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Fire growth modelling at multiple scales

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ABSTRACT: This paper presents a method to model fire growth over multiple time scales. These scales correspond to the confidence levels that can be placed in forecasted weather products, changing the model from deterministic to probabilistic as the range of the weather forecasts increases. Fire growth is modelled through the various stages in sequence, providing probability maps of potential fire extents. The short-range model predicts fire growth on an hourly scale using a deterministic, eight-point fire growth model. The medium-range model predicts fire growth over several days. This model uses the same fire-growth engine but introduces forecast reliability through the use of ensemble techniques. The long-range model predicts fire growth on a scale of weeks. This model combines the probabilities of fire spread and of survival to produce a probable fire extent map. A case study of a large fire in Wood Buffalo National Park, Canada, is conducted to illustrate the use of the model.

1 INTRODUCTION

Modelling the spread of fires across the landscape has been an area of significant study in fire research since the introduction of personal computers (Kourtz *et al.* 1977). Since then, a variety of models have been produced emphasizing one technique over another (Feunekes 1991, Richards 1994, Finney 1998).

One aspect that has not been fully addressed is that of the role of the weather forecast and the reliability of such forecasts over time. For the most part, deterministic fire growth models have worked on the assumption that the detailed meteorological data being used by the system is accurate and reliable. Since weather cannot be accurately predicted beyond a few days (Smagorinsky 1967), this severely limits the medium to long-range application of fire growth modelling.

Meteorologists work under the framework of scales in their studies; micro, meso, and macro scales are established terminology in the field (American Meteorological Society 1959). Micrometeorology deals with the smallest scale physical and dynamic occurrences within the atmosphere, such as turbulence and diffusion; macrometeorology covers the large scale dynamics from cyclones to the global-scale waves; mesoscale meteorology deals with the phenomena between the two scales, such as tornadoes and thunderstorms. Much like the meteorological scales, forest fires also have scales growing from the initial ignition (micro) through detected fire (meso) to a possible campaign fire (macro). With each scale transition, the detail of controlling parameters must change as well.

This paper presents a method to model fire growth over multiple time and space scales. These scales correspond to the confidence levels that can be placed in forecasted weather products, changing the methodology from deterministic to probabilistic as the range of the weather forecasts increases. Fire growth is modelled through the various stages in sequence, providing probability maps of potential fire extents.

2 METHODOLOGY

To predict fire growth over several scales, three models have been produced. The short-range model is a deterministic model designed to predict fire growth on the scale of hours. The medium-range fire growth model is a blend of probabilistic and deterministic modelling used to predict fire growth on the scale of days. The long-range growth model is probabilistic and based upon climatology. The three models interact in a nested fashion such that the results of one model serve as input for the next.

2.1 *Short-range model*

The short-range model predicts fire growth on an hourly scale. This model uses a deterministic, eight-point propagation routine (Kourtz *et al.* 1977), estimating the time of ignition of each cell. Spread from one cell to the next is calculated through a series of 15-minute time steps, allowing for diurnal variation while limiting spread to the cells in question.

The Canadian Forest Fire Behaviour Prediction (FBP) System (Forestry Canada Fire Danger Group 1992) is used to estimate the rate of spread. The FBP system is an empirical model that predicts fire behaviour conditions for 17 fuel types found in Canada. Using daily and hourly weather values and indexes from the Canadian Forest Fire Weather Index (FWI) system (Van Wagner 1987) as inputs, the FBP system predicts measurable physical parameters, including the forward rate of spread (ROS) in metres per minute. For the purposes of this paper, the Fine Fuel Moisture Code (FFMC) was set to be in equilibrium with the environment (Van Wagner 1987).

The directional component of spread is calculated assuming elliptical fire growth. With the ignition point at one of the foci, the direction component of the rate of spread becomes

$$r(\theta) = r_h(1-\sqrt{1-1/LB^2})/[(1-\sqrt{1-1/LB^2})\cos(\theta)] \tag{1}$$

where θ is the departure from the wind direction, $r(\theta)$ is the rate of spread with respect to θ, r_h is the head fire rate of spread and LB is the length to breadth ratio, an FBP system output primarily dependent on the wind speed.

The assumption of the short-range model is that it uses accurate and reliable meteorological forecasts, and from this information the fire is grown deterministically. The input meteorological data can be produced from a number of sources such as a spot forecast provided by an experienced weather forecaster, output from a mesoscale meteorological model, or numerical guidance from a global model. Regardless of its source, it is assumed to be accurate and thus there is no allowance for confidence or error.

2.2 *Medium-range model*

The medium-range model predicts fire growth over several days. This model uses the same fire-growth engine as the short-range model, but it introduces the reliability of the input meteorological data into the calculations. From this, probabilistic estimates of fire growth are generated.

The assumption of the medium-range model is that accurate hourly meteorological data is unavailable or unreliable, and that hourly predictions of weather conditions are outside the skill level of an experienced forecaster. In its place, generalized forecasts of the weather conditions are used – specifically maximum and minimum temperatures and wind speeds – and allowances for errors in the forecasted values are introduced using ensemble techniques.

Ensemble forecasts and techniques are commonly used in numerical weather prediction (Toth and Kalnay 1993). In ensemble forecasts, the initial conditions fields are modified with perturbations equal to common measurement errors. The models are then run providing variation in the output fields. Based upon these observable variations, weather forecasters can assess their confidence in the numerical products, reflecting this in their forecasts.

The medium-range model begins by predicting the diurnal tendencies of temperature, humidity and wind speed as described by Beck and Trevitt (1989). This procedure uses maximum and minimum values of the temperature and wind speed. In turn, diurnal variation of the relative humidity is predicted by assuming the vapour pressure is constant over the time period.

The diurnal trends of temperature, wind speed and humidity are calculated for each day of the modelling period from forecast values. Wind direction is held constant for a given day. From these daily trends, a data stream is created for the multi-day modelling period and the hourly FFMC values are calculated as in the short-range model. This data stream is henceforth referred to as the unaltered stream.

Uncertainty is introduced into the medium-range model in the form of an error range for the predicted value. For example, a temperature forecast may have an error range of plus or minus a degree ($\pm 1^{o}C$). Based on the error ranges of each of the four forecasted fields (temperature, humidity, wind speed and direction), eight new data streams are created, each differing from the original, unaltered stream by the application of a *systematic error*[1] equal to the reliability error range to one of the fields. Thus, one altered data stream would use all the unaltered information except that the temperature would be increased an amount equal to the error range ($+1^{o}C$ in the above example), the next stream would be the same but with the temperature decreased an amount equal to the error range, and so on.

Using these nine streams – the original unaltered data stream and the eight error-altered data streams – the medium-range model conducts nine fire growth simulations producing an ensemble of fire perimeters. These show nine possible variations of the final fire perimeter. Assuming each perimeter has an equal probability of occurring, a final fire perimeter map can be constructed with probability contours showing the likelihood of regions being burned.

A forecast field so far unaddressed in the medium-range model is precipitation. Precipitation is difficult to forecast and often handled poorly by numerical models. Spatially, precipitation amounts can be highly variable, which are often averaged by the models. As a result, forecasts are often provided as a probability with predicted amounts when it occurs. The medium-range fire growth model could handle such information more directly, independent of the ensemble technique described above, but has not been included at this stage in the model's development.

2.3 *Long-range model*

Long-term fire growth from one location to another within a given time period can be expressed as the probability that the fire will spread across the distance before a fire-stopping rain event occurs (Anderson *et al.* 1998). Mathematically, this takes the following form

$$p(t) = p_{spread}(t) \times P_{survival}(t) \qquad (2)$$

where $p(t)$ is the probability of the fire reaching a certain point at a given time t, $p_{spread}(t)$ is the probability of the fire spreading to that point at time t in the absence of a fire stopping event, and $P_{survival}(t)$ is the cumulative probability of the fire surviving through possible fire stopping events up to and including time t.

The probability of spread depends on fuel types and weather conditions, while the probability of survival depends on the moisture content of the forest floor. The model produces a spatial representation of potential fire growth, shown as probabilities on a map referred to as the probable fire extent map.

The probability that a fire will spread to a location in a given time depends on the variation of the fire's propagation speed, or rate of spread (r), over time. In turn, this is dependent upon fire weather conditions and on the forest fuel types. Assuming the rate of spread follows an exponential distribution, the distribution can be defined by lambda (λ), the reciprocal of the mean observed rate of spread. From this, we can predict the probability of exceeding a critical rate of spread, r_c, defined as the spread rate necessary to move a fire across one grid pixel in one time period

$$P(r > r_c) = e^{-\lambda rc} \qquad (3)$$

Spread across multiple cells then becomes the product of these probabilities along the path.

The probability of survival is a function of fuel moisture conditions. A fire is naturally extinguished when these moisture conditions within the forest floor preclude smouldering combustion. The Duff Mois-

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[1] An error that affects all measurements equally such as a miscalibrated thermometer or a fast running clock (Taylor 1982).

ture Code (DMC) of the Canadian Forest Fire Weather Index (FWI) system (Van Wagner 1987) is an index of such conditions. When the DMC drops below a certain value due to rain or cooling weather, it can be assumed that a smouldering fire will expire. This value is called the DMC of extinction (DMC_{ex}). The probability that over time the DMC will drop below the level of extinction can be estimated using first order Markov chains.

The final probability that a fire will reach a location on a given day is the product of the probability of spread for that day and the cumulative probability of survival until that day. A probable fire extent map can be produced by calculating the cumulative final probability for each grid cell on the map.

3 CASE STUDY

A case study of a large fire in Canada's Wood Buffalo National Park (Figs. 1 and 2) is presented to illustrate the use of the model. Fire WB99004 was ignited by lightning and was first detected on June 3, 1999 near Carlson's Landing. Within 4 hours, the fire grew from 50 to 600 hectares and was exhibiting crown fire intensities greater than 10,000 kW/m. A significant high-pressure ridge dominated the area from June 14 to 21 resulting in fire growth from 10,000 hectares to more than 50,000 hectares.

The three fire growth models were run in sequence as follows:

- short-range model from time of ignition to 48 hours using hourly weather from Fort Smith, Northwest Territories.
- medium-range model from 48 hours to 7 days using maximum and minimum temperatures and wind speeds, estimated from noon weather measures and climatological maximum-minimum ranges for Fort Smith (Canadian Climate Program 1993).
- long-range model using climatology of all weather stations in Wood Buffalo National Park

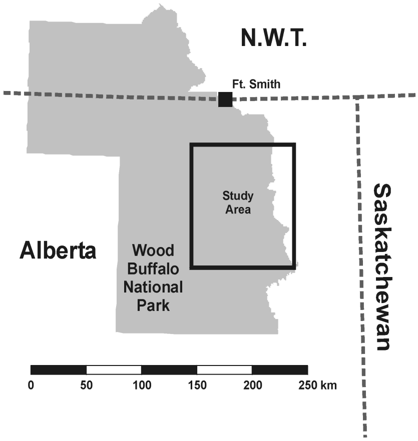

Figure 1. The study area within Wood Buffalo National Park.

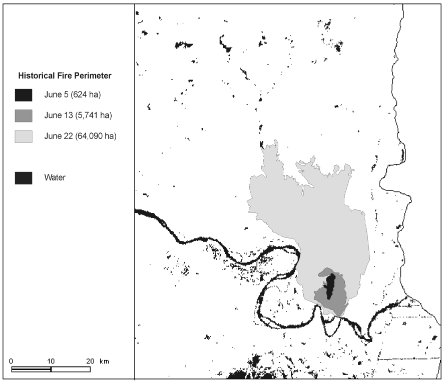

Figure 2. Historical fire perimeters for WB99004.

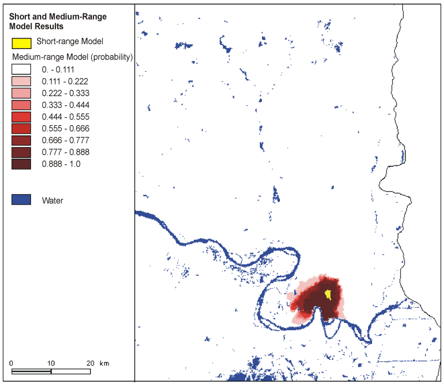

Figure 3. Short and medium-range fire growth model output.

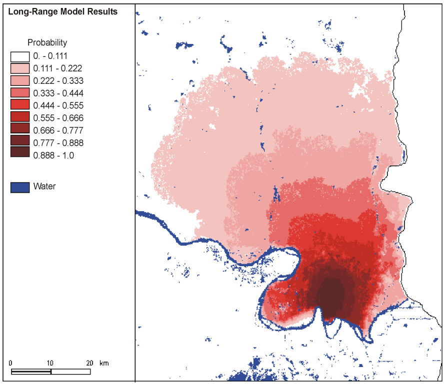

Figure 4. Long-range fire growth model output.

The models were run on a 141-metre resolution forest fuels grid. The grid was built from a forest inventory map of Wood Buffalo National Park and FBP fuel types were assigned to each grid cell, based upon the expert opinion of the park wardens.

Figure 3 shows the results of the short and medium-range fire growth models. The short-range model was run first, producing a fire 264 hectares in size. This fire was then used as the starting point for the medium-range model, which produced an ensemble of perimeters varying in size from 4,298 to 17,649 ha. While the short-range model fell short of the 600 ha size observed in the initial 4-hour fire run, the medium-range model apparently captured the fire size (5,741 ha on June 13) within the ensemble's range.

Figure 4 shows the results of the long-range fire growth model. In this case, the models produce results that approximate the same growth as the actual fire, with the final fire perimeter falling within what the model predicted as the 30 to 40% probable growth range.

4 CONCLUSIONS

The multiple-scale fire growth model presented in this paper allows for the long-range prediction of fire spread as the forecast period moves through stages of weather predictability. With each step further away from the present, detailed input meteorological data is replaced with more generalized information and then with climatology, and with each step, the models move from the deterministic to the probabilistic.

To illustrate the models in use, a case study was presented, showing how the three models, when run in succession, predict the growth of a fire over a 3-week period.

As forest protection agencies re-evaluate the role of fire in the landscape and its ecological benefits, as they face the prospect of excessive fuel build up resulting from years of fire exclusion policies, and as they contend with fiscal constraints, these agencies must start looking at possible fire growth over extended periods. The methods presented through these models may serve as a foundation for such evaluation.

It is worth noting that this model uses a simple cell-based growth procedure. Other fire growth models use more sophisticated techniques such as the wave-propagation models developed by Richards (1994) and Finney (1998). This paper does not advocate one method over another but focuses on the multiple-scale issue, using tools at hand. Techniques presented in this paper can be applied to any growth model.

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