duration of these stages: the first half of this time is assumed to be smoldering, the second half residual smoldering.

Table 3 describes typical emissions factors of pollutants used in CFFEPS. These are based on the average emissions factors used in CONSUME. Depending on the three stages of combustion, time series of emissions released in the atmosphere are created for each pollutant in accordance with the emissions factors and the duration of the combustion stages.

Table 3. Emissions factors (g/kg) of pollutants.

	PM	PM10	PM2.5	CO	CO2	CH4	NMHC
Flaming	11.5	7.5	6.5	45	1261	1.5	2.5
Smoldering	17	12	9.5	104.5	1142.5	5.5	5
Residual	17	12	9.5	104.5	1142.5	5.5	5

Note that the values presented in Table 3 are only examples (based on those used by the USFS). The CFFEPS program allows for user defined emissions rates per forest fuel type through the emissions CSV file and the emissions model CSV file (as described in the section *CFFEPS Files*).

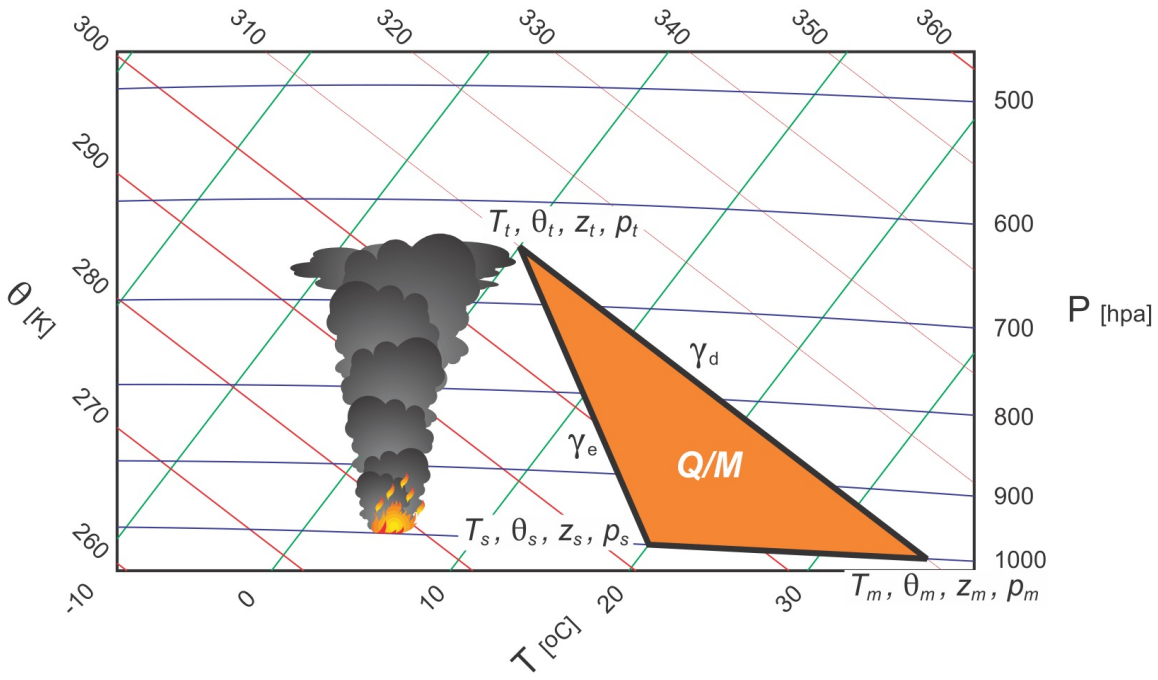

Figure 6. Representation of a smoke plume on a tephigram. The area, *Q/M*, indicates the energy released by the fire, which is constrained by the environmental lapse rate γ_e and the dry adiabat γ_d. Values for the temperature, potential temperature, height and pressure (T, θ, z and p) can be determined at the surface, the top and within the modified zone (subscripts s, t, and m).

Plume Rise

Plume rise in the CFFEPS model is based on the thermodynamic plume model developed by Anderson *et al.* (2011). This model predicts the penetration height of a plume based on an amount of energy injected into the atmosphere and a constant environmental lapse rate.

The energy per unit mass, $Q/M = q$, required to modify the atmosphere can be calculated using the tephigram (Fig. 6). The quantity q can be derived from an enclosed area on the tephigram as

$$q = -c_p \oint T d\ln\theta$$

where q is the energy per unit mass [J kg^{-1}], c_p is the heat capacity of dry air [1005 J kg^{-1} K^{-1}], T is the temperature [K] and θ is the potential temperature [K]. The area within the closed curve, as shown in Figure 2, equals

$$q = -\frac{1}{2} c_p (T_t - T_m) \ln(\theta_m / \theta_s)$$

Not all the energy released by a forest fire enters the plume. Instead, a portion of the energy is projected ahead of the fire to heat fuels to combustion temperatures, into the ground underneath a fire (to be released later but after plume development), etc. To calculate the energy injected into the plume, an energy balance for a wildland fire was devised for CFFEPS as

$$Q_{plume} = Q_{fire} - Q_{moisture} - Q_{fuel} - Q_{radiation} - Q_{surface} - Q_{incomplete}$$

where Q_{plume} is the energy injected into the plume, Q_{fire} is the total energy of the fire, $Q_{moisture}$ is the energy lost to evaporate moisture in the fuel, Q_{fuel} is the energy required to heat the fuel to the temperature of combustion, $Q_{radiation}$, is energy lost into space away from any fuels and the plume, $Q_{surface}$ is energy injected into the ground only to be released after plume development, $Q_{incomplete}$ is energy lost due to incomplete combustion. These values are solved for in CFFEPS based on parameters from the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987) and the Canadian Forest Fire Behaviour Prediction (FBP) System (Forestry Canada Fire Danger Group 1992). This will be documented in a future publication.

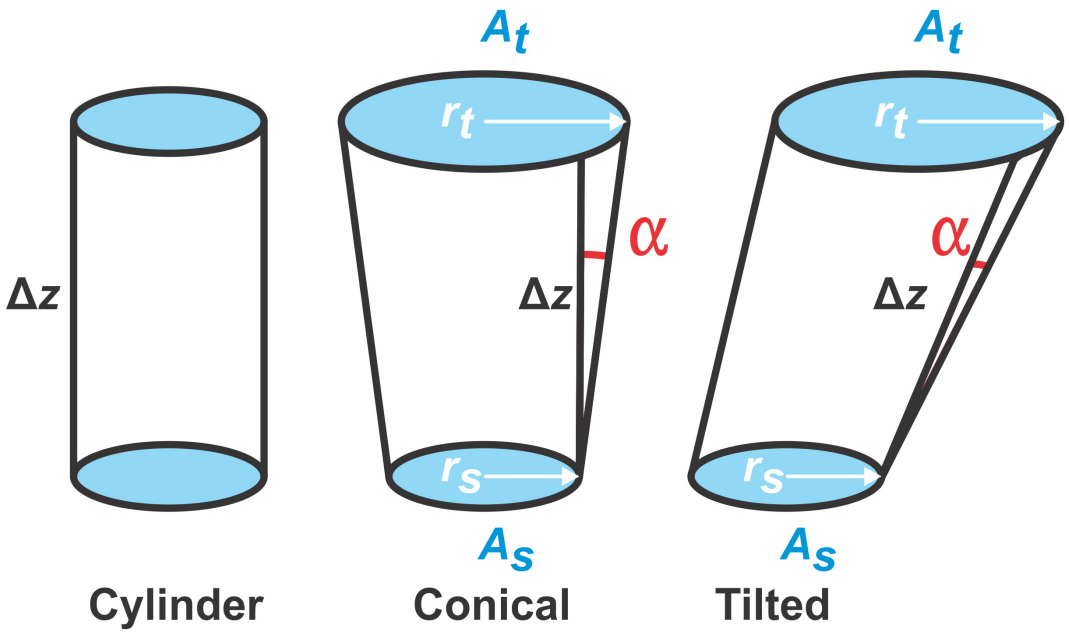

Figure 7. The effects of entrainment: without entrainment, the plume assumes a cylindrical shape; with entrainment, it assume a conical shape following the entrainment angle α. The plume may be tilted due to winds but the plume volume and mass remains constant.

The CFFEPS model provides the user with the choice of entrainment, which is represented by an entrainment angle α (Fig. 7). Essentially, the plume rises in a conical fashion expanding with height. The modified volume of the plume as captured by entrainment depends on fire size. Entrainment has a more significant role in smaller fires than in larger fires. On a large fire, the proportional volume contributed to the plume from entrainment is minimal, while on a small fire, it is substantial (Fig. 8)..

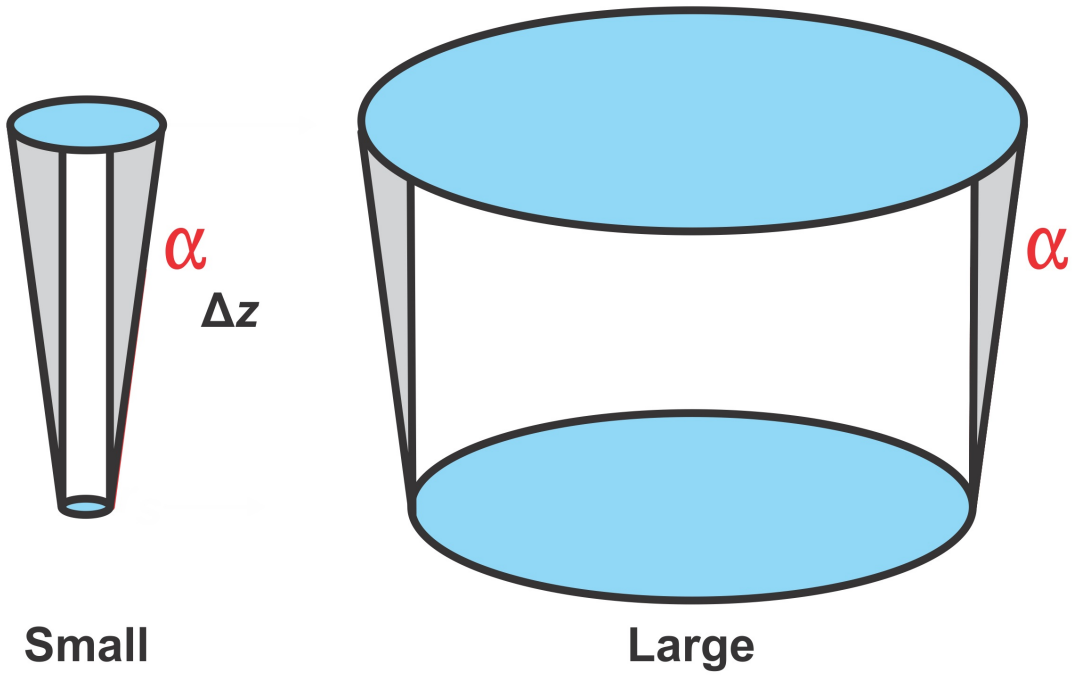

Figure 8. The contribution on entrainment (grey) is proportionally larger on the small than on the large fire.

Vertical Distribution of Emissions

As a plume rises, the density of smoke diminishes, as does the density of air. An assumption is thus made that the mixing ratio of smoke emissions to clear air is constant in the plume due to convective mixing. Given the total mass of emissions ($M_{emissions}$) and the mass of the plume (M_{plume}), the mixing ratio (r_{smoke}) can be calculated as

$$r_{smoke} = M_{emissions} / M_{plume}$$

where

$$M_{plume} / A = (p_s - p_t) / g$$

and A is the area of the fire, p_s and p_t are the pressures at the surface and the top of the plume. In the case of entrainment, the mass of the plume can be calculated using the average of the plume top area at the area of the fire.

Given the mixing ratio of smoke to clear air, the density of the smoke becomes a function of the density of air.

METHODOLOGY

Introduction

Environment and Climate Change Canada (ECCC) is mandated to include smoke emissions from forest fires in their Air Quality and Health Index (AQHI). The FIREWORK model was developed to meet this need (Pavlovic *et al.* 2016). Initially, FIREWORK used predictions based on the USFS BlueSky smoke modeling framework (Larkin *et al.* 2010) but the system is now adapting CFFEPS for its calculations. Over the last year, CFFEPS has gone through changes and adjustments as it approaches an operational status with ECCC.

Pre-processing

Smoke emissions produced in FIREWORK are based on satellite-detected fires, commonly referred to as hotspots, collected by the Canadian Wildland Fire Information System (CWIFS). Run by the Natural Resources Canada (NRCan) at the Northern Forestry Centre (NoFC) in Edmonton, the CWFIS collects this data several times a day and attaches forecasted fire weather, forest fuels to each hotspot.

Canadian Wildland Fire Information System

The Canadian Wildland Fire Information System (CWFIS) provides most of the data required to calculate smoke emissions and plume rise. The CWFIS is a computer-based fire information system that monitors fire activity and fire danger conditions across Canada. Daily weather observations and forecasts (up to 48 hours) are collected and used to produce fire-weather and fire-behaviour maps based on the Canadian Forest Fire Danger Rating System (CFFDRS) (Stocks *et al.* 1989). The CWFIS can be found at http://cwfis.cfs.nrcan.gc.ca/ during the fire season.

Forecast weather for the CWFIS is provided by the Canadian Meteorological Centre of Environment Canada. Forecast data from the Global Environmental Multiscale (GEM) model (Côté *et al.* 1998) are presented in the form of SCRIBE matrices (Verret *et al.* 1997; Landry *et al.* 2005). These matrices consist of weather elements forecast from the GEM model and interpreted to specific locations within Canada. These forecast values are then adjusted using a model output statistics (MOS) approach (Wilson and Vallée 2002, 2003). The benefit of the MOS approach is that it removes any biases inherent in the GEM output. SCRIBE matrices are provided for over 800 Canadian stations or sample points on 3-h intervals for a 48-h period from the GEM model run. SCRIBE matrices are routinely available 2 h after the GEM model run times (0000 and 1200 hours Coordinated Universal Time, UTC).

Fire detection and mapping

The Northern Forestry Centre collects hotspots detected nationally using MODIS,

NOAA/AVHRR, and VIIRS satellite imagery (Quayle *et al*. 2003; Englefield *et al*. 2004). Image pixels containing actively burning areas (also referred to as hotspots) are mapped with each satellite pass (approximately every 6 hours). Fire monitoring using hotspots has various drawbacks, the most significant being the inability of the sensors to penetrate cloud. Also, geostationary satellites such as GOES are not used in this process because the resolution over Canada is judged as insufficient for this type of mapping.

Because of the resolution of the imagery used, determining hotspot sizes is not possible using this method. Instead, fire sizes at the time of detection are assigned based on annual area burned statistics per province and fuel type. In Canada, provincial and territorial agencies provide annual data on area burned. Given knowledge of the number of hotspots, an average fire size per hotspot can be calculated. Originally, this method was followed nationally but now is being conducted by fuel type provincially and territorially. Thus, for example, a hotspot detected in a C2 fuel type in Saskatchewan is assigned a fire size of 42.33 ha based on historical records. A method following ecoregion instead may be used in the future.

For each hotspot, a fire-growth simulation environment is assembled. This includes the forest fuel type, noon weather and fire weather conditions. Forest fuel type is mapped and managed in the CWFIS. In Canada, the forest protection agencies of the provinces, territories, and national parks are responsible for fire management and fuel-type mapping. Fuels are mapped from various sources, typically forest inventory, Landsat imagery, or a combination of the two. Where agency maps are not available, a national fuel type map (Nadeau *et al.* 2005) is used. The national map is based on forest inventory and Satellite Pour l'Observation de la Terre Vegetation sensors (SPOTVGT) land cover (Latifolia *et al*. 2004) and has a coarser resolution (1 km^2) than the agency maps. Noon weather and fire weather indices are assigned to each hotspot based on the CWFIS. Conditions are interpolated between stations using an inverse-distance weighted approach.

All the information described to this point is collected and processed by NRCan staff at the Northern Forestry Centre in Edmonton. Information is recorded into an ASCII, comma-separated variable flat file and passed onto ECCC colleagues at the Canadian Meteorological Centre (CMC) in Montreal for further processing.

Global Environmental Multiscale (GEM) Model

Once CWFIS information is received by ECCC staff at the Canadian Meteorological Centre, 72-hour point forecasts are created for each hotspot using GEM (Fig. 8). Forecasted values include surface conditions (temperature, humidity and wind speed) along with upper air (temperature and height) at mandatory levels (850, 700, 500, 250 mb). Each hourly forecast is included as a separate line of data. This expanded data is stored as the input file for CFFEPS.

CFFEPS Calculations

Once the necessary pre-processing has been done, the CFFEPS model is run by ECCC staff at CMC.

Fire Growth

Using the GEM forecasted hourly weather, CFFEPS calculates the fire behaviour (Fig. 9). This includes hourly calculation of the fine fuel moisture code (FFMC), rate of spread (ROS, m/min), crown fraction burned (CFB, %), surface fuel consumption (SFC, kg/m^2), total fuel consumption (TFC, kg/m^2), and head fire intensity (HFI, kW/m).

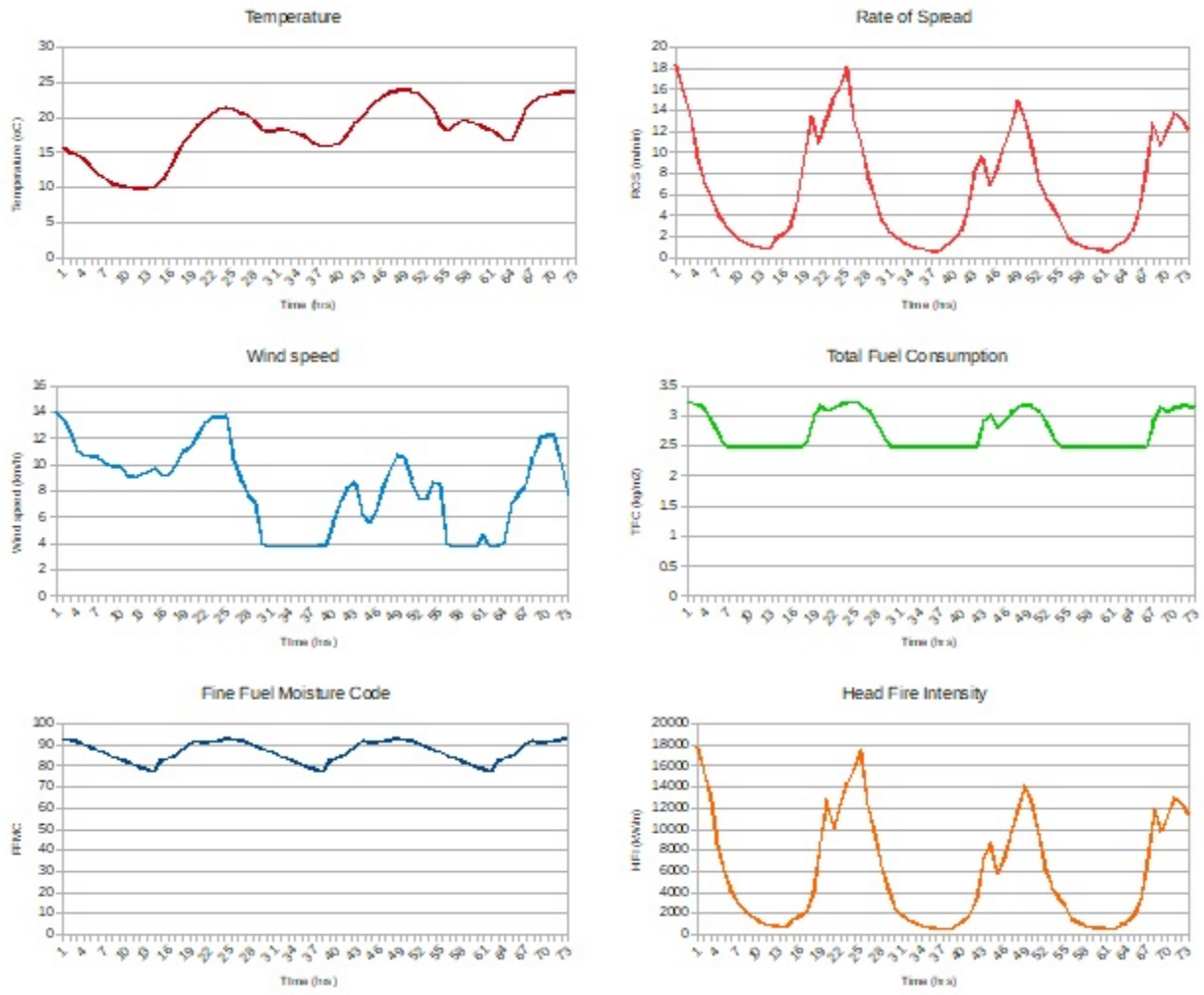

Figure 9. Modelled hourly values of temperature and wind speed from a 72 hour GEM forecasts and the resulting diurnal trends of Fine Fuel Moisture Code (FFMC), rate of spread (m/min), total fuel consumption (kg/m^2) and head fire intensity (kW/m).

The next step conducted by CFFEPS is the synchronization of information with the detected hotspot. The CFFEPS input file is read in one hotspot at a time (each consisting of 72 lines of hourly forecasted weather). The reported detection time (e.g., 2016-05-02 20:45) and size (e.g., estarea = 11.69 ha) is synchronized to the appropriate line of the forecast file. A detection time (in LST) is determined for fire behaviour prediction purposes.

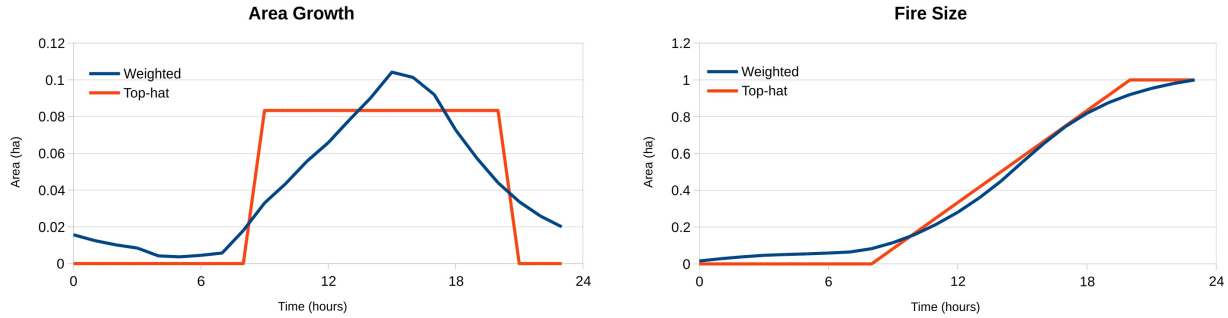

Figure 10. Area growth and fire size (accumulated area growth) over 24 hours using top-hat or weighted approach based on a detected hotspot size of 1 ha.

From the detection time and size and the hourly fire behaviour, the diurnal growth of the fire is calculated. It has been determined that the persistence of daily fire growth (using the detected hotspot size as the daily area burned and reusing it each day) is most appropriate to create realistic overall results. From this value, the hourly distribution of the growth can be either a top-hot approach, where the daily area burned is applied evenly over a 12 hour period from 9:00 AM to 9:00 PM, or a weighted approach using a generalized diurnal trend of rate of spread over 24 hours (Fig. 10).

It is important to understand that a fire has started before the satellite passes overhead and detects it. The daily fire growth rate is thus fitted to the size at detection time. This may result in undetected growth on previous days (Fig 11).

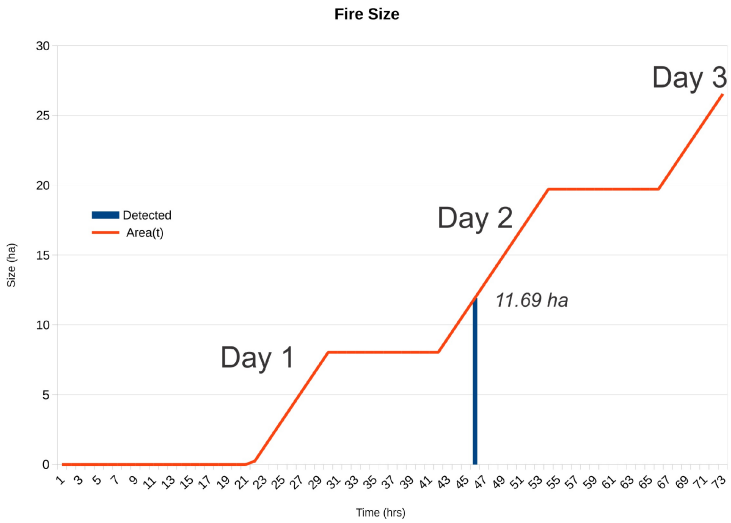

Figure 11. Fire growth using top-hat approach synchronized with the detection time (2045 UTC, 1145 LST) and size (11.69 ha). Following persistence, the fire is assumed to burn 11.69 ha per day. This results in the fire burning on the day prior to detection.

Because of the nature of the persistence approach, the GEM model forecast does not drive the area growth. This is recognized as a deficiency and will be addressed in future versions. Adhering to persistence first will establish a baseline for error checking and comparative purposes.

Energy over Time

Once the hourly growth is established, CFFEPS calculates fuel consumption by depth and then flaming, smoldering and residual times for energy (and later emissions) calculations. The fraction of energy released during to the three stages is based on the USFS CONSUME 3.0 model, bulk densities from the Canadian FBP system and additional expert opinion where required (Table 2).

Fuel consumption from the current hour's fire growth is thus spread out over time. The flaming stage is assumed to occur in the first 15 minutes of combustion. Afterwards, a fire is assumed to burn into the forest floor at a rate of 1 cm/h. Knowing the depth of burn (based on surface fuel consumption and bulk density), the burn time can be calculated. Half of this time is assigned to the smoldering stage, the second half to the residual stage.

Energy values are then calculated over time (Fig. 12). Note that because of the top-hat approach used in this example for fire growth, there is no energy released at night during certain hours (after the residual smoldering has finished), plume rise is turned off. Also, smoldering and residual is no longer limited to the bottom layer (as done in BlueSky).

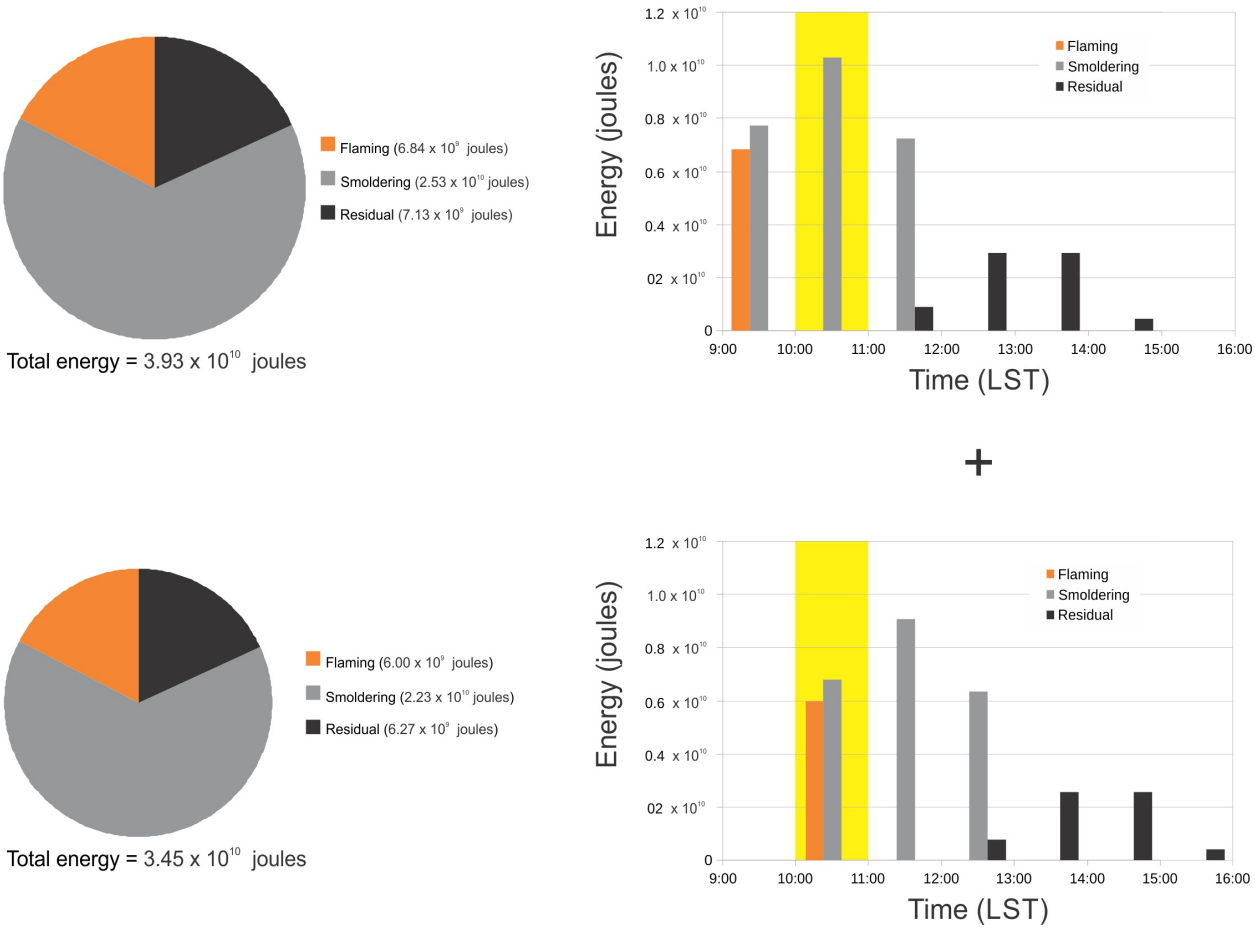

Figure 12. An example of hourly energy released (over the first two hours). During the first hour (between 9:00 and 10:00), a fire grows 0.555 ha. The energy emitted from this area burned (3.93 x 10^{10} joules) is spread over the next 5.15 hours (beginning at 9:00 LST) with flaming lasting 15 minutes (0.25 hours), while smoldering and residual last 2.45 hours (based on a 4.9 cm depth of burn and a smoldering rate of 1 cm/hour). During the second hour (between 10:00 and 11:00), the fire grows 0.451 ha to a total size of 1.001 ha. The energy emitted from this area burned (3.45 x 10^{10} joules) is also spread over the next 5.15 hours (beginning at 10:00 LST). This energy is then added to the energy released from the first area burned between 10:00 and 11:00 LST (shown in yellow). As the model steps through each hourly time step, the energies associated with each hourly area burned are distributed over time and added.

Plume Rise

Hourly energy values are now used to calculate plume rise. Plume rise is calculated in one of two ways. The traditional approach, as described in Anderson *et al.* 2011, heats the air above a fire, adjusting the environmental lapse rate above the fire to a dry adiabat. The environmental lapse rate used is a single average value and the choice of lapse rates depends on the predicted plume height:

- first, the lapse rate from the surface to 850 mb is used,
- if the predicted plume is above 2000 m, the lapse rate from the surface to 700 mb is used,
- if the predicted plume is above 4000 m, the lapse rate from the surface to 500 mb is used,
- if there are problems with the predictions (e.g., superadiabatic from the surface to 850 mb), the lapse rate from 700 to 850 mb is used
- if there still are problems, the lapse rate from 850 to 500 mb is used

A new alternative is a method that calculates plume rise using the upper air profile, integrating the energy piecewise through the atmosphere. An example of the two approaches is shown in Figure 13.

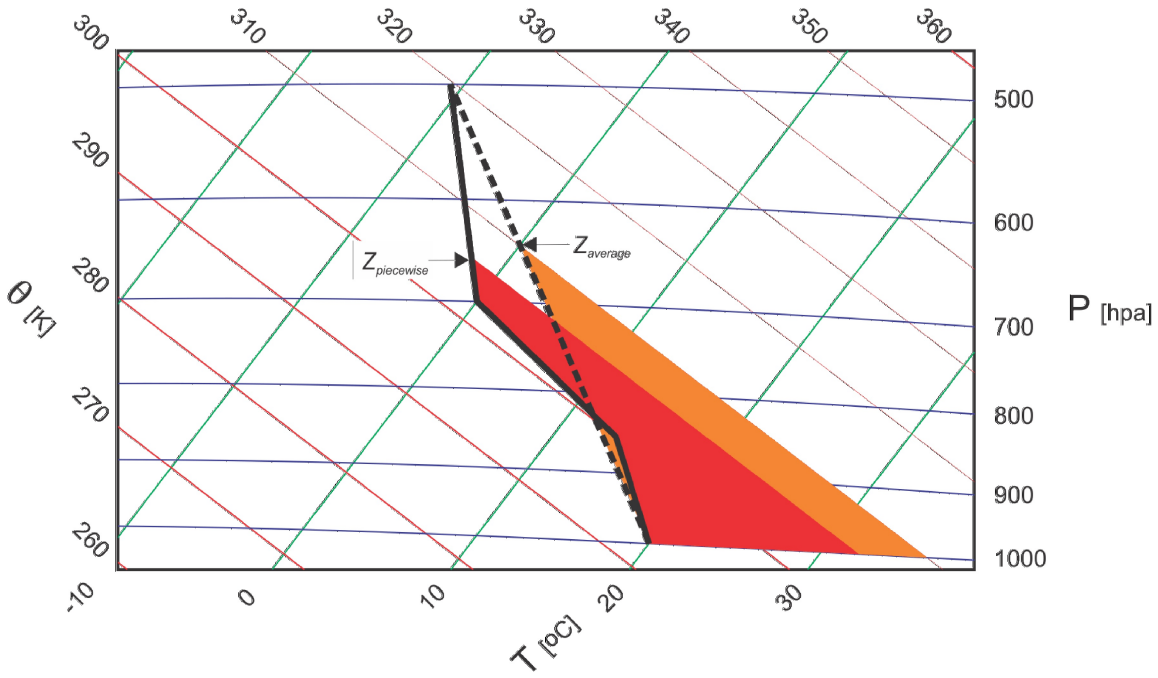

Figure 13. Example of the two methods of calculating plume rise. The traditional approach (Anderson *et al.* 2011) uses the lapse rate from the surface to 500 mb (dashed line) as the environmental lapse rate. The piecewise approach uses the upper air profile (solid line). The areas shown in orange and red, equal in size, represent the energy involved in heating the profiles to a dry adiabat. The resulting plume heights, $Z_{average}$ and $Z_{piecewise}$, are slightly diffferent.

Emissions per Species

The CFFEPS program manages emissions per species. The user defines the emissions per

species as related to the total fuel consumption through the emissions CSV file and the emissions model CSV file (as described in the section *CFFEPS Files*). This is controlled through each stage of combustion (flaming, smoldering, residual) similar to the method presented for energy. By calculating the total fuel consumption (tonnes/h), emissions per species are calculated (tonnes/h) (Fig. 14).

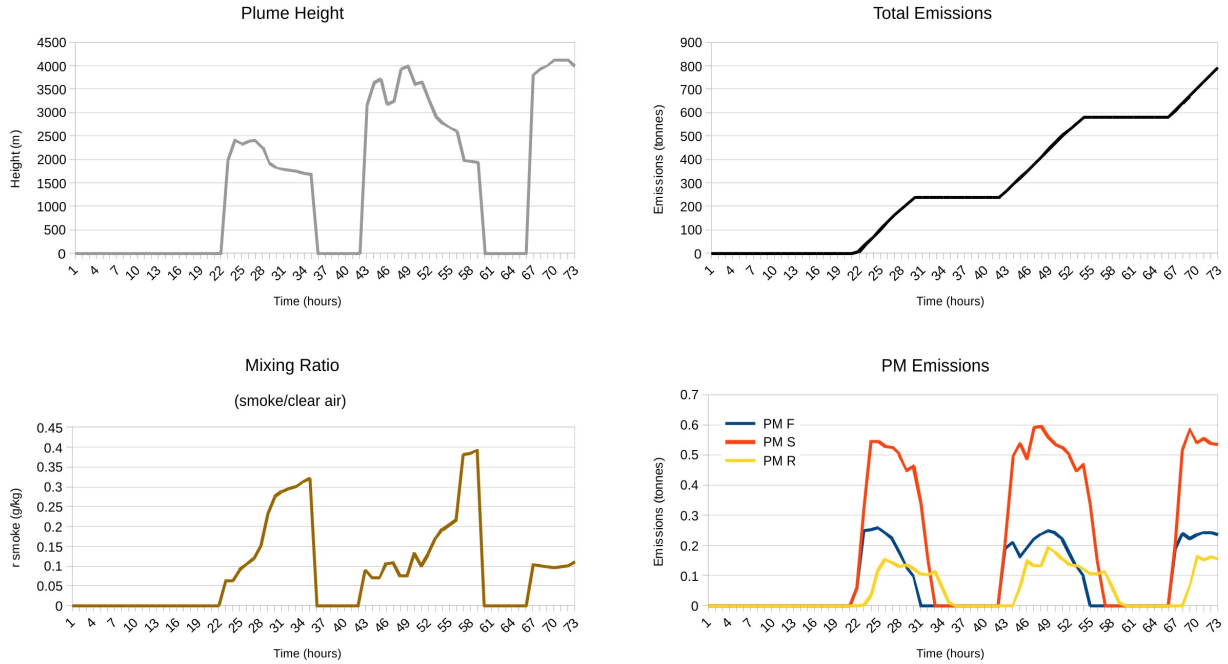

Figure 14. Examples of plume rise (m), total emissions (tonnes), mixing ratio (g/kg) and particulate matter (PM) over time.

Emissions are controlled through a file (e.g., emissions.csv) that contains all the emissions rates per species per stage of combustion in grams per kilogram of fuel consumption as defined by ECCC. Emissions factors can be defined by input fuel type referenced by the field *emodel*, which is linked to a file (e.g., emodel.csv). Actual files and file names are controlled in the CFFEPS input file (e.g., CFFEPS.INI). Currently, ECCC uses one set of emissions factors for all fuels.

Post-processing

As CFFEPS runs, it creates an output file. This output file contains the same information, line by line, as the input file but has predictions appended to it. These predictions include energy, total emissions, plume rise, and emissions by species and separated by flaming, smoldering and residual stages. This information is passed to GEMMACH for further modelling processes.

CFFEPS Program

Software has been developed to run the Canadian Forest Fire Emissions Prediction System (CFFEPS) for Environment and Climate Change Canada. This is contained in the single, executable program, **CFFEPS.EXE**, that calculates fire-growth modelling, energy balance, plume rise and fire emissions.

Running CFFEPS

CFFEPS.EXE is run from the command line as follows.

```
> CFFEPS [inputfile]
```

Where *inputfile* is the input file name, the default input filename is **infile.dat** in the current directory.

Input

Input is passed to CFFEPS through an input file. The file reads words from the file. These words are separated by spaces or tabs. A typical ECCC input file is as follows

```
csvfilename    C:\path\cmc2016050200_out250mb.csv
emissions      C:\path\emissions.csv
emodels        C:\path\emodels.csv
method         cmc
shape          weighted
```

The program looks for key words (such as *method*) and when it finds a keyword, it reads the following word as the data associated with the keyword (in this case *cmc* for the method).

Keywords are case insensitive and often the first three or four letters of the keyword are used for keyword recognition. Subsequent letters are recommended to make the input file more readable to the user but are not required.

The file must end with a Line Feed <LF> or the last line may not be read successfully.

Additional information may be included in the input file (for example a fire number or a weather station name). As these are not recognized keywords, the program will overlook them and move to the next word.

Keywords

The CFFEPS program was originally a robust, dynamic program designed to model plume

development under a variety of conditions and scenarios. Such an approach is beyond the scope of the current project with ECCC and so the inputs to CFFEPS are focussed specifically on ECCC needs. As a result, the keywords that drive the model are more limited.

Default values are show in square brackets (e.g., [*default*])

ALPha *or*
ENTrainment — the entrainment half angle in degrees on the edge of the plume (default value based on personal observations of prescribed fires) [*12.*]

CSVFilename — The filename (including path) of the CFFEPS input data as created by the GEM forecast. The file description will be discussed in the next section [*input.csv*].

EMISsions — The filename (including path) of the emissions rates of species [*emissions.csv*]

EMODels — The filename (including path) of the fuels-based emissions models [*emodel.csv*]

METhod — The method followed by the CFFEPS program. For ECCC, the method used is ***CMC***. Other methods were used in the past (*AB*, *Hourly*, *ICAO*) but are no longer part of this program. [*cmc*]

MINimum — minimum plume height [m] [*-999*]

OUTputfilename — The filename (including path) of the output data as created by CFFEPS. The file description will be discussed in the next section [*output.csv*].

RESet — reset time of smoke plume calculations [decimal hours LST] (off if < 0) [*-1*]

SHApe — The choice of fire growth modelling. Options include:

Ellipse (the original elliptical growth method - not recommended);
PERSistence (same as top-hat);
TOPhat (persistence of daily fire growth, with hourly rate constant between 9:00 AM and 9:00 PM);
WEIGhted (persistence of daily growth, with hourly growth that follows an average diurnal trend of rate of spread).

[*weighted*]

THStart time to start (exclusive) top-hat fire growth [decimal hours LST] [*9.*]

THEnd time to end (inclusive) top-hat fire growth [decimal hours LST] [*121.*]

TYPe The type of method used to heat the atmosphere to dry adiabat

AVErage (heating of average lapse rate to dry adiabat, following methodology used in Anderson *et al.* 2011);
DRY (piecewise integration of upper air profile heated to dry adiabat);
PIEcewise (same as dry).

[*average*]

CFFEPS Files

The processing cycle of CFFEPS includes information collected by NRCan from the CWFIS and passed on to ECCC at CMC. Next, ECCC reads the file and from GEM creates 72 lines of hourly forecasts for each line of the NRCan file. This is read by CFFEPS and CFFEPS predictions are appended to the end of each line.

The file being passed from one program to the next is a comma-separated variable (CSV) text file. The first line of the file contains a header line of field names, which is read but not used.

The following fields are included in the file. The order of information is strictly followed.

1a. NRCan CFFEPS CSV file

The file created by NRCan contains the input information from the CWFIS. This includes hotspot, weather and fuel information. One line of data is produced per hotspot.

lat	Latitude of the hotspot [decimal degrees]
lon	Longitude of the hotspot [decimal degrees]
rep_date	The report date of the hotspot [YYYY-MM-DD HH:MM]
source	Source of the hotspot data (NASA, NOAA, USFS)
sensor	Sensor (AVHRR, MODIS, VIIRS)
FFMC	Fine Fuel Moisture Code (CFFWIS)
DMC	Duff Moisture Code (CFFWIS)
DC	Drought Code (CFFWIS)
ws	Noon wind speed [km/h]
FWI	Fire Weather Index (CFFWIS)
fuel	Fuel type (CFFBPS)
ROS	Rate of spread (CFFBPS) [m/min]
SFC	Surface fuel consumption (CFFBPS) [kg/m^2]
TFC	Total fuel consumption (CFFBPS) [kg/m^2]
BFC	BORFIRE fuel consumption (no longer used) [kg/m^2]
HFI	Head fire intensity (CFFBPS) [kW/m]
estarea	Estimated hotspot area [ha]

where CFFWIS is the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987) and CFFBPS is the Canadian Forest Fire Behaviour Prediction (FBP) System (Forestry Canada Fire Danger Group 1993). Source and sensor are not used in the CFFEPS model but are there for record keeping. BORFIRE fuel consumption (BFC), also referred to as the Forest Floor Fuel Consumption (FFFC), was a field used in the original BlueSky methodology but not used in CFFEPS (de Groot *et al.* 2009, Pavlovic *et al.* 2016).

1b. CMC GEM forecast CSV file

The CMC GEM file builds on the NRCan data set by expanding each line of hotspot data into 72 lines of forecasted hurly data. Additional forecasted hourly surface and upper air data is attached to each line.

All the above fields plus the following:

UTC	forecast time
temp	temperature [ºC or K]
rh	relative humidity [% or fraction]
ZS	surface geopotential height [m or dam]
ws-met	wind speed [km/h or knots]
Precip rate	Precipitation rate [mm/h or m/s]
TS	Surface temperature [ºC or K]
T850	850 mb temperature [ºC or K]
T700	700 mb temperature [ºC or K]
T500	500 mb temperature [ºC or K]
T250	250 mb temperature [ºC o K]
Z850	850 mb geopotential height [m or dam]
Z700	700 mb geopotential height [m or dam]
Z500	500 mb geopotential height [m or dam]
Z250	250 mb geopotential height [m or dam]

Note that the program is designed to recognize units. The program conducts it calculations in the first listed but if it encounters the latter, it makes a conversion (e.g., if it comes across a temperature greater than 100, it assumes the value is in K and thus converts it to ºC).

1c. CFFEPS predictions CSV file

The CFFEPS output file appends fire growth, plume rise, energy and smoke emissions to each of the hourly forecasted hotspot lines.

All the above fields plus the following:

Area (t)	Cumulative fire area [ha]
Growth (t)	Hourly fire growth [ha]
TotalEmissions	Total emissions [tonnes]
r_smoke	mixing ratio of smoke to clear air [g/kg]
Zplume	Plume height [m]
Mplume	Plume mass [kg]

Qo	Total cumulative energy of the fire [joules]
Qplume	Cumulative energy injected into the plume [joules]
PM F	Hourly particulate matter from flaming combustion
PM S	Hourly particulate matter from smoldering combustion
PM R	Hourly particulate matter from residual combustion

...

Note that the last three fields are repeated for every species listed in the emissions csv file.

---

2. Emissions CSV file

The emissions CSV file contains emissions factors associated with each desired species. The user is given the flexibility to include any species needed but is expected to provide the necessary emissions factors associated with the species (that is CFFEPS does not provide these values).

Species	Chemical species being modelled
Flaming	Emissions factor of species from flaming combustion [g/kg]
Smoldering	Emissions factor of species from flaming combustion [g/kg]
Residual	Emissions factor of species from flaming combustion [g/kg]
Model	Emissions model link to fuel type

An example emissions file ("csv" or comma separated variable file) is as follows

```
Species,Flaming,Smoldering,Residual,Model
PM,23,34,34,99
PM10,8.59,19.63,19.63,99
PM2.5,7.28,16.63,16.63,99
CO,83,135,248,99
CO2,1662.33,1600,1383,99
CH4,3.23,7.32,9.94,99
NMHC,19.85,33.87,56.08,99
NOX,1.83,2.0,0.45,99
NH3,0.99,1.50,1.94,99
SO2,0.93,1.06,1.76,99
```

---

3. Emissions models CSV file

Emissions model CSV file provides a means of linking emissions factors to specific fuel types.

Fuel	Fuel type (CFFBPS)
Model	Emissions model link to fuel type

An example emodel file is as follows

```
CWFIS,emodel
O1a,99
O1b,99
O1,99
C1,99
C2,99
C3,99
C4,99
C5,99
C6,99
C7,99
D1,99
D2,99
M1,99
M2,99
M3,99
M4,99
S1,99
S2,99
S3,99
```

Pseudo Code for CFFEPS

The current CFFEPS code consists of two principal programs and several additional subroutine programs. CFFEPS is the main program that calls the EnergyCalc, PlumeCalc and EmissionsCalc subroutines. Other programs, such as **FWI84.c** and **FBP_2009.c**, are established programs that are not discussed in this document.

CFFEPS

The program **CFFEPS.c** contains the main program that runs CFFEPS.

1. Set up the run:
    a. Read the argument line for the name of the input file. If this is missing, use the default **infile.dat**.
    b. Read the FBP defaults (subroutine *FBPdefaults* found in **fbp_2009.c**)
    c. Read the FEPS inputfile (subroutine *ReadFEPSData* found in **readfeps.c**)
    d. Define time series arrays for emissions of each pollutant (subroutines *ReadEmissionsData* and *ReadEmissionsModels* found in **reademissions.c**)
    e. Open CMC GEM forecast CSV file as input. Read in header line.
    f. Print (to the screen), new header line for the CFFEPS predictions CSV file.
2. Begin reading CFFEPS predictions CSV file:
    a. Reset arrays to zero.
    b. Read line of data into buffer. Parse comma separated variables in buffer. Make adjustments for possible variation in units (e.g Kelvin instead of Celsius, etc.)
    c. Assign upper air values into arrays uP, uZ and uT for future use in piecewise calculation (subroutine *PlumeCalcDry* found in **plume.c**)
    d. Determine if the line read in is a new hotspot (if the latitude, longitude or date does not equal previous line's values). If new, reset arrays to zero.
    e. Reassign FBP fuel type (if required). If there is no matching FBP fuel type, set to non-fuel (NF).

f. Determine time zone (longitude/15) and parse detection date and time. Adjust detection time from UTC to local time such that noon is at solar zenith . Adjust LDT to LST. Determine UTC and LST time of the forecast record.

g. Recalculate the BUI value from DMC and DC values. Determine whether the BUI effect is being used (subroutine *BUICalc* found in **fwi84.c**)

h. If new fire, determine the hours from the first hourly CMC forecast to the detection time: if less than zero, the fire starts at the detection size; if less than 24 hours, an initial fire size is calculated (based on persistence routine); if greater than zero, then the fire starts at zero size.

i. Calculate FFMC from yesterday's value using the technique described in Lawson et al. (1996) (subroutine *bdl_ffmc* found in **bdlffmc.c**). This is based on the observed noon FFMC. If the time is before noon, yesterday's FFMC is required. This is converged on so that yesterday's FFMC will predict today's observed FFMC (set to 11:59AM, 23:59 hours later).

j. Calculate FBP values at time of detection (and then at current time) (subroutine *FBPCalc* found in **fbp_2009.c**) [Note there are a number of calculations using subroutine *ProCalc* found in **fbp_2009_pro.c**. These are done for elliptical growth modelling, which is not being used by FIREWORK.]

k. Determine discovery time (the number of hours of growth required to reach the detection size). When persistence is being used, this time is assumed to be 24 hours. When elliptical growth modelling is being done, this is solved using *ProCalc* [see note above].

l. If current time is prior to discovery, the fire has not yet occurred and does not grow; else:

    i. If the current time corresponds to the reset time (if being used, not the default), set the area, cumulative energy and total emissions to zero.

    ii. Determine difference in time between current time and detection time. If less than an hour, calculate partial hour growth; otherwise, calculate hourly growth according to top-hat or weighted approach. Add to total area.

    iii. Calculate energy of the fire (subroutine *EnergyCalc* found in **energy.c**)

    iv. Calculate the energy released from flaming, smoldering and residual

combustion (subroutine *EmissionsCalc* found in **emissions.c**). Calculate flaming, smoldering and residual emissions rates in tonnes/h

v. Distribute the energy over time (subroutine *EmissionsOverTime* found in **emissions.c**)

vi. From the area growth and energy released, calculate the plume rise (subroutine *PlumeCalc* found in **plume.c**)

(1) if the type of calculation chosen is "dry", follow a piecewise piecewise integration of upper air profile heated to dry adiabat (subroutine *PlumeCalcDry* found in **plume.c**), otherwise

(2) follow the standard average lapse rate method outlined in Anderson *et al.*, 2011 (subroutine *PlumeCalc* found in **plume.c**)

(a) calculate height based on surface to 850 mb lapse,

(b) if recalculated height greater than 2000 m, recalculate height based on surface to 700 mb lapse rate (if resulting height less than 2000, use average),

(c) If recalculated height greater than 4000 m, recalculate height based on surface to 500 mb lapse rate (if resulting height less than 4000, use average).

(d) if superadiabatic from surface up to 500m, begin recalculate using 850 mb as the base

(e) if recalculated height greater than 2000 m, recalculate height based on 850 to 700 mb lapse rate (if resulting height less than 2000, use average)

(3) limit height to 250 mb height

(4) impose a minimum plume height

vii. Find emodel that matches the fuel type

viii. Distribute the emission over time (subroutine *EmissionsOverTimeNew* found in **emissions.c**).

ix. Calculate total emissions and r_smoke

m. Print results to the output file.

n. Read next line (go back to step 2. a.)

EmissionsCalc

The program **Emissions.c** contains the subroutine *EmissionsCalc* used to estimate the amounts of flaming, smoldering and residual fuel consumptions used by CONSUME 3.0.

1. Apply the average bulk density per fuel type to bulk densities for 2, 4 6 and 8 cm depths.
2. Overwrite these values with depth specific values for certain fuels.

3. Calculate the bulk densities of the L (0-1.2 cm), F (1.2-7 cm) and H (7-18 cm) layers from the 2 cm depth data.

    a. If grass fuel type (O1), burn off the entire grass fuel load. Use the grass reduction values for flaming, smoldering and residual combustion (see Table 2).

    b. else, if slash, use the total fuel consumption (TFC). Use the slash reduction values for flaming, smoldering and residual combustion (see Table 2).

    c. else, burn off the LFH layers in sequence until the entire SFC is accounted for. Then use the crown fuel consumption (CFC) for any canopy burned. Use the corresponding reduction values for flaming, smoldering and residual combustion (see Table 2).

EmissionsOverTime

The program **Emissions.c** contains the subroutine *EmissionsOverTime* used to distribute smoke emissions over time for a species.

The CFFEPS program creates pointers to arrays to represent the time series of smoke emissions. An array is created for each chemical species and each array element represents one time step in CFFEPS. During each time step in CFFEPS, new flaming, smoldering and residual fuel consumptions are calculated in *EmissionsCalc*, then *EmissionsOverTime* is called to distribute the emissions into the arrays (one array per chemical).

1. Calculate the total residence time in hours for flaming, smoldering and residual stages

2. Calculate the emissions rates [tonnes/hr] (or energy if jModel <0) for flaming, smoldering and residual stages

3. Stepping through each hour,

4. Calculate depth of burn [cm] per stage

5. Calculate energy release per stage

EnergyCalc

The program **Energy.c** contains the subroutine *EnergyCalc*. Parameters are passed to *EnergyCalc* through the structures FEPS and FBP. These structures are filled through information passed to CFFEPS through the input file.

1. Units are converted to SI units.

2. Determine fire area, growth, perimeter and radius.

3. Assign default duff characteristics by fuel type based on the literature.

4. Calculate depth of burn and the duff consumption from the surface fuel consumption (SFC) and densities

5. Water mass is calculated from the moisture content as described by the FFMC, (top 2 cm), DMC (2-5 cm), DC (5+ cm) and the depth of burn. Add the water mass from the crown fuel consumption (TFC-SFC) and the foliar moisture content (FMC).

6. Calculate *Qfire*, *Qw*, *Qf*, *Qs*, *Qr*, *Qinc* and from these *Qplume*

Note: the energy calculations are not finalized and there are a few alternate means of calculating these. For the current radiation model, *Qr* is based on the ratio of the surface area of the flame wall to the size of the fire. For the current incomplete combustion model, *Qinc* is based on *Qf* alone (multiplied by CFB/2).

PlumeCalc

The program **Plume.c** contains the subroutine *PlumeCalc*. Parameters are passed to *PlumeCalc* through the structures FEPS and FBP. These structures are filled through information passed to CFFEPS through the input file.

1. If the environmental lapse rate is unstable (<= -9.8ºC/km), or if the area or *Qplume* is less than zero, the plume height is set to -9999 (missing) and the subroutine is exited, else

2. Units are converted to SI units.

3. *Qplume* is the energy injected into the plume as calculated by EnergyCalc.

4. If past energy *Qo* present, add it to *Qplume* to get *Qt*.

5. Starting with an estimate height of 1000 m and converge on the plume height.

    a. Calculate the energy per unit mass q needed to heat plume to dry adiabat

    b. Calculate the column mass of the plume *M*

    c. Calculate air density in plume

    d. Adjust mass for entrainment

    e. Calculate total energy needed to heat plume to dry adiabat

    f. If energy greater than *Qt*, halve the height-step size and reduce the height, otherwise increase the height.

    g. Repeat calculations until the height-step size is less than a metre.

6. From the previous plume energy *Qo*, calculate the black body radiation loss *Qbb*.

PlumeCalcDry

The program **Plume.c** contains the subroutine *PlumeCalcDry*. Parameters are passed to *PlumeCalcDry* through the structures FEPS and FBP. These structures are filled through information passed to CFFEPS through the input file.

1. If the area or *Qplume* is less than zero, the plume height is set to -9999 (missing) and the subroutine is exited , else

2. Units are converted to SI units.

3. *Qplume* is the energy injected into the plume as calculated by EnergyCalc.

4. If past energy *Qo* present, add it to *Qplume* to get *Qt*.

5. Set array pointers to first upper air data point.

6. Set cumulative energy per unit mass, cumulative mass and plume height to zero.

7. Begin converging on plume height.

    a. If stepping upwards (Qatm < Qt), read in next level of data

i. Level 2 is the upper air data for the current level,

ii. Level 1 is the upper air data for the next level

b. Else, level 2 remains the same; reduce level 1 by 1 m, adjust pressure and temperature accordingly.

c. Calculate energy required to heat atmosphere to dry adiabat. Solution is found by calculating energy contained in trapezoid defined by (*T1*, *theta1*), (*T2*, *theta2*), (*T3*, *theta3*), (*T4*, *theta4*) where the temperatures are at the next level (T1), the current level (*T2*), while *T3* and *T4* are those when lowered adiabatically to the surface (*T1* to *T4*, *T2* to *T3*)

i. Calculate *T3* and *T4* using dry adiabat,
ii. Calculate potential temperatures,
iii. If stepping upward, *qc* and *Mc* are updated (when stepping down, *qc* and *Mc* remain constant),
iv. Calculate area in trapezoid (new strategy, subtracting triangles to calculate area in trapezoid),
v. Add new energy and mass to previous values *qc* and *Mc*.

d. Calculate air density in plume.

e. Adjust mass for entrainment.

f. If energy required to heat the air mass (*Qatm*) is greater than plume energy (*Qt*), begin calculations downward, reducing the top level by 1 metre until $Qatm < Qt$ again, in which case the soluiton is reached.

8. From the previous plume energy *Qo*, calculate the black body radiation loss *Qbb*.

References

Anderson, G. K., Sandberg, D. V., Norheim, R. A. 2004. Fire Emission Production Simulator (FEPS) User's Guide. USDA Forest Service, 99.

Anderson, K.R. 2000. Incorporating smoldering into fire growth modelling. Pages 31-36 in 3rd Symp. on Fire and Forest Meteorology, Jan. 9-14, 2000, Long Beach, CA. Am. Meteorol. Soc., Boston, MS.

Anderson, K.R., Englefield, P.E. 2001. Quantile characteristics of forest fires in Saskatchewan. Pages 9-16 in 4rd Symp. on Fire and Forest Meteorology, Nov. 12-15, 2001, Reno, NV. Am. Meteorol. Soc., Boston, MS.

Anderson, K.R., Pankratz, A. 2011. A thermodynamic approach to estimating smoke plume heights. In 9th Symp. on Fire and Forest Meteorology, Oct 18-20, 2011. Palm Springs, CA. Am. Meteorol. Soc., Boston, MS.

Côté, J., Gravel, S., Méthot, A., Patoine, A., Roch, M., Staniforth, A. 1998. The operational CMC MRB Global Environmental Multiscale (GEM) model: Part I Design considerations and formulation. Monthly Weather Review 126, 1373B1395.

de Groot, W.J., Pritchard, J.M., Lynham, T.J. 2009. Foerest floor fuel consumptionand carbon emissions in Canadian boreal fores fires. Can. J. For. Res. 39: 367-382.

Englefield, P., Lee, B.S., Fraser, R.H., Landry, R., Hall, R.J., Lynham, T.J., Cihlar, J., Li, Z., Jin, J., Ahern, F.J. 2004. Applying geographic information systems and remote sensing to forest fire monitoring, mapping and modelling in Canada. In Proceedings of the 22nd Tall Timbers Fire Ecology Conference: Fire in Temperate, Boreal and Montane Ecosystems, Kananaskis, Alberta. Tall Timbers Research Station: Tallahassee, FL

Forestry Canada Fire Danger Group. 1992. Development and structure of the Canadian Forest Fire Behavior Prediction System. Inf. Rep ST-X-3. Forestry Canada, Science and Sustainable Development Directorate, Ottawa, Ont., 63 pp.

Larkin, N.K., O'Neill, S.M., Solomon, R., Raffuse, S., Strand, T., Sullivan, D.C., Krull, C., Rorig, M., Peterson, J., Ferguson, S.A., 2010. The BlueSky smoke modeling framework. International Journal of Wildland Fire, 18(8), pp.906-920.

Landry, C., Parent, R., Deschênes, J.-F., Giguère, A., Hardy, G., Verret, R. 2005. Operational Scribe nowcasting sub-system: objective verification results. In 21st International Conference on Interactive Information Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology, San Diego, CA. Am. Meteorol. Soc., Boston, MS.

Lawson, B.D., Armitage, O.B., Hoskins, W.D. 1996. Diurnal Variation in the Fine Fuel Moisture Code: Tables and Computer Source Code. "Canada-British Columbia Partnership Agreement on Forest Reource Development: FRDA II." Can. For. Serv./B.C. Min. of Forestry, Victoria, B.C. FRDA report 245.

Nadeau, L.B., McRae, D.J., Jin, J.-Z. 2005. Development of a national fuel-type map for Canada using fuzzy logic. Information Report NOR-X-406. Can. For. Serv., Edmonton, AB)

Pavlovic, R., Chen, J., Anderson, K., Moran, M. D., Beaulieu, P. A., Davignon, D., Cousineau, S. 2016. The FireWork air quality forecast system with near-real-time biomass burning emissions: Recent developments and evaluation of performance for the 2015 North American wildfire season. Journal of the Air & Waste Management Association, 66(9), 819-841.

Prichard, S.J., Ottmar, R.D., Anderson, G.K. 2006. Consume 3.0 User's Guide. Seattle, WA: USDA Forest Service, Pacific Northwest Research Station, Pacific Wildland Fire Sciences Laboratory, Fire and Environmental Research Applications Team. 234 p.

Quayle, B., Lannom, K., Finco, M., Norton, J., Warnick, R. 2003. Monitoring wildland fire activity on a national-scale with MODIS imagery. In 2nd International Wildland Fire Ecology and Fire Management Congress and 5th Symposium on Fire and Forest Meteorology. Am. Meteorol. Soc., Boston, MS.

Stocks, B.J., Lawson, B.D., Alexander, M.E., Van Wagner, C.E., McAlpine, R.S., Lynham, T.J., Dubé, D.E. 1989. The Canadian Forest Fire Danger Rating System: an overview. Forestry Chronicle **65**: 450-457.

Van Wagner, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Can. For. Serv., Ottawa, Ont. For. Tech. Rep. 35. 37 pp.

Verret, R., Vigneux, D., Marcoux, J., Petrucci, F., Landry, C., Pelletier, L., Hardy, G. 1997. SCRIBE 3.0 A Product Generator. Pp. 392-395 in 13th International Conference on Interactive Information and Processing Systems for Meteorology, Oceanography and Hydrology, Long Beach, CA. Am. Meteorol. Soc., Boston, MS.

Wilson, L.J., Vallée, M. 2002. The Canadian Updateable Model Output Statistics (UMOS) system: design and development tests. Weather and Forecasting 17, 206B222.

Wilson, L.J., Vallée, M. 2003. The Canadian Updateable Model Output Statistics (UMOS) system: validation against perfect prog. Weather and Forecasting 18, 288B302.