2.4 USING ENSEMBLE TECHNIQUES IN FIRE-GROWTH MODELLING

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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 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.

This paper presents the use of ensemble techniques in fire-growth modelling. Errors and uncertainties in the evolution of meteorological parameters are introduced into a deterministic eight-point fire-growth model to produce an ensemble of possible final fire perimeters. Errors, whether they be from forecasts or observations, take the form of systematic or random errors and the probabilities associated with these errors are calculated and presented in the final perimeter fields. Detailed time series of temperature, humidity, wind speed and direction are examined to show the nature and extent of these observational errors. Finally, this approach is applied on an observed forest fire in Wood Buffalo National Park.

1.1 *Ensemble Modelling*

Ensemble modelling is a numerical modelling technique used in meteorology (Roebber et al 2004; Toth and Kalnay 1993) as well as other sciences such as genetics, biochemistry, and artificial intelligence. In ensemble meteorological forecasts, numerical weather models are run repeatedly with perturbations to the initial condition fields. These perturbations are equal to expected measurement errors. The multiple runs provide variation in the output fields. Alternatively, several different models can be run to provide the variation. Based upon these observable variations, weather forecasters can assess their confidence in the numerical products, reflecting this in their forecasts.

Ensemble modelling provides the probabilistic calculations required for risk management. This approach has been successfully used to track hurricanes, to predict precipitation amounts and the dispersion of atmospheric pollutants, and to aid in long-range weather forecasting.

1.2 *Errors*

Ensemble theory is based on the assumption that conditions required for numerical models cannot be accurately measured everywhere, and that there will be errors inherent in the dataset – both spatially and temporally. Errors can take on two forms: random and systematic (Taylor 1982).

A *random error* is an error in measurement related to the observational accuracy of the measuring device. For example, the period of a pendulum may be measured as 2.5 seconds on the first swing, 2.4 seconds the swing, and so on. Through repeated measurements, one gets a distribution of possible results, the best estimate being the average value, while the range of results would be from random error.

A *systematic error* is a consistent error that affects all measurements equally and is not revealed through repeat experiments. Often these errors are related to the measuring device whether it be a clock that runs fast or an instrument not properly calibrated.

Both errors play a role in meteorology. Random errors in measurement are often a result of turbulent air motion and these fluctuations happen down to the microscale. Systematic errors often enter through forecast bias. For example, a forecaster's overprediction of the next day's maximum temperature would consistently affect all the afternoon's temperatures.

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2. METHODOLOGY

This paper sets out to incorporate ensemble modelling techniques into fire-growth modelling. For this, two studies were conducted. The first was a simulated fire study using detailed, one-minute weather observation streams. These data were used to determined the effects of random errors on hourly growth model runs. The second was a case study examining a large fire in Wood Buffalo National Park. Here, the impact of systematic errors are examined and how well ensemble models capture the effects.

2.1 *Fire-growth model*

The fire-growth model in this study uses a deterministic, eight-point propagation routine (Kourtz *et al*. 1977) to estimate the time of ignition of each cell. Spread from one cell to the next is calculated through a series of one-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 this study, the Fine Fuel Moisture Code (FFMC) was set to be in equilibrium with the environment (Van Wagner 1987).

The directional component of the rate 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

$$r(\theta) = \frac{(1 - \sqrt{1-1/LB^2}\ )\ r_h}{1 - \sqrt{1-1/LB^2}\ \cos\theta} \qquad (1)$$

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 wind speed.

It is worth noting that this paper 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 ensemble technique, using tools at hand. Techniques presented in this paper can be applied to any growth model.

2.2 *Simulated Fire Study*

Two sets of weather data (three afternoons in total) were used in this study. Each of these data sets contained one-minute measurements of temperature, relative humidity, wind speed and direction. There was no precipitation on these days.

The first set contains data from a prairie grass restoration fire conducted on April 30, 2000 near Coldwater, Ontario. The weather station was set up in a large open field about 250 metres upwind of the fire. For this study, wind was measured from an anemometer positioned 2.5 metres above the surface. As this is a hypothetical study, no adjustments were made to the wind data.

The second set is from the LaFoe Creek mixedwood experiment, May 19 and 20, 2000 . The burn site is about 60 kilometres north of the town of Thessalon, Ontario. Data is taken from the main weather station for that site, with an anemometer height of 10 metres.

In the Coldwater dataset, the measurements were by the minute from 1207 to 1524. Measurements in the LaFoe dataset were made by the minute from 1213 to 1655 on May 19 and from 1350 to 1621 on May 20.

The one-minute weather data were used as a basis for a set of ensemble runs. Hourly averages of the temperature, relative humidity, wind speed and direction were calculated. Random error values for each parameter were calculated as the standard deviation of the perturbations of each minute observation from the hourly means.

The fire growth was calculated on a homogeneous boreal spruce (C2) fuel type, with 10-metre grid cells.

The fire-growth model was run using the averaged hourly weather values. This represents the baseline prediction. Next, the model was run using the detailed minute data.

The model was then run with random errors added to each value of the averaged hourly weather stream. In this case, the random errors were generated assuming normal distributions with the calculated standard deviation of observed values. The model was run 100 times in a Monte Carlo fashion to produce a distribution of possible final fire perimeters.

Finally, the model was run using the standard deviation of observed values as systematic errors. By applying a systematic error positively or negatively to one of the averaged hourly weather parameters, eight permutations of the weather stream were derived. These along with the unperturbed weather produced nine possible fire perimeters for the ensemble.

2.3 *Case Study: Fire 03WB007*

A case study was conducted to test the ensemble technique on a large fire in Canada. For this purpose, Fire 03WB007 in Wood Buffalo National Park was chosen.

Ignited by lightning on July 28, 2003, Fire 03WB007 was discovered on the July 30 at a size of 350 ha. Because of resource limitations due to the severe fire situation in southern British Columbia (Filmon 2004), 03WB007 was placed under monitoring status. Strong winds on August 15 to 17 resulted in explosive fire growth from 20 000 ha to 84 500 in three days. Attempts were made with air tankers and drip torches to slow the fire spread but these were ineffective due to high intensities, rapid growth and poor visibility. After August 18, high humidity and small amounts of precipitation reduced the fire intensity, allowing for limited suppression activity and eventual containment of the fire. The final fire size on August 24 was 84 750 ha.

For this historical analysis, the fire-growth model was run for August 16 to 19 using a 141 metre resolution fuels grid for the park.

A daily ignition grid was built using a 707 metre buffer around the previous day's observed hotspots as detected by MODIS and NOAA AVHRR (Quayle *et al.* 2003; Englefield *et al.* 2004). August hotspots prior to the previous day were considered burned area and thus excluded from potential fire growth.

Weather from Fort Smith was used for the analysis. Hourly weather was used with the fire-growth model to approximate the actual fire growth, while daily maximum/minimum temperatures and wind speeds, and minimum humidity were used to approximate a daily weather forecast. Wind direction at the time of maximum wind speed was used for the forecast. Diurnal trends were built following Beck and Trevitt (1989). The precipitation on Aug 18 (trace) and 19 (5 mm) were ignored for this study.

Ensemble model runs were conducted on the forecast data. Random errors of 2.9°, 11.3%, 7.5 km/hr and 58° were derived from the standard deviation of the perturbation of Beck and Trevitt's diurnal trends from actual hourly weather. On the other hand, systematic errors of 2° for temperature, 10% for humidity, 10 km/hr for wind and 45° for wind direction were arbitrarily chosen based on estimated errors of forecasted weather conditions.

3. RESULTS

3.1 *Simulated Fire Study*

Table 1 shows the results of averaging the hourly weather values from the minute data for Coldwater and LaFoe data sets. The standard deviations of the observed minute data were used as the random error terms for the ensemble model runs.

Table 1. Hourly weather values and errors used from minute data.

Date	Hour	Temp	RH	WS	WD
Apr 30	1200	11.48	31.52	10.31	287.14
	1300	11.81	26.78	8.89	298.00
	1400	11.70	25.85	10.18	299.75
	1500	12.16	24.36	11.43	299.12
	Error	0.52	3.19	3.95	21.69
May 19	1200	12.67	22.42	0.26	66.28
	1300	14.07	20.41	1.72	264.94
	1400	15.21	19.55	1.29	272.46
	1500	15.95	18.17	0.82	242.71
	1600	15.91	18.48	1.56	218.43
	Error	1.28	2.26	3.00	71.70
May 20	1300	18.20	18.77	2.13	229.26
	1400	18.79	17.33	1.80	288.94
	1500	19.60	15.89	1.29	203.66
	1600	19.80	15.53	0.95	273.11
	Error	0.61	1.47	2.76	63.26

Table 2 shows the predicted fire sizes for the three simulated fires using the averaged hourly data and the detailed minute data.

Table 2. Fire growth results for simulated fires

Date	Ignition time	Burn Period (hrs)	Fire size (ha)	
			Hourly	Minute
Apr 30	1200	3.2	176.31	209.65
May 19	1200	4.4	978.67	1091.55
May 20	1300	2.4	444.53	538.23

Table 3 shows the predicted fire size for the ensemble runs for the three simulated fires. The probability values capture the average and standard deviation of the fire size.

Table 3. Ensemble model results for simulated fires

	Fire Size (ha)		
Probability:	0.8414 (0.777)	0.5 (0.555)	0.15865 (0.222)
Random:			
Apr 30	128.24	184.69	262.64
May 19	793.56	963.32	1153.79
May 20	344.49	440.25	531.9
Systematic:			
Apr 30	126.72	174.8	238.48
May 19	803.01	971.97	1154.86
May 20	378.99	443.15	526.76

Note that because the systematic ensemble consists of only nine possible perimeters, the resulting probabilities are in steps of 0.111 or fractions of 1/9. As a result, the standard deviation range captures the probability range of 0.777 and 0.222.

3.2 *Case Study: Fire 03WB007*

Table 4 shows the predicted fire sizes for the Wood Buffalo National Park fire using the observed hourly data and the forecast data.

Table 4. Fire growth results for Fire 03WB007

	Daily fire growth (ha)	
Date	Hourly data	Forecast data
Aug 16	10 778	16 370
Aug 17	19 646	26 506
Aug 18	15 972	24 356
Aug 19	1 700	4 699

Table 5 shows the predicted fire size for the ensemble runs for the Wood Buffalo National Park fire. The probability values capture the average and standard deviation of the fire size.

Table 5. Ensemble model results for Fire 03WB007

	Daily fire growth (ha)		
Probability	0.84135 (0.777)	0.5 (0.555)	0.15865 (0.222)
Random:			
Aug 16	15 352	22 043	30 922
Aug 17	26 426	35 206	47 555
Aug 18	24 706	30 694	37 383
Aug 19	3 923	5 684	8 245
Systematic:			
Aug 16	7 739	15 698	34 194
Aug 17	17 739	25 936	36 657
Aug 18	16 710	24 262	32 987
Aug 19	2 228	4 583	7 813

Note that because the systematic ensemble consists of only nine possible perimeters, the resulting probabilities are in steps of 0.111 or fractions of 1/9. As a result, the standard deviation range captures the probability range of 0.777 and 0.222.

4. DISCUSSION

4.1 *Simulated Fire Study*

In this study, fire-growth model runs based on detailed, minute weather data were compared with those based on averaged hourly weather data. In turn, these were compared with ensemble predictions to see if the ensembles captured some of the lost details.

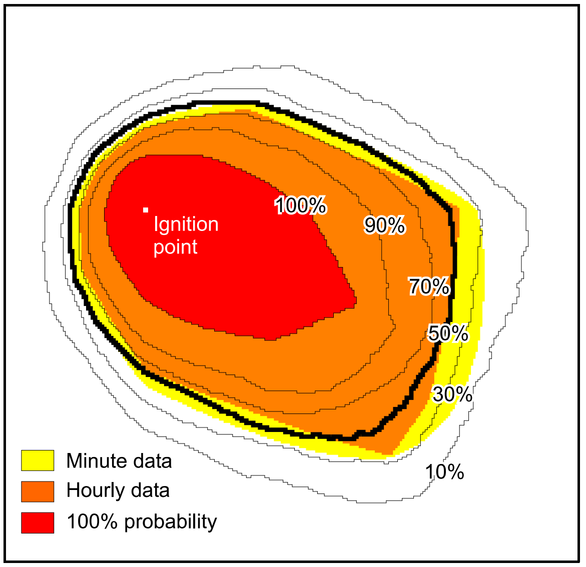

Figure 1. Fire-growth simulations for Coldwater data set. Yellow and orange indicate the minute-data and hourly-data model runs. Contours indicate the distribution of the ensemble of 100 random-error models runs (red indicates area burned in all runs).

Figure 1 shows the fire-growth simulations for the Coldwater (April 30) data set. Orange indicates the hourly-data model run, while yellow shows the minute-data model run. Contours indicate the distribution of the ensemble of 100 random-error models runs (red indicates area burned in all runs).

Table 2 shows the fire-growth simulation based on the averaged hourly data produced a smaller fire than the detailed simulation based on the minute data. In this case, the detailed run was 19% larger than the averaged run. This tendency carried through the other two simulations with the detailed runs 12% and 21% larger than the averaged runs. This result is consistent with the non-linear relationship of rate of spread with wind speed for the boreal spruce (C2) fuel type of the FBP system (Forestry Canada Fire Danger Group 1992). The contribution to forward spread from wind gusts is greater than that lost during the lulls.

The random-error ensemble model runs produced forward fire spread comparable to the averaged hourly data as indicated by the ensemble's 50% contour, while the minute-data forward spread reached 20%. The ensemble model produced flank and back spreads comparable to the detailed minute simulation. This is due to the variable wind direction, which is causing the fire to spread out. This did not show in the LaFoe Tower runs due to the already light, variable wind speed.

The systematic-error ensemble model runs produced results similar to the random-error runs but with less of a smooth spread. This is shown in Figure 2. The step-like pattern is a result of the limited number of runs in this ensemble (9 versus 100).

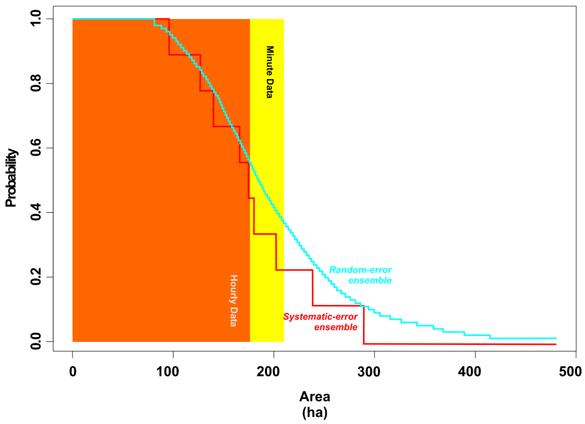

Figure 2. Fire sizes and ensemble predictions for Coldwater (April 30) simulation. Solid boxes indicate the final fire sizes of the hourly-data (orange) and minute-data (yellow) runs. Curves indicate the probably of area burned.

Overall, the detailed minute-data fire size fell within the 35% probable fire size as predicted by the random-error ensemble and the 22% probable fire size as predicted by the systematic-error ensemble. This suggests at this time and space (micro) scale that the errors are more random in nature.

Naturally, fire behaviour officers will not have minute data upon which to conduct their fire-growth predictions, nor would this data be consistent spatially across the fire. In this case, it is demonstrated that the random-error ensemble model runs capture some of the variability lost when meteorological parameters are averaged up to the more commonly-used hourly data sets. Typically, these sets provide only the ten-minute average conditions on the hourly, overlooking any events that may occur between measurements.

4.2 *Case Study: Fire 03WB007*

In this study, the ensemble approach was applied to a historical case study. Fire growth based on forecasted weather was compared to historical fire growth as approximated by hourly weather data. This was compared with ensemble runs to see if they captured any deficiencies in the forecast.

Note that by using the actual weather to approximate the historical fire growth, we eliminate any deficiencies in the fuel map, the FBP system or how well the Fort Smith weather data represented conditions on the fire site. All model runs used the same background data except where specifically addressed. With that said, fire progress based on the actual hourly weather corresponds well with that based on observed daily hotspot but such a validation is left for future study.

Figure 3 shows the fire-growth simulations for August 17 using the hourly (in orange) and forecasted (in yellow) data sets. Contours show the systematic-error ensemble model run. The previous day's hotspots used as the ignition source are shown in black, while prior hotspots are shown as grey. These are interpreted as burned area.

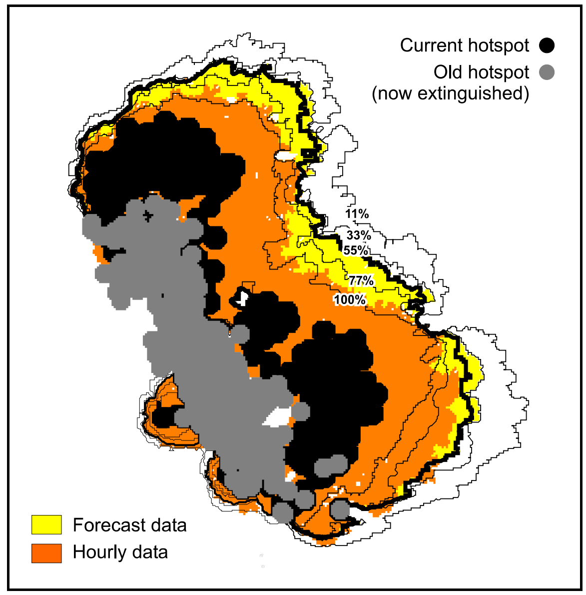

Figure 3. Fire-growth simulations and systematic-error ensemble model runs for Fire 03WB007 for August 17, 2003.

The predicted fire growth based on the forecasted weather data is 35% larger than the historical fire growth as approximated by the hourly weather data. The general shape and direction of fire growth is in agreement though suggesting the importance of accurately forecasted wind directions.

The 55% systematic-error ensemble model prediction closely matches the fire growth based on forecasted weather. This is natural as the no-error data stream is one of the nine streams used in the ensemble. The approximated historic fire spread generally follows the systematic-error ensemble model's 77% contour.

Table 4 shows that fire growth based on forecasted data over-predicted the historical growth on all days – by over 200% on August 19, and by 35% to 55% on the other days. This suggests that in this case the forecasted diurnal trends of the weather values are too high. The ensemble model runs using systematic-error compensate for this error with two days out of the four falling within the 22%-77% probability range (approximately one standard deviation) and the other two days slightly outside the range (possibly falling within a standard deviation of error). Comparatively, none of the random predictions captured within one standard deviation the approximated historical size suggesting that at this meso time and space scale the errors are more systematic in nature.

5. CONCLUSIONS

This paper presents an ensemble approach to fire-growth modelling. Ensembles of the input weather stream were built to compare the effects of random and systematic errors on fire growth.
In the simulated fire study, minute data were used to create a detailed fire-growth simulation. This was compared with fire growth based on the more commonly-used hourly data. Results showed that the detailed weather produced fire growth larger and wider than the hourly-based data. Variations in the flank and back-fire spread were captured by the random-error ensemble model while the forward spread fell within the 20 to 30% prediction.

The case study showed that fire predictions based on weather forecasts over-predicted the fire growth based on actual weather. The systematic-error ensemble models were capable of compensating for this error with the predicted fire perimeters falling with the predicted range of the models.

Results of both studies show that ensemble models are capable of capturing the variations of meteorological data. While both random and systematic errors are important to fire spread, random errors appear to be more important at the smaller, hourly scale, while systematic errors appear more important at the larger, daily scale. Admittedly, these statements are based on a limited number of study and more extensive study is needed to substantiate these conclusions. Still, errors and uncertainties, whether they be random or systematic, are a significant element in modelling fire spread. Capturing their effects and measuring them are a valuable step in predicting potential fire behaviour.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Peter Englefield for his GIS assistance, Mike Wotton for the detailed, minute weather data sets, the staff of Wood Buffalo National Park for the fire weather and fuels data for the park and Tanya Letcher for her description of Fire 03WB007.

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