Predicting Forest Fire Danger Using Improved Model Derived Soil Moisture and Antecedent Precipitation

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Abstract: Few, if any, Forest Fire Danger Index (FFDI) schemes have considered routinely, soil moisture status, which is a key factor in assessing the dryness of vegetation and hence bushfire risk. Two methods are explored in an attempt to improve FFDI prediction. Firstly, improvements are made to the HIgh RESolution meso-scale numerical weather model (HIRES), developed by one of the authors, to output more realistic soil moisture fields. Secondly, Antecedent Precipitation Index (API) is compared with Drought Factor (DF) in FFDI prediction. These two methods were investigated by applying HIRES to the Goulburn River catchment, Hunter Valley, NSW, Australia over a period covering approximately six weeks (November/December, 1997) prior to and following a large bushfire that occurred in the catchment. A more structured soil moisture scenario is produced as a result of the improvements to the HIRES model. It is shown that API, as an alternative, is a simple and very direct index that can represent the role of precipitation in the calculation of FFDI. The results are sufficiently encouraging to research further these two methods in their respective roles of FFDI prediction.

Keywords: *Forest Fire Danger index, numerical weather prediction model, Antecedent Precipitation Index, Goulburn catchment*

1. INTRODUCTION

Early warning of fire danger is one of the most important tasks in fire weather related research. Almost every country has a Forest Fire Danger Index (FFDI) map (Global Fire Monitoring Center (GFMC, http://www.fire.uni-freiburg.de/). There are many documented fire danger index models, such as, BEHAVE fine fuel moisture model (Rothermel et al.,1986; Viney, 1991), Canadian Fire Weather Index and codes (Van Wagner, 1987), Portuguese index (Gonçalves and Lourenço, 1990), Forest Potential Index (Burgan et al, 1998; Sebastian, et al, 2002) and many others (San-Miguel-Ayanz, 2002). Among many factors affecting fire danger, such as vegetation moisture and ambient temperature, which have been widely recognized, less well known and less analyzed, is the importance of soil moisture. The Finnish Forest Fire Index Calculation System and Italian Fire Danger index are two of the few exceptions, which were based on surface moisture estimation of a 60 mm thick surface layer. High temperatures and limited moisture supply both in soil and vegetation lead to vegetation stress and deterioration of vegetation health. Therefore, improving soil moisture can be used as a proxy for improving fire danger prediction.

As observed soil moisture data is very limited, and most Numerical Weather Prediction (NWP) models, that are used for fire danger index forecasting, do not treat soil moisture as a model predicted variable, providing a more realistic soil moisture status for FFDI prediction is a big challenge.

Most of the FFDI models use complex, experimental algorithms to calculate Drought Factor (DF), which is one of the most important inputs to FFDI prediction. To develop both a simple and realistic index to represent DF would be another way of improving fire danger predictions.

In this paper, we explore two methods to improve Forest Fire Danger Index prediction. One is via improvement to the NWP model (HIRES) to approach a more realistic soil moisture status. Another is to introduce an alternative index to describe DF for FFDI prediction that is simpler and has a more direct response to precipitation than the classical DF index. Before we describe the two methods, details of the catchment and the fire are presented. Finally, a short conclusion is given.

2. CATCHMENT AND FIRE

The Goulburn River catchment is located in the Hunter Valley, in the State of New South Wales (NSW), in Australia. The Goulburn River divides the vegetation of the catchment into two sections. In the south, it is dense forest, with mainly woodland occasionally combined with shrub. The banksia, one of the main species in the area, has a very hard leaf surface with stoma on the sunshaded face which reduces evaporation. In its north, the catchment is covered by grass for grazing combined with a sparse distribution of Eucalyptus. There are many varieties of Eucalyptus in the catchment that are able to resist drought by possessing such varied properties as cold-touched skin and the shallow colour to reflect heat for reducing transpiration, thick skin to resist fire, and twisted skin to reduce transpiration. The immature leaf of Eucalyptus is small and round, compared to the mature Eucalyptus leaf, which is very long and narrow, again for reducing evaporation..

Although the vegetation resists fire and drought, the landscape has still suffered from many fires in the last two decades. As in other areas of southeastern Australia, bushfires usually occur here when a vigorous cold front approaches a slow-moving high pressure system in the Tasman Sea off the east coast, advecting hot, dry, northwesterly winds from the arid interior toward the southeast drying the soil and abundant forest fuel (many tonnes of wood per square km are usually available).

In this paper we focus on a 1997/98 fire, one of the most severe fires ever to occur in the Goulburn River catchment. The fire originally started on November 27 due to a lightning strike. It grew substantially in area by December 2, and lasted a further seven days (Liu et al , 2003a).

3. IMPROVED NWP MODEL FOR FFDI PREDICTION

The Numerical Weather Prediction (NWP) model used in this paper is the University of New South Wales HIgh RESolution limited area model (HIRES). HIRES operates over a limited domain with high resolution (up to 5 km or less). The HIRES forecasts are bounded by the appropriate global forecast. The HIRES model has been successfully applied in a variety of applications, including modeling fire spread rate (Speer et al. 2001). In Speer et al. (1996) it was shown that HIRES can provide much improved guidance to that of the operational model at the time in depicting mesoscale atmospheric features and in producing skilful predictions of the Forest Fire Danger Index.

As in many other NWP models, HIRES treats soil moisture simply using the Force-Restore method. By replacing the Force-Restore method with the advanced soil moisture simulation scheme (Richards) plus precipitation revision (see Liu et al. 2003b), the improved HIRES gives a more structured soil moisture scenario (Figure 1).

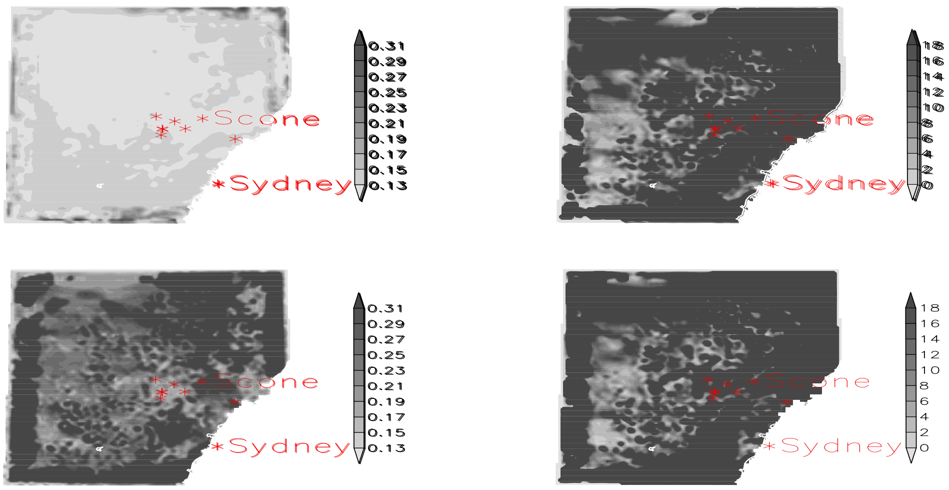

Figure 1. Simulated soil moisture ratio (left column) and precipitation (mm) (right column) before (upper panel) and after scheme revision (lower panel).

The soil deficiency descriptor, Keetch Byram Drought Index (KBDI) or Mount Soil Dryness Index (SDI), used in classical FFDI prediction in Australia, is defined, more or less, arbitrarily based on annual rainfall, temperature, and recent rain. Providing a more realistic soil moisture status is a very important step further in attempting to improve FFDI prediction. At this stage, the simulated precipitation from our model has not satisfactorily matched the observed precipitation (Figure 2).

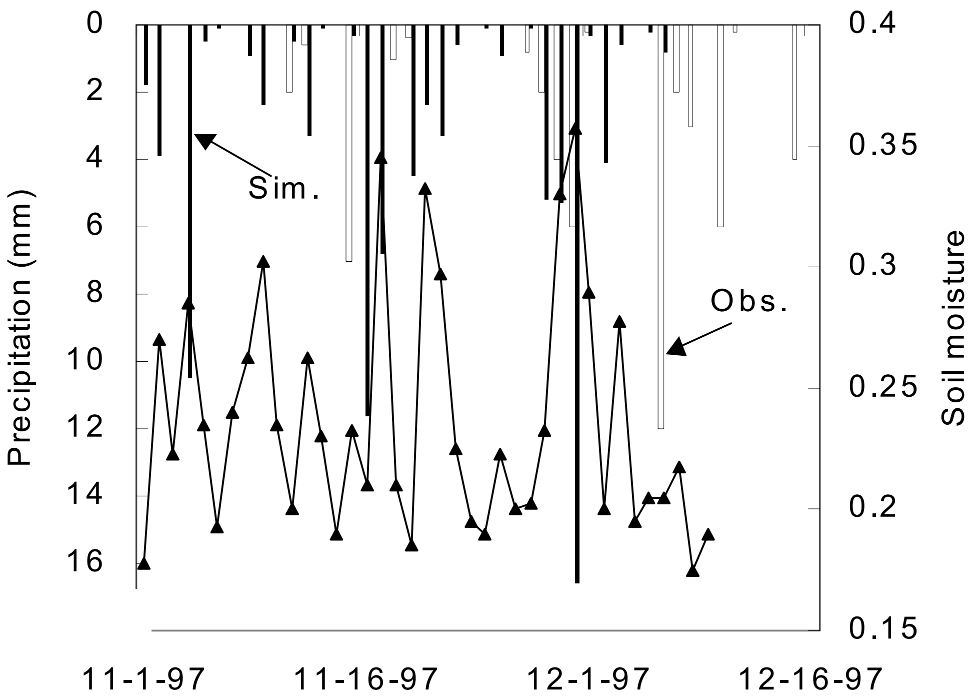

Figure 2. The observed precipitation (mm) compared with the simulated precipitation (mm) and soil moisture ratio.

However, the model results of the more structured soil moisture fields are more encouraging.

4. AN ALTERNATIVE DROUGHT INDEX FOR FFDI PREDICTION

The Australia Forest Fire Danger Index (FFDI) which is used to assess the likelihood and severity of bushfires, is empirically derived by McArthur (McArthur 1967) and is expressed as:

$$FFDI = 1.275D^{0.987} exp\{[T/29.5858] - [H/28.9855] + [V/42.735]\} \quad (1)$$

where D is a drought factor:

$$D = 0.19[I+104][N+1]^{1.5} /\{3.52[N+1]^{1.5} + R - 1\} \quad (2)$$

where T is the daily maximum temperature (°C), H is the daily minimum relative humidity (%), V is the daily-mean wind speed (km/h), N is the number of days since the last rain, R (mm) is the total rain in the most recent 24 hours with rain, I (mm) is the amount of rain needed to restore the soil moisture content to 200 mm (using KBDI).

It was shown that by Nobel et al. (1980) that McArthur sometimes underestimates the most extreme cases as it only produces a High Forest Fire Danger (two categories lower than the most extreme) while Nobel's formula results in a very high forest fire danger category (one category lower than most extreme)

Griffiths (1999) proposed a new formula to calculate drought factor:

$$D = min\{10.5[1 - exp\frac{-(I+30)}{40}] \frac{y+42}{y2+3y+42}, 10\} \quad (3)$$

where y is defined by

$$y = \begin{cases} (P-2)/N^{1.3}, if \quad N \geq 1 \;\; \& \;\; P > 2 \\ (P-2)/0.8^{1.3}, if \quad N = 0 \;\; \& \;\; P > 2 \\ 0 \qquad if \quad P \leq 2 \end{cases} \quad (4)$$

In the above equations, P is rainfall in mm during an event, N time since the rain event in days, I soil dryness in mm equivalent (Keetch and Byram 1968). Each rain event is assigned a nominal 24 hour period in which it is deemed to have occurred. If the rain event occurred in the 24 hours to 9 am on the current day then $N=1$. If the rain occurred since 9 am then $N=0$. The measure of significance of a rain event is given by variable y. The most significant rain event ($P.N$) is that event in the last 20 days which maximizes y or equivalently, minimizes the drought factor *DF*. The higher the DF, the drier the fuel.

The quantity *I*, *i*.e *KBDI*, in equation (2) and (3) is related to the previous day's screen temperature, annual rainfall and days since last rain and last rain.

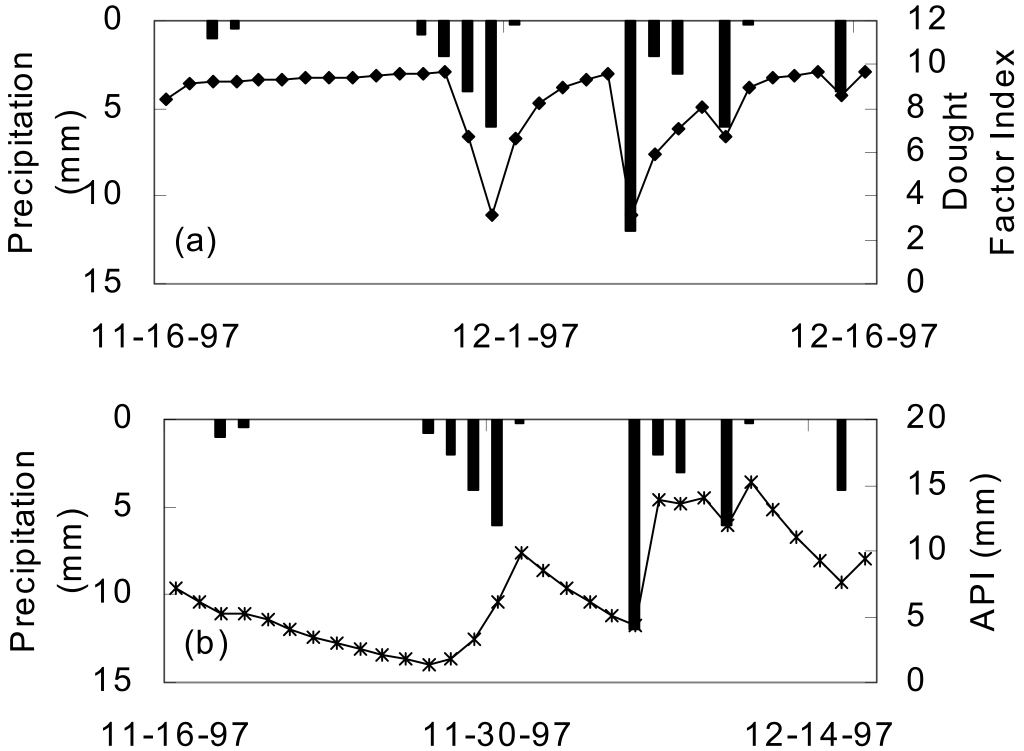

Figure 3. The Drought Factor (a) and API (b) corresponding to precipitation at Scone

Figure 3a shows the DF calculated from Griffiths formula at Scone, a station near the Goulburn River, using archived data from the Australian Commonwealth Bureau of Meteorology. It is shown that there is not an exact correspondence between the precipitation and DF. For example, when there is additional rain on the following day, DF increases without adequate reason. We can also see that DF decreases sharply before the rain event starts. Although based on Equation (3) DF is not only dependent on P and N but also on KBDI, any rain should intuitively always reduce the effects of moisture deficiency. We therefore recommend using the Antecedent Precipitation Index (API) (Linsley et al 1958; Lin 2001) for FFDI prediction. API has been widely used in hydrological forecasting. When used in describing drought, its meaning is opposite to that of DF, that is, the lower the API, the drier the soil. API is calculated as,

$$P_{a,t} = kP_{t-1} + k^2 P_{t-2} + ... + k^n P_{t-n} \qquad (5)$$

where $P_{a,t}$ is the API at the *t*th day (at 8:00 am), n is the number of days considered to influence the drought status at the time t, usually about 15 days, k is a constant, taken to be 0.85, and P is daily rainfall (mm). Figure 3b shows the API at the same station with the observed precipitation as in Figure 3a. It is seen that there is a more direct correspondence between the index and precipitation.

To derive FFDI from API needs further research based on more data including various categories of drought. Here we simply replace D with 1/API in Equation (1) to estimate FFDI from API. The result is shown in Figure 4. It can be seen that API derived FFDI compares favorably to the maximum FFDI derived using DF.

From Table 1, it is interesting to note that the highest correlation coefficient exists between DF derived FFDI and relative humidity, which is much higher than the correlation coefficient between the effect of precipitation (API) and the DF derived FFDI. However, when using API to derive FFDI, the role of humidity is almost the same as the role of precipitation in FFDI prediction, as shown by the correlation coefficient between API derived FFDI and relative humidity, and the correlation coefficient between API derived FFDI and API. From this result we can say that API derived FFDI uses the role of precipitation in the calculation of FFDI more effectively than in DF derived FFDI.

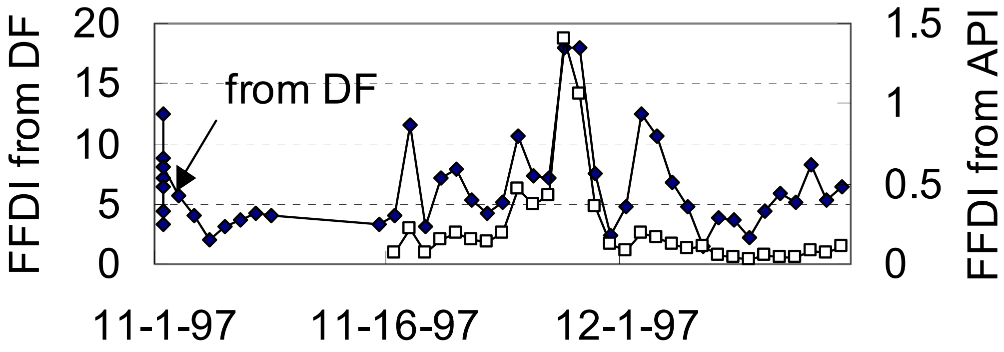

Figure 4. The Forest Fire Danger Index derived by Drought Factor (DF) and Antecedent Precipitation Index (API)

It is noted that API derived FFDI is lower than DF derived FFDI in general terms (Figure 4) as API does not consider other climatic factors, such as annual precipitation whereas DF does. However, it is also seen in DF derived FFDI that the calculation is highly dependent on the use of temperature, while the role of temperature shown by the correlation coefficient in Table 1 is not very high. Using API is helpful in clarifying the complex relationship between the fire danger and related factors.

Table 1 The correlation coefficients between the Dought Factor (DF) derived FFDI and the related variables and correlation coefficients between the Antecedent Precipitation Index (API) derived FFDI and the related variables (Tmax: Daily Maximum temperature; H: relative humidity; V:wind speed).

	DF	Tmax	API	H	V	KBDI	Rain
FFDI(DF)	0.46	0.46	-0.40	-0.86	0.18	0.01	-0.30
FFDI(API)	0.26	0.56	-0.58	-0.59	0.09	-0.02	-0.06
	ln(DF)	ln(Tmax)	ln(API)	ln(H)	ln(V)	ln(KBDI)	FFDI(Rain)
FFDI(DF)	0.44	0.45	-0.50	-0.88	0.21	0.02	
FFDI(API)	0.22	0.54	-0.75	-0.62	0.08	-0.01	

5. CONCLUSIONS

After revising the soil moisture scheme and some related processes, the HIRES NWP model provides more structured soil moisture fields which is sufficiently encouraging to seek improvements to FFDI prediction via NWP modelling. By obtaining more accurate precipitation matched with observed station data, routinely assessed soil moisture, which is output directly from the HIRES model, will improve FFDI prediction.

We also tested the possibility of replacing Drought Factor (DF) with Antecedent Precipitation Index (API) in FFDI prediction. The simple API showed a more direct relationship with precipitation.

Our research will benefit from a closer tighter integration with the operational needs of bushfire management. At present the system is in the testing phase of real-time bushfire forecasting at the NSW Rural Fire Service. The results of this initial real-time test will be published when the testing is completed.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Burgan, R.E., Klaver, R.W., Klaver, J.M. . Fuel Models and Fire Potential from Satellite and Surface Observations. International Journal of Wildland Fire 8(3):159-170. 1998.

Goncalves Z. J. and Lourengo, L., Meteorological index of forest fire risk in the Portuguese mainland territory. Proceedings of the International Conference on Forest Fire Research. Coimbra, B07, pp1-14. 1990.

Griffiths, D. Improved formula for the drought factor in McArthur's Forest Fire Danger Meter. *Australian Forestry Journal,* 62(2), 210-214, 1999.

Keetch, J.J. and Byram, G.M., A drought index for forest fire control. *Forest Service Paper Se_38* (United States Department of Agriculture), 1968Lin S(edit). Hydrological Forecasting. China Hydraulic Press. (in Chinese). 2001

Linsley, Kohler, and Paulhus, 'Hydrology for Engineers', McGraw-Hill, 1958

Liu S., L.M.Leslie, M. Speer, R. Bunker and R. Morison. Approaching realistic soil moisture status with an improved meso-scale numerical weather prediction model. IAHS Publication. (reviewed and pre-published proceedings for the XXIII General Assembly of the International Union of Geodesy and Geophysics, Sapporo, Japan, June 30 – July 11, 2003). (in press) 2003a.

Liu S., L.M.Leslie, M. Speer, R. Bunker and X. Mo. The effects of bushfires on hydrological processes using a paired-catchment analysis. Meteorology and Atmospheric Physics. (in press) 2003b.

McArthur, A.G., Fire behaviour in Eucalyptus Forests. *Leaflet No. 107* (Forest Research Institute, Forestry & Timber Bureau, Canberra). 1967.

Nobel, I.R., G.A.V. Bary and A.M. Gill, McArthur's fire danger meters expressed as equations. *Australian Journal of Ecology*, 5, 201-203. 1980

Rothermel R. C., Wilson R.A., Morris G.A., Sackett S.S. Modelling moisture content of fine dead wildland fuels: input to BEHAVE fire prediction system. USDA For. Ser. Res. Pap. INT-359. Interm. Res. St., Odgen, Utah. p. 61. 1986.

San-Miguel-Ayanz, J. Methodologies for the evaluation of forest fire risk: from long-term (static) to dynamic indices, in Forest Fires: Ecology and Control, Anfodillo T. and Carraro, V. (Eds), Forest Fires: Ecology and Control, Univesity degli Studi di Padova, pp. 117-132.2002.

Sebastian Lopez, A. San-Miguel-Ayanz, J and R. Burga .Integration of satellite sensor data , fuel type maps , and meteorological observations for the evaluation of forest fire risk at the pan-European scale。 International Journal of Remote Sensing, 123(13): 2713-2719. 2002.

Speer, M.S, L.M. Leslie, J. R. Colquhoun and E. Mitchell. The Sydney Australia Wildfires of January 1994- Meteorological Conditions and High Resolution Numerical Modeling Experiments. Int. J. Wildland Fire. 6(3), 145-154. 1996.

Speer, M.S, L.M. Leslie, R. Morison, W. Catchpole, R. Bradstock and R. Bunker. Modelling fire weather and fire spread rates for two bushfires near Sydney. Aust. Met. Mag. 50, 241-246, 2001.

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

Viney NRA. Review of Fine fuel moisture modeling. International Journal of Wildland Fire 1:215-234. 1991.