Front propagation in heterogeneous media: mathematical, numerical, and statistical issues in modelling a forest fire front

Chris Bose (University of Victoria),
Anne Bourlioux (Universite de Montreal), W. John Braun (University of Western Ontario)

October 17–October 22, 2010

1 Overview of the Field

The main objective of this workshop was to bring together applied mathematicians, statisticians, and forest fire researchers and managers to discuss key issues relating to numerical algorithms, physical modelling and mathematical/statistical analysis relevant to the simulation of a propagating forest fire front.

Numerical Algorithms

The most popular wildfire spread simulators used in Canada and the United States are PROMETHEUS (Tymstra, 2005) and FARSITE (Finney, 2004). Both of these simulators are based on a marker method solution of a Lagrangian form of partial differential equations which describe the evolving fire front (for example, Richards, 1990). The principal difference between the two simulators lies in the manner in which the input parameters are determined. Inputs are derived from fuel type (i.e. type, density and characteristics of vegetation), weather (wind speed and direction, relative humidity, temperature, and precipitation), and topography (i.e. elevation, slope and aspect). In Canada, an empirical modelling approach (based on observations on a large inventory of experimental and well-documented wildfires) has been employed in order to relate the partial differential equation parameters to these inputs, while in the United States, a physical process approach (based on extensive laboratory experimentation) has been employed. Remarkably (or perhaps because of the robustness of the equation solutions), the two approaches often yield similar results.

However, because of the highly spatially heterogeneous nature of the media through which wildfires often burn, there is potential for much less smoothness than postulated by the original equations of Richards. Thus, there are a number of numerical issues that have arisen in association with this marker solution. Most notable among these issues is the frequent production of tangles in the numerical modelled fire front. Among the solutions that have been proposed in the past is a turning point algorithm. Unfortunately, such solutions have not always been successful in removing complicated tangles. Furthermore, these algorithms add to the computational complexity of the algorithm and slow the simulator down. Thus, there has been a perceived need for improved methods for handling tangles.

Another issue is the need for stochasticity. Prometheus and Farsite are deterministic, but fire managers would benefit from burn probability maps, since there is much uncertainty associated with the outcome of a given fire ignition. Many of the current methods for generating such maps rely on repeated runs of the deterministic simulator on randomized weather streams. An example is Burn-P3 (Parisien et al., 2005) which is based on Prometheus. In order for burn probability maps to be produced in real time, there is a need for improvements in the computational speed of the solution algorithm.

Modelling Issues

Forest wildfire behaviour is strongly related to weather conditions, particularly wind. Some progress has been achieved in including qualitative predictions of micro-weather conditions but there is much left to be done in formulating fully coupled models. Particularly challenging is the issue of how to include small-scale intermittent effects on the effective propagation of the front, even if one limits oneself to the class of models considered in this workshop where the fire is represented as an infinitesimally thin interface.

Another challenging modelling issue is formulation of a probabilistic model to describe the process by which a fire can "jump" over an obstacle or can be ignited by firebrands at remote locations ahead of the front, so-called fire-spotting.

Mathematical/Statistical Issues

Even though the phenomenon being modelled is that of a deterministic spread, for all practical purposes, the significant small scales fluctuations in the various parameters affecting the burning rate lead to a very noisy process and very noisy predictions, best interpreted in a probabilistic sense. Statisticians approach this by relying on stochastic process models, such as cellular automata.

On the other hand, applied mathematicians have formulated idealized advection-reaction-diffusion models to analyse the effective propagation of fronts in heterogeneous or even random media as needed in turbulent combustion for instance (although the models typically considered would not apply to the type of solid, immobile fuel we are talking about here).

2 Presentation Highlights

Many of the issues discussed in the overview were reviewed and discussed in the initial presentations given by Mark Finney, John Braun, Robert Bryce and Chris Bose. Finney reviewed the history of fire growth modelling, while Braun and Bryce focussed their attention on the Prometheus fire growth model.

Finney's talk also included an extensive discussion of the fire risk assessment modelling program being carried out in the United States. Assessments are being done at various scales from the level of a single project to the level of the entire nation. Finney reaffirmed the generally held belief that weather is the principal driver behind the uncertainty in fire behaviour, and by randomizing weather streams, one can generate realistic burn probability maps using deterministic simulators. Thus, FARSITE is used to study the problem of a single fire under a single weather scenario, FSPro is used to study the risk due to a single fire under an all-weather scenario, FlamMap is used to study large-scale fire risk under a single weather scenario, and FSim is used for large scale fire risk under an all-weather scenario. Because of the importance of the weather, some time was devoted to the problem of generating realistic weather scenarios, recognizing that only about 20-30 years of high quality weather data is available across the United States. The current approach is to use linear methods to model and simulate a fire moisture code. Even with this relatively simple method, Finney observed that the methods yield a "pretty good correlation" between fires by size class with simulated fires by size class, thus concluding that the resulting burn probability maps are reasonably realistic.

Braun's description of Prometheus was designed so that mathematicians and statisticians could see precisely how weather, fuel and topographic data are assimilated. The latter part of his talk focussed on some of the shortcomings of the modelling approach used and described how forecast uncertainty, diurnal variation in wind speed and rate of spread variability are not properly accounted for.

Robert Bryce, the chief Prometheus programmer, gave an overview of recent developments in the Prometheus simulator, highlighting the implementation of a new untangler. Chris Bose described the new untangler in detail in his presentation. The theoretical basis for this untangler lies in a two-colour theorem, and the resulting algorithm has proved to be much faster while at the same time handling more artifacts correctly compared to previously implemented untanglers.

Burn Probability Mapping and Stochastic Models

David Martell discussed the production of burn probability maps from a fire management perspective. Accurate maps will facilitate best practices in the scheduling of timber harvesting. Part of his presentation focussed on a case study based in northeastern Ontario for which a contagion type fire spread model was coupled with climate and historic ignition data to predict burn probabilities.

Kerry Anderson continued the theme of producing burn probability maps. Anderson considered multiple time scales as well as multiple spatial scales in his treatment of the problem. Satellite data was combined with Environment Canada weather data to calibrate a simple model for fire spread which was then applied to ensembles of simulated weather series. Validation studies indicated some issues for the short-range and medium-range model, but the long-range model appears to be reasonably accurate.

Jonathan Lee described a case study conducted in the Muskoka District in which Burn-P3 was used to obtain a burn probability map. Model assessment was undertaken by comparing the fire size distribution in the simulations with the historic fire size distribution. Part of this study involved field work in which it was found that substantial portions of the most recent fuel map were inaccurate.

Reg Kulperger presented an interacting particle system model for fire spread as an alternative to the more popular deterministic front propagation methods. The advantages of interacting model is that it is stochastic and it is raster based. The latter characteristic leads to realizations which do not have tangles.

Hao Yu discussed parallel computing approaches to fire spread modelling. This approach may be necessary to reduce the amount of time required to do repeated simulations in fire risk assessment studies.

Rob Deardon applied an Ising-type model to some particular fire burn patterns using Bayesian MCMC methods. The models have previously been successfully applied to the spread of infectious disease and this led naturally to the question of whether the spread of fire follows an analogous mechanism.

Fluid Dynamics, Eulerian and Reaction-Diffusion-Advection Approaches

Mary Ann Jenkins discussed her work with large eddy simulators, focussing on the behaviour of fire as it travels up hill under variable winds. A particular challenge for this type of modelling is the wide multi-scale nature of the process, with length scales ranging from millimeters (detailed combustion processes) to kilometers (weather inputs).

Alexandre Desfosses-Foucault described the level-set approach to the fire front propagation problem. This approach has several theoretical and computational advantages over the marker approach, largely avoiding the issues connected with tangling.

Thomas Hillen discussed existence and uniqueness of travelling wave solutions to semi-physical combustion models for wind driven fires. In some specific situations, rather surprisingly, there can exist multiple (slow and fast) propagation fronts.

Anne Bourlioux discussed the use of *homogenization* in the modelling of front propagation in heterogeneous environments (such as patchy fuel loads) and the effects of wind gustiness on the rate of spread of fire.

Petro Babak derived a probabilistic model for fire propagation using coupled parabolic differential equations (containing the diffusion, advection and reaction components) together with an ordinary differential equation (which specifies the cumulative probability distribution of the fire). The advantage of this kind of approach is that confidence bands for the fire perimeter can be derived without resorting to lengthy simulations.

Jonathan Martin discussed the problem of fire-spotting, by deriving the landing distribution, given the lofting height distribution for burning firebrands. He considered several special cases.

Statistical Approaches: Fire Weather Index and Ignitions

Sylvia Esterby discussed statistical models for the Forest Fire Weather Index (FWI) which gives a numeric rating of fire intensity. The focus was on British Columbia data, and the objective was to model the index temporally, taking into account spatial location. This theme was followed up later by Lengyi Han, who described some time series models for the FWI.

Doug Woolford discussed models for wildfire ignitions in Ontario, taking into account possible effects due to climate change.

Ed Johnson presented his work on process models for moisture in the duff layer and the effects of fire on soil erosion.

The Banff Prescribed Burn Program

Ian Pengelly (Parks Canada) gave a presentation on prescribed burns which highlighted the unpredictability of fire, and how prescribed burns can sometimes run out of control. Of particular interest was his description of a fire which spread surprisingly fast under winter conditions.

Following his presentation, Pengelly led the group on a bus tour of prescribed burns in Banff National Park and described the FireSmart program followed in the park. This experience occurred early on in the week and provided participants with an opportunity to see firsthand the effects of wildfire on surface and canopy fuels.

Poster Session

A number of posters were presented on one of the evenings. Sean Michaletz, a graduate student in ecology at the University of Calgary, presented some of his work on process models for tree mortality. Lengyi Han, a graduate student at the University of Western Ontario, presented work on a new empirical model for the rate of spread in jack pine fuels, and showed how the estimated variance of the error for this model could be used to model the uncertainty in the input parameters in a deterministic simulator such as Prometheus. Jonathan Lee, also of Western, provided more details on his risk assessment of the Muskoka District based on Burn-P3.

3 Open Problems

Although much progress has been made in the numerical and statistical modelling of fire fronts, a large number of issues remain unresolved. The problem of fire-spotting remains largely unsolved. Certain aspects of the problem have been addressed as discussed in the presentations of Mary Anne Jenkins and Jonathan Martin. However, much work remains to be done: spotting frequency distributions are completely unknown, and lofting height distributions are still not well understood.

The problem of ignition prediction plays a key role in fire risk assessment. For this purpose, basic stochastic models are now available. For the purpose of predicting particular fire flaps, there are currently no adequate models.

Extinguishment also remains a largely unsolved problem. When will a fire stop spreading? Under certain weather conditions and when fire suppression activities are effective, a fire will be extinguished, but a completely specified model for extinguishment remains to be developed.

4 Roundtable

Thursday afternoon was devoted to a roundtable discussion for all participants. The session began with a review of the somewhat different needs and perspectives of the (roughly) two groups of scientists represented at the meeting.

Fire Scientists (mostly industry and government scientists):

NEEDS	RESOURCES
access to students	scientific expertise and experience
new methods of solution	a historical context
	data/brains
	choice of relevant problems
	critique of mathematical approaches
	database of historical fire size/shape
	avenue for real fire experience for students/researchers
	ability to host academic visitors
	Modus hot spot data
	infrared image library

Mathematical and Statistical Scientists (mostly university academics):

NEEDS	RESOURCES
access to fire scientists	student manpower
real data	expertise and novel techniques
relevant problems	knowledge of useful approaches from other modelling fields
critique of approaches	model validation
broader prespective (ecosystem, water etc)	willingness to solve toy problems requiring new approaches
spotting data	
knowledge of sources of data	
lines of communication on the subject	
participation in experiments (students and researchers)	

The participants observed that there appear to exist many opportunities to match needs and resources between the two groups. Some specific ideas were:

- joint publications
- co-supervision of HQP
- research collaboration
- MITACS/NSERC internships
- joint conferences

There also appear to be opportunities for NSERC Industrial postdoc and MITACS internship placements at CFS and other government labs. These need an academic and industrial supervisor in collaboration.

Promising new directions for research

The original PROMETHEUS development committee proposed a large number of projects – only some of these have been addressed to date. A (partial) list of topics still needing attention was collected:

- spotting experiments
- improved spread algorithms
- incorporating spotting into spread (models?)
- incorporation of realistic diurnal weather data
- models of extinguishment
- FBP fuel parameters
- spatial weather (wind!) modelling at many scales.
- suppression models
- operations research
- resource management approaches
- fire occurrence prediction
- ignition models (physical or semi-physical)

It was observed that some of these items are already under consideration by various groups in the fire modelling community (for example, see the Open Problems section above)

There was a general discussion about the process by which mathematical ideas and models become developed and accepted by the fire scientists, and if possible, implemented in the field (the latter is of course a serious but realistic challenge). It was felt that one mechanism to encourage this would be to get mathematical scientists (and/or their students) into the field to meet the managers, firefighters and if possible observe real fires. There are obvious administrative barriers to this (safety, security. . .).

Further observations on spotting: there is very little data from large-scale experimental burns and not likely to be more in the near future. Lofting data from wind tunnel experiments may continue to appear, and detailed studies of ignition processes could be done. Both of these would be aimed at understanding sub-processes in the spotting model.

Realistic Coupled Wind models: A simulation was presented at the workshop based on a real fire. Video images from the real fire are available on You Tube. The presenter pointed out that while the fire was lit in calm conditions, there was considerable wind involvement once the fire got started. This points to the large effect that thermally generated 'wind' contributes. This needs to be incorporated into realistic models.

Data Gathering Exercises known to be ongoing:

- Modus hotspot data. (NOAA data also)
- Weather Data
- Fire size/shape data

Upcoming Meetings/SummerSchools:

- Fire and Forest Meteorology New Mexico FAll 2011 (AMS)
- Wildland Fire Canada 2012, Calgary (Tymstra and McAlpine)
- Western Region Fire Research Ctr (UofA)(Mike Flannigan head)

5 Conclusions

As had been proposed, the workshop did bring together a wide range of perspectives on forest fire modelling. It attracted participants from both government and academia, the latter including graduate students and postdoctoral researchers. Both mathematical and statistical approaches to a range of common problems were treated in depth during the workshop and both theoretical and applied aspects were represented. The conference was attended by Canadian and US Fire Scientists, some of whom had not had a chance to interact before.

References

[1] Finney, M.A. 2004. FARSITE: Fire Area Simulator-model development and evaluation. Res. Pap. RMRS-RP-4, Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

[2] Parisien, M.A., Kafka, V.G., Hirsch, K.G., Todd, J.B., Lavoie, S.G. and Maczek, P.D. 2005. Mapping wildfire susceptibility with the Burn-P3 simulation model. Information Report NOR-X-405.

[3] Richards, G. 1990.

[4] Tymstra, C. (Project Leader) 2005. Prometheus: The Canadian Wildland Fire Growth Model. Forest Protection Division, Alberta Sustainable Resource Development, Edmonton, AB <http://www.firegrowthmodel.com>.