3A.4 A COMPARISON OF HOURLY FINE FUEL MOISTURE CODE CALCULATIONS WITHIN CANADA

Kerry Anderson[1]
Canadian Forest Service

1. INTRODUCTION

The Fine Fuel Moisture Code (FFMC) is an important component of the Canadian Fire Weather Index (FWI) System (Van Wagner 1987) and the Canadian Forest Fire Behavior (FBP) System (Forestry Canada Fire Danger Group 1992). It and the wind determine the Initial Spread Index (ISI), which is used to predict the rate of spread in all FBP fuel types. In addition, the FFMC is used to predict surface fuel consumption in the C-1 (spruce-lichen woodland) and C-7 (ponderosa pine - Douglas-fir) fuel types, and thus the fire intensity. In terms of fire-growth modelling, it is important to have correct diurnal trends in the fine fuels in order to produce realistic fire behaviour.

The purpose of this paper is to compare methods of calculating hourly values of the Fine Fuel Moisture Code (FFMC) used in Canada. The equations used in the standard daily FFMC calculations within the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987) are explained and compared to those used in the hourly FFMC calculations developed by Van Wagner (1977). The diurnal FFMC approach described by Lawson *et al.* (1996) provides tabulated hourly values for the FFMC based strictly on the standard daily FFMC and expected diurnal variation. A third approach using just the Equilibrium Moisture Content (EMC) is introduced in this paper. The three methods are compared using a generalized diurnal weather trend and observed weather. A fire-growth model is used to assess the impact of each method using the predicted FFMC values within the model.

2. THEORY

2.1 *Standard Daily FFMC*

The current equations for the standard daily Fine Fuel Moisture Code calculations have been documented by Van Wagner (1987). Equation numbers used in this section correspond to those in the 1987 document preceded by the publication's year.

Currently, the FFMC F is related to the moisture content m (%) as

$$F = 59.5\,(250 - m)\ /\ (147.2 + m) \qquad \text{(87-2a)}$$

$$m = 147.2\ (101 - F)\ /\ (59.5 + F) \qquad \text{(87-2b)}$$

This pair of equations is referred to as the *FF* scale. The drying and wetting terms (k_o) are respectively related to the humidity H (%) and wind speed W (km/h) as

$$k_o = 0.424\,[1 - (H/100)^{1.7}] + 0.0694\,W^{0.5}\,[1 - (H/100)^{8}] \qquad \text{(87-4)}$$

$$k_o = 0.424\,[1 - (\frac{100 - H}{H})^{1.7}] + 0.0694\,W^{0.5}\,[1 - (\frac{100 - H}{H})^{8}] \qquad \text{(87-5)}$$

In turn, the drying/wetting term is related to the temperature T (°C) as

$$k = k_o \times 0.581\,e^{0.0365\,T} \qquad \text{(87-6)}$$

Equations for the equilibrium moisture content E_d and E_w (%) are related to the temperature and humidity as

$$E_d = 0.942\,H^{0.679} + 11\,e^{(H-100)/10} + 0.18\,(21.1 - T)\,(1 - e^{-0.115\,H}) \qquad \text{(87-8a)}$$

$$E_w = 0.618\,H^{0.753} + 10\,e^{(H-100)/10} + 0.18\,(21.1 - T)\,(1 - e^{-0.115\,H}) \qquad \text{(87-8b)}$$

the choice of which depends on whether there is drying or wetting in action.

Finally, the new moisture content is calculated as

$$m = E_d + (m_o - E_d) \times 10^{-k_d} \qquad \text{(87-9)}$$

when drying is in effect (m_o is greater than E_d), or

$$m = E_w + (E_w - m_o) \times 10^{-k_w} \qquad \text{(87-10)}$$

when wetting occurs (E_w is greater than m_o). Note that k_d and k_w are equal to k in equation 87-6, with the subscript indicating the wetting or drying process.

[1]*Corresponding author address*: Kerry Anderson, Canadian Forest Service, Northern Forestry Centre, 5320 122 Street, Edmonton, AB T6H 3S5; (780) 435-7320; kanderso@nrcan.gc.ca

Rainfall enters into the standard daily FFMC calculations modifying the moisture content, but for the purpose of this paper it has been ignored for now. Implications of this will be discussed later.

2.2 *Hourly FFMC*

In 1977, Van Wagner published an hourly version of the calculations, referred to as the hourly FFMC. Equation numbers used in this section correspond to those in the 1977 document preceded by the publication's year (variables are consistent with the daily calculations).

$$m = 205.2\ (101 - F)\ /\ (82.9 + F) \quad (77\text{-}1)$$

$$E_d = 0.942\, H^{0.679} + 11\, e^{(H-100)/10} + 0.18\,(21.1 - T)\,(1 - e^{-0.115H}) \quad (77\text{-}2a)$$

$$E_w = 0.618\, H^{0.753} + 10\, e^{(H-100)/10} + 0.18\,(21.1 - T)\,(1 - e^{-0.115H}) \quad (77\text{-}2b)$$

$$k_a = 0.424\,[1 - (H/100)^{1.7}] + 0.0694\, W^{0.5}\,[1 - (H/100)^{8}] \quad (77\text{-}3a)$$

$$k_d = k_a \times 0.0579\, e^{0.0365\,T} \quad (77\text{-}3b)$$

$$k_b = 0.424\,[1 - (\frac{100 - H}{H})^{1.7}] + 0.0694\, W^{0.5}\,[1 - (\frac{100 - H}{H})^{8}] \quad (77\text{-}4a)$$

$$k_w = k_b \times 0.0579\, e^{0.0365\,T} \quad (77\text{-}4b)$$

$$m = E_d + (m_o - E_d) \times e^{-2.303\,k_d} \quad (77\text{-}5a)$$

$$m = E_w + (E_w - m_o) \times e^{-2.303\,k_w} \quad (77\text{-}5b)$$

$$F = 82.9\,(250 - m)\ /\ (205.2 + m) \quad (77\text{-}6)$$

The differences between the hourly and the standard daily calculations are as follows:

- Equations 77-1 and 77-6 use an older method to convert to and from the FFMC, *F*, and the moisture content *m*. This is referred to as the *F* scale. The *FF* scale used in daily calculations (equations 87-2a and 87-2b) has replaced the *F* scale and is used in the current version of the hourly calculation.
- The constant term of 0.0579 used in equations 77-3b and 77-4b is different from 0.581 used in 87-6. The term reflects the drying/wetting rate for each set of calculations; the former is used to create the smaller, hourly changes, while the latter is used for daily changes.
- The drying rates in equations 77-5a and 77-5b use a power of *e* while equations 87-9 and 87-10 use a power of 10. Equations 77-5a and 77-5b are equal to equations 87-9 and 87-10, with a conversion factor of -2.303 (which may lead to some rounding error).

Another difference (though not formally addressed in this paper) is that the canopy effect on the net rainfall has been removed. In the daily calculations, 0.5 mm is removed from the observed rainfall to account for loss in the overhead canopy. The removal of this term is a necessary step as there is no easy way of tracking this loss on an hourly basis.

2.3 *Diurnal FFMC*

An alternate, recognized approach to calculating diurnal values of the FFMC was presented by Lawson *et al*. (1996). This method, referred to as the diurnal FFMC, provides a tabulated set of hourly values. These are based on the standard daily FFMC as calculated at noon and on assumed diurnal weather changes over the course of the next 24 hours.

The Lawson *et al*. publication was an update of previous tabulated values prepared by Muraro *et al.* (1969), Van Wagner (1972) and by Alexander (1982). Lawson *et al.* improved on previous work through regression analysis of Muraro *et al.*'s original data and Van Wagner's harmonized curves (1972), use of the *FF* scale (Van Wagner 1987), interpolation for intermediate times and extrapolation out to the next day. Lawson *et al*. presents the underlying equations; computer source code was also provided by the authors upon request.

The four iterations of the tabulated values are based on the work originally done by Muraro *et al.*(1969). Forest litter was sampled up to eight times a day in a dry lodgepole pine site near Prince George, B.C. Van Wagner combined these data with similarly measured jack pine litter data taken at Petawawa, Ontario (1972). Other work conducted by Van Wagner (1977, 1987) is based on jack pine litter alone taken at Petawawa. Differences between the sites and the species have contributed to differences in calculated values (Beck and Armitage 2004; Lawson and Armitage 2008).

2.4 *Equilibrium Moisture Content*

A final approach is to use the equilibrium moisture content (EMC). These are the E_d or E_w values of equations 87-8a and 87-8b of the standard daily calculations. In physical terms, this eliminates any drying and wetting rates and assumes the fine fuels are in a state of equilibrium with the environment – in other words, instantaneous drying and wetting. The reason for using the EMC is to create a wider range in the FFMC, which is discussed later.

3. METHODOLOGY

The three methods of diurnal FFMC calculations, hourly (Van Wagner 1977), diurnal (Lawson *et al.* 1996) and EMC, were used to calculate hourly values of the FFMC. These values were then entered into a simple 16-point fire-growth model (Anderson *et al.* 2007; Anderson *et al.* 2009) to assess the impact of the different methods.

For the first stage of this study, a generalized diurnal cycle of temperature, relative humidity and wind speed was used to conduct the FFMC calculations. The derived diurnal cycle was based on trends developed by Beck and Trevitt (1989). The climatology of Petawawa and its latitude were used to mimic conditions under which the FFMC was originally developed. Maximum and minimum temperatures were set at 25° and 10° C; maximum and minimum wind speeds were set at 10 and 5 km/h. The minimum relative humidity was set at 30%, with the vapour pressure held constant through the day. Beck and Trevitt's alpha, beta and gamma terms were set to 0.88, 1.86 and -2.2 for temperature and 1.0, 1.24 and -3.59 for wind speed. Hourly values of the weather were then used where required by the three FFMC calculation methods.

A four-day time series of hourly weather and FFMCs using this generalized diurnal cycle were used as input into a fire-growth model. In this case, the fire-growth model used a homogeneous C-2 (boreal spruce) fuel type (Forestry Canada Fire Danger Group 1992) with a 150-m cell size.

The second stage of this study used historical weather from Fort Smith, NWT (Figure 1). In this case, a four-day period from June 1 to 4, 2007 was chosen (to match the fire-growth modelling period discussed later). The same homogeneous fuel fire-growth exercise was conducted using the observed hourly weather for Fort Smith, 2007. Observed hourly wind direction (not shown in the figures) was introduced into the fire-growth predictions.

In the third stage, fire-growth predictions were compared against historical fire growth. Anderson *et al.* (2009) evaluated the performance of a fire-growth model in an operational setting by comparing daily predictions of area burned to observed patterns of satellite-detected hotspots for two large fires in Wood Buffalo National Park, Canada (Figure 1). Fires 07WB001 and 07WB002 burned more than 200 000 ha in size from May into July, providing 54 fire simulation days for the study. A set of skill scores were used to measure the performance of the model.

A final consideration was included in the third stage, where FFMC calculations were turned off at night (that is, setting the FFMC to zero between sunset and sunrise). This is a commonly used technique to compensate for differences between the hourly and diurnal methods (Lawson and Armitage 2008).

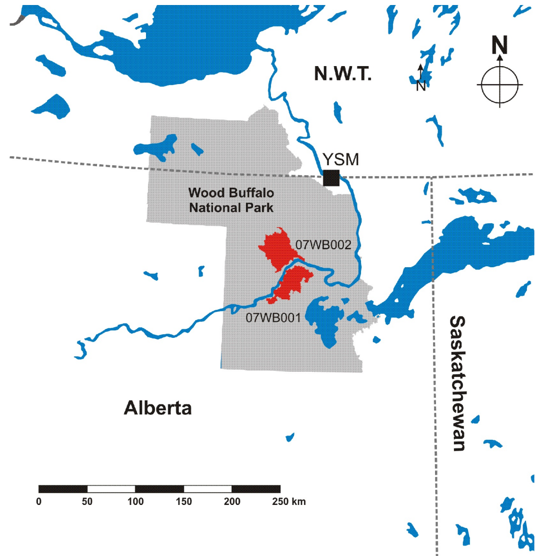

Figure 1. Fires 07WB001 and 07WB002 within Wood Buffalo National Park, Canada. Fort Smith is indicated by its three letter identifier (YSM).

4. RESULTS

4.1 *Generalized Diurnal Cycle*

The resulting weather cycles, as calculated using Beck and Trevitt (1989), are shown in Figure 2. Based on these diurnal trends, Figure 3 compares the calculated FFMC values using the three methods: Van Wagner's hourly FFMC calculations (CVW), the Equilibrium Moisture Content (EMC), and Lawson's tabulated diurnal FFMC (BDL). The spikes appearing in the BDL curve correspond to the change from a 23-hour forecasted value at 11:00 to the 12:00 observed value. Note the gradual rise in values reflects the expected rise of the daily FFMC embedded within Lawson's equations.

Figure 3 shows significant differences between calculated values of the FFMC using the three methods. Values based on Lawson *et al.* show the largest degree of variation between the peak values of 91.5 in the afternoon and the lowest value 72.7 near dawn. Contrasting this, values based on Van Wagner's hourly calculations show a smooth transition between night and day with FFMCs varying between 86.4 and 90.6. The EMC method has a larger variation from 81.8 to 92.0. It does not drop as low as that of Lawson *et al.* and predicted slightly higher than the other two.

Figure 4 shows the predicted fire growth based on the three methods of calculating the FFMC. Predicted fire sizes reflect the implications of using the various diurnal FFMC calculations in a fire-growth modelling

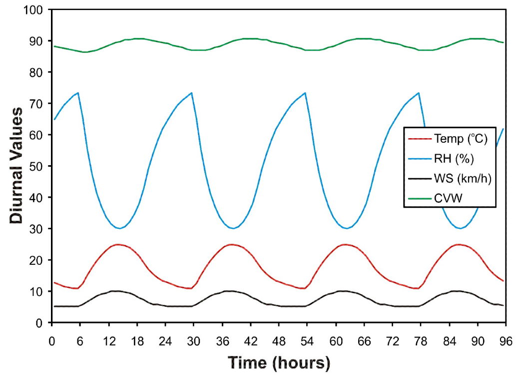

Figure 2. Generalized diurnal cycles of temperature (Temp [°C]), humidity (RH [%]), wind speed (WS [km/h]) and Van Wagner's hourly FFMC (CVW).

environment. Van Wagner's method produced an area-burned prediction that was more than twice as large (124% larger) as that using Lawson's method, while the EMC method was 65% larger than Lawson's. Note that the unusually large fire sizes are a result of the simulated weather and homogeneous fuel type.

4.2 *Observed Weather*

The same exercise as conducted with the general diurnal trends was done with observed weather. In this case, the hourly weather from Fort Smith, NWT was used in the FFMC calculations.

Figure 5 shows a four-day period from June 1 to 4, 2007 (chosen to match the fire-growth modelling period discussed later). During this period, the temperature varied from 10 to 27 °C, humidities from 20 to 81%, and winds from calm to 22.2 km/h. A cross-over where the observed humidity dropped below the observed temperature was experienced on June 1.

Figure 6 shows the hourly FFMCs following the three methods. In this case, the EMC closely mimics the pattern predicted by Lawson *et al.* Again, Van Wagner's calculations produce values of much less variation than the other two methods.

The same homogeneous fuel fire-growth exercise was conducted using this four-day series of observed hourly weather for Fort Smith. Observed hourly wind direction (not shown in the figures) was introduced into the fire-growth predictions. In this case, the three methods predicted increasing sizes of predicted area burned (97 242, 164 561, and 233 588 ha for BDL, EMC, CVW respectively). Again, Van Wagner predicted a fire 140% larger than Lawson *et al.*, while the EMC approach was 69% larger.

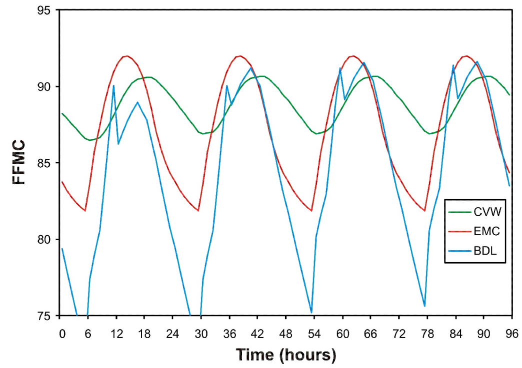

Figure 3. Observed variance of FFMC following the generalized diurnal cycles using three methods of FFMC calculation: Van Wagner's hourly FFMC (CVW), equilibrium values (EMC), and Lawson *et al.*'s diurnal FFMC (BDL).

4.3 *Historical Fire Growth*

Table 1 presents results of 54 fire simulation days covering the period from May 30 to June 28, 2007 for the two large fires, 07WB001 and 07WB002. The original comparison of equilibrium versus Van Wagner's hourly FFMC (EMC vs CVW) as conducted by Anderson *et al.* (2009) are shown. In addition, results based on the diurnal method (BDL) are included in the

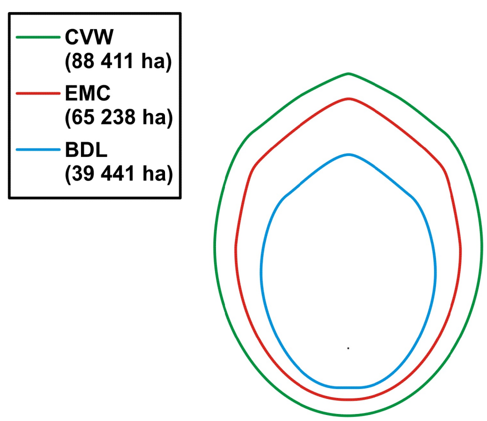

Figure 4. Predicted four-day fire growth sizes following the generalized diurnal cycles using three methods of FFMC calculation: Van Wagner's hourly FFMC (CVW), equilibrium values (EMC), and Lawson *et al.*'s diurnal FFMC (BDL).

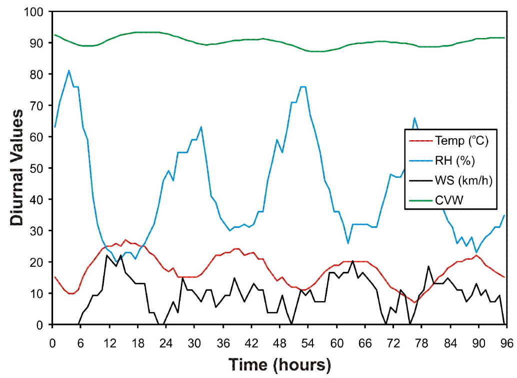

Figure 5. Observed hourly temperature (Temp [°C]), humidity (RH [%]), wind speed (WS [km/h]) and Van Wagner's hourly FFMC (CVW) for Fort Smith, NWT, June 1 to 4, 2007

comparison. Finally, the option of turning off the calculations at night (from sunset to sunrise) is also included in the growth predictions. These results are also shown in Figure 7.

Table 1. Comparison of bias scores for daily fire-growth predictions for two large fires in Wood Buffalo National Park, 2007.

	Bias	
Hourly FFMC Methodology	07WB001	07WB002
Diurnal (BDL)	1.33	1.11
Hourly (CVW)	2.05	1.78
Equilibrium (EMC)	1.70	1.49
Diurnal (BDL) night off	1.23	1.01
Hourly (CVW) night off	1.51	1.29
Equilibrium (EMC) night off	1.51	1.31

The table shows the biases (ratio of the sums of predicted and observed areas burned) resulting from the various methods of calculating the hourly FFMC. When using Lawson's method, biases of 1.33 and 1.11 were observed. The EMC method resulted in biases of 1.70 and 1.49, and when Van Wagner's hourly calculations were used, the biases increased to 2.05 and 1.78. This would suggest that each method for calculating the hourly FFMC is resulting in over-predictions of area burned: 11-33% for Lawson *et al.*, 49-70% for the equilibrium, and 78-105% for Van Wagner's.

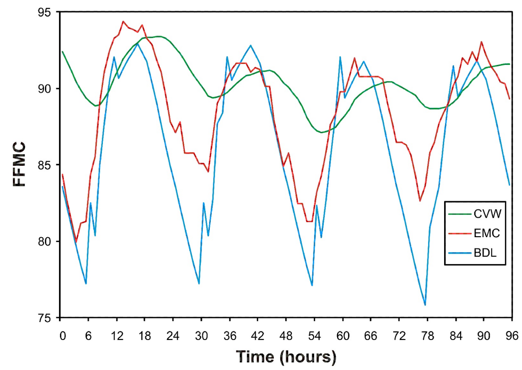

Figure 6. Observed variance of FFMC following the observed weather from Fort Smith, June 1 to 4, 2007, using three methods of FFMC calculation: Van Wagner's hourly FFMC (CVW), equilibrium values (EMC), and Lawson *et al.*'s diurnal FFMC (BDL).

When the additional step of turning the calculations off at night is conducted (effectively eliminating any fire growth), the biases dropped substantially. Bias values using Lawson's approach dropped to 1-23% over-prediction values (nearing equity). The EMC and Van Wagner's methods both dropped to 29-51% over-prediction while showing negligible differences between the two methods.

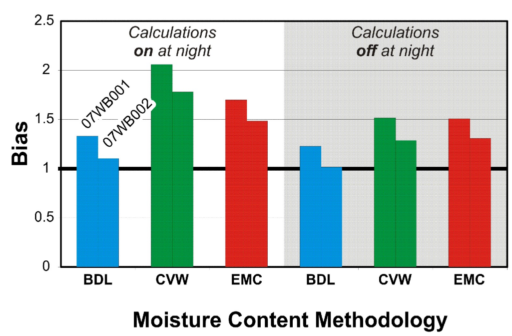

Figure 7. Comparison of bias scores for daily fire-growth predictions for two large fires in Wood Buffalo National Park, 2007.

5. DISCUSSION

Results indicate that the diurnal method presented by Lawson *et al.* produced the best bias scores and thus the best predictions of the diurnal variation in the fine fuels moisture. Over-predictions of predicted fire growth as measured by the bias score, are between 11 and 33% when using this method.

With that said, the diurnal method does not include hourly weather observations, which are important to capture. Specifically, in the diurnal method the only weather used is the noon weather conditions to calculate the standard daily FFMC. This value is then projected out into the afternoon and evening with no input of hourly weather conditions (allowance is made for humidity conditions the next morning). Weather beyond noon is assumed to follow a general pattern that leads to the projected FFMCs. Hourly variations in wind, temperature and humidity are lost in these projections.

Another concern with using the diurnal FFMC would be the discontinuities that occur during the transition from 23-hour predictions at 11:00 to observed values at noon. Figures 3 and 6 show sudden drops of 2 to 4 points during these transition periods, which could result in fires dropping from the crowns to the surface.

Where the diurnal method likely succeeds is in the range of variation and specifically in its representation of the overnight moisture conditions. This is evident when calculations are turned off at night. Under these conditions, the over-predictions of the hourly and the EMC models are reduced substantially, while over-predictions of the diurnal model are only marginally reduced. If the over-predictions were due to another cause, for example an incorrect choice of fuel models or over-predictions inherent within the FBP system, one would expect a systematic reduction of over-prediction of all three models when night calculations are turned off.

A visual comparison of Figures 3 and 6 shows the daytime FFMCs of all three models in relatively close agreement while the overnight values predicted by the diurnal model presumably better reflect the observed diurnal ranges. The EMC method approaches these ranges and thus has better bias scores than those of Van Wagner.

When FFMC calculations are shut off at night, all three methods see a reduction in bias scores with negligible differences between EMC and Van Wagner's method (this would be consistent with the agreement in daytime FFMCs). While recognized as an artificial fix to the bias problem, this indicates that radiation is a critical process missing from both Van Wagner's hourly and the EMC calculations.

This is not the first paper addressing discrepancies between Van Wagner's hourly calculations and the tabulated values presented by Lawson *et al*. Beck and Armitage (2004) studied fine fuel samples taken during the International Crown Fire Modelling Experiment (Stocks *et al*. 2004); they found that both the hourly and the diurnal FFMC methods over-estimated the minimum moisture content of feather moss and jack pine needles on dry days, while both overestimated needle moisture content and underestimated feather moss moisture content after rain. Lawson and Armitage (2008) also warned that during extended dry periods, the hourly method will predict excessive fire growth at night, and that the diurnal method produces more realistic values during such times.

Two other issues need to be discussed. It was mentioned earlier that this study does not include rain in its calculations. Both the standard daily and the hourly methods of calculating the FFMC do include rainfall in their calculations, while the EMC and Lawson *et al*. do not. My interest lies in fire-growth modelling, and from the operational perspective, fire behaviour during periods of rain is of little interest. Modellers are more interested in aggressive rather than marginal fire behaviour.

A second issue is that fire behaviour models within the Canadian Forest Fire Behaviour Prediction (FBP) System are based on predicted values of the FFMC using Van Wagner's hourly method; using another method, such as the EMC, is not valid. The response to this is that the experimental burns used to develop the FBP system were conducted in high fire-danger conditions, presumably the fine fuels were in equilibrium with the environment during these experiments. To this author's knowledge, no burns were conducted in the rain, nor on days immediately after rain.

6. CONCLUSION

The efforts here show the shortcomings of the current hourly FFMC calculation developed by Van Wagner. Simply put, this method does not produce the expected range of diurnal values of the FFMC. When used in fire-growth modelling exercises, predicted area burned is as much as double that measured by observation.

The constant term of equation 87-6 controls the dampening of the drying/wetting terms in the diurnal trend. Eliminating this term sets the moisture content into equilibrium with the environment. This approach produces diurnal variations closer to expected values and when used in fire-growth modelling, over-predictions are reduced by 30%.

Results from this study suggest that the current methods of calculating the diurnal variation of the FFMC are lacking radiation as a physical component in their calculations. Turning off the calculations at night is a quick fix to the over-prediction problem but a physical process of including radiation is the next logical step in producing a more accurate fine fuel moisture model.

7. ACKNOWLEDGEMENTS

I thank Parks Canada staff for their support and assistance in providing the necessary fuels and topographic information; the Canadian Meteorological Centre (CMC) for providing the forecast weather information; and the University of Maryland Department of Geography and the NOAA National Environmental Satellite, Data and Information Service for providing the hotspot data. Also, thanks are extended to Brad Armitage, Marc Parisien, and Mike Wotton who provided helpful comments.

8. REFERENCES

Alexander, M.E. 1982. Diurnal adjustment table for the Fine Fuel Moisture Code. Can. For. Serv. Nor. For. Centre, For. Manage. Note 17, Edmonton, Alta.

Anderson, K.R.; Englefield, P; Little, J.M.; Reuter, G. 2009. An approach to operational forest fire growth predictions for Canada. Int. J. Wildland Fire (in press).

Anderson, K.R.; Reuter, G.; Flannigan, M.D. 2007. Fire-growth modelling using meteorological data with random and systematic perturbations. Int. J. Wildland Fire 16(2), 163-172.

Beck, J.A.; Armitage, O.B. 2004. Diurnal fine fuel moisture characteristics at a northern latitude. Pages 211–221 in R.T. Engstrom, K.E.M. Galley, and W.J. de Groot, eds. Fire in temperate, boreal and montane ecosystems: Proc. 22nd Tall Timbers Fire Ecol. Conf., 15–18 Oct. 2004, Kananaskis, AB. Tall Timbers Res. Stn., Tallahassee, FL.

Beck, J.A.; Trevitt, A.C.F. 1989. Forecasting diurnal variations in meteorological parameters for predicting fire behavior. Can. J. For. Res. 19: 791-797.

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.

Muraro, S.J.; Russell, R.N.; Lawson, B.D. 1969. Devempent of diurnal adjustment table for the Fine Fuel Moisture Code. Can. For. Serv., Pac. For. Res. Centre, Victoria, B.C. Inf. Rep. BC-X-35.

Lawson, B.D.; Armitage, O.B. 2008. Weather guide for the Canadian Forest Fire Danger Rating System. Nat. Resour. Can., Can. For. Serv., North. For. Cent., Edmonton, AB.

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.

Stocks, B.J.; Alexander, M.E.; Lanoville, R.A. 2004. Overiew of the International Crown Fire Modelling Experiment (ICFME). Can. J. For. Res. 34: 1543-1547.

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.

Van Wagner, C.E. 1977. A Method of Computing Fine Fuel Moisture Content throughout the Diurnal Cycle. Can. For. Serv., Chalk River, Ont. Inf. Rep. PS-X-69. 15 pp.

Van Wagner, C.E. 1972. A table of diurnal variation in the Fine Fuel Moisture Code. Can. For. Serv., Petawawa For. Exp. Sta., Chalk R., Ont. Inf. Rep. PS-X-38.