Advances in Forest Fire Research

DOMINGOS XAVIER VIEGAS
EDITOR

2014

Evaluating crown fire rate of spread from physics based simulations to field data

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Abstract
Wildland fire behavior models are commonly used to augment expert opinions, experiments and field observations by both the research and management communities. However, modelling wildfires is challenging in part due to complex set of coupled processes that drive the properties of a spreading wildfire. Further these processes occur over a vast span of spatial and temporal scales that further complicate the development and validation of models. Due to these complications there has been a variety of model types developed for a variety of specific applications. Regardless of the type and purpose of a model, well quantified fire behavior data from wildland fires and field and laboratory experimental fires are necessary for a variety of reasons including the calibration of empirically based models, the evaluation of physically based or theoretical models, and to provide model developers with potential areas to improve model performance by identifying inadequacies in the code. Here we utilize a compiled data set of crown fire rate of spread from Alexander and Cruz (2006) to evaluate published crown fire rate of spread predictions from two physics-based fire behavior models HIGRAD/FIRETEC developed at Los Alamos National Laboratory and the Wildland Urban Interface Fire Dynamics Simulator (WFDS) developed by the National Institute of Standards and Technology and the USDA Forest Service. Our preliminary results suggest that physics based models reasonably predict the crown fire rate of spread given the current data set. In addition we discuss the sensitivity of physics based models to a variety of parameters which likely influence crown fire rate of spread.

***Keywords**: Physics-based model, fire behaviour, model evaluation*

1. Introduction

Wildland fire behaviour models are commonly used to augment expert opinions, experiments and field observations by both the research and management communities. However, modelling wildfires is challenging in part due to complex set of coupled processes that drive the properties of a spreading wildfire. Further these processes occur over a vast span of spatial and temporal scales that further complicate the development and validation of models. Due to these complications there has been a variety of model types developed for a diversity of specific applications. Along with these developments has also come a wide array of assumptions, simplifications and approximations that are employed in the development of the models to achieve the desired level of detail and calculation time. Regardless of the type and purpose of a model, well quantified fire behaviour data from wildland fires as well as field and laboratory experimental fires are necessary for a variety of reasons including the calibration of empirically based models, the evaluation of physically based or theoretical models, and to provide model developers with potential areas to improve model performance by identifying inadequacies in the code. If model limitations and uncertainties are understood model simulations can provide insights into the interpretation of experimental data, help inform the design of future experiments and be utilized as a cost-effective and safer way to study wildland fire behaviour. However, large field-scale fire experiments or wildland fires can be expensive to conduct, often have limited data about the environmental conditions and fuels complex and rarely if ever have replication;

whereas laboratory-scale experiments, though less expensive and easier to replicate, generally do not provide data that cover the range of spatial and temporal scales typical of free burning wildfires.
The speed at which a fire propagates across a landscape, referred to as the rate of spread, depends upon interactions between a number of processes including the heat transfer rate, moisture evaporation and combustion rates and is one of the most commonly predicted metrics of fire behaviour. Recent studies have compiled empirical data from wildland fires and large-scale experimental fires on the rate of fire spread for surface and crown fires. This data has been utilized to evaluate current empirical surface and crown fire rate of spread models and to suggest potential inadequacies in current empirical fire behaviour modelling systems. However to date there have been no comparisons of simulations performed with physics-based models. Instead these evaluations have primarily involved empirical fire behaviour models.
In this paper we utilize a compiled data set of crown fire rate of spread from Alexander and Cruz (2006) to evaluate published crown fire rate of spread predictions from two physics-based fire behaviour models HIGRAD/FIRETEC developed at Los Alamos National Laboratory and the Wildland Urban Interface Fire Dynamics Simulator (WFDS) developed by the National Institute of Standards and Technology and the USDA Forest Service. In addition to evaluating crown fire rate of spread predictions from physics-based models we also utilize our results to investigate the potential sources of variation in crown fire rate of spread measurements and provide guidance on future research needs.

2. Description of physics based models

Physics based models such as HIGRAD/FIRETEC and WFDS use a computational fluid dynamics approach and a three-dimensional grid to describe to model the critical physical phenomena and their interactions that control the behaviour of a wildland fire through a set of coupled partial differential equations. This approach allows for the evolution of various quantities such as temperature, velocity of gaseous species and the characteristics of the fuel to be described spatially and temporally in the simulation domain. The vegetation in physics-based models is often described as a porous medium with mean or bulk quantities such as surface area to volume ratio, moisture content and density within the 3-d grid. Such an approach allows for the simulation of fires in areas with complex fuel beds (i.e. varying at small spatial scales) and variable topography.

3. Methods

3.1. Database Compilation

Alexander and Cruz (2006) compiled a total of 57 wildfire observation from North American forests. The data set consisted of 43 fires from Canada primarily occurring in boreal forest fuel types and 14 fires from the United States that occurred in pine dominated fuel types in the interior Rocky Mountains, the Lake States and the south-eastern U.S. During the development of this data set, any case study that lacked adequate data, occurred in areas with a mix of fuel types that do and do not support crown fire or occurred in areas with complex topography (>10% slope, or cross slope fire spread) were removed. For the remaining observations they reported the major fuel type, the temperature (°C), the relative humidity (%), the effective fine fuel moisture (%), the Canopy Bulk Density (kg m^{-3}) and the 10-m open wind speed (km h^{-1}). Although this data set did have a relatively large amount of detailed information regarding the rate of fire spread several calculations were performed by Alexander and Cruz (2006) to ensure a complete data set. Specifically they: 1) adjusted the 6.1 meter open wind speed for the U.S. data by a factor of 15% to approximate the 10-m open wind speed, 2) inferred the canopy bulk density using a variety of methods on a case-by-case basis, and estimated the effective fine fuel moisture content using equations published by Rothermel (1983) and assumed that all fuels were shaded from solar radiation. Despite the need for additional calculations to complete the data set, this remains the largest data set assembled to date on crown fire rate of spread.

3.2. Crown Fire Rate of Spread Predictions From Physics-Based Models

Because various models require data in different forms and with different levels of details, it was not possible to directly simulate the wildfires contained in the Alexander and Cruz (2006) data set. Rather we identified published crown fire rate of spread values from physics based simulations and developed a data base that included their rate of spread (m s^{-1}), the 10-m open wind speed (m s^{-1}), the maximum canopy bulk density (kg m^{-3}), and the effective fine fuel moisture content (%). We identified a total of 50 simulations from physics based models, 22 of which were conducted using HIGRAD/FIRETEC and 28 of which were conducted using WFDS. These simulations were conducted using primarily fuels data from pine dominated or mixed conifer systems.

3.3. Analysis

Because we were not able to directly simulate the 57 fires contained within the Alexander and Cruz (2006) data set we used linear regression to evaluate the relationship between the 10-m open wind speed and the crown fire rate of spread and predicted non-simultaneous 95% confidence bounds for a new observation. We than compared the simulated crown fire rates of spread from HIGRAD/FIRETEC and WFDS to these bounds.

4. Results and Discussion

Our results to date show that overall crown fire rate of spread predictions from HIGRAD/FIRETEC and WFDS perform fairly well as compared to the field derived estimates of crown fire rate of spread from Alexander and Cruz (2006). Of the 50 physics-based simulations we compared, 12% (6 total simulations) did not fall within the 95% confidence prediction bounds (figure 1). These 6 points represented 21% of the WFDS simulations and over-predicted the expected rate of spread. There are a variety of reasons that could explain the larger than expected number of points that fall outside the 95% predictive bounds including the sensitivity of the simulated results to wind flow parameters, horizontal and vertical fuel distribution, ignition methods, and fireline shape. Our future work will explore the sensitivity of physics-based models to these parameters. In addition uncertainties in measurements for field experiments such as those compiled by Alexander and Cruz (2006) need to be better documented.

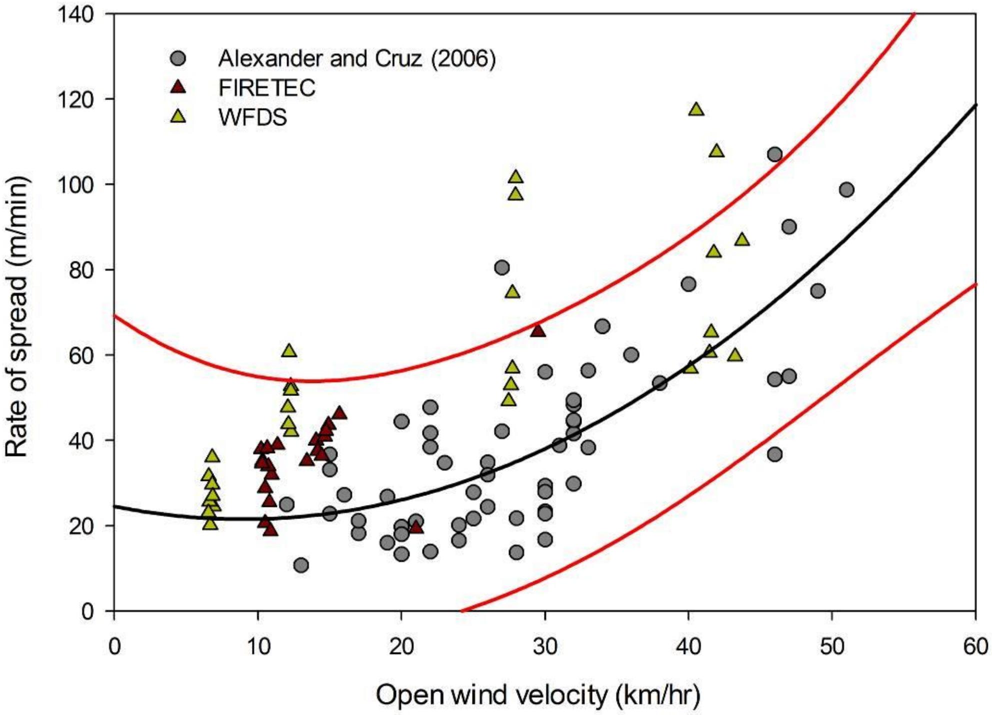

Figure 1. Comparison of crown fire rate of spread predictions from HIGRAD/FIRETEC and WFDS to observed crown fire rates of spread from Alexander and Cruz (2006).