Proceedings for the 5th International Fire Behavior and Fuels Conference
April 11-15, 2016, Portland, Oregon, USA
Published by the International Association of Wildland Fire, Missoula, Montana, USA

Field-Scale Testing of Detailed Physics-Based Fire Behavior Models

Eric Mueller*
University of Edinburgh, Institute for Infrastructure and Environment, Edinburgh, EH9 3JL, UK, e.mueller@ed.ac.uk

William Mell
USDA Forest Service, Pacific Wildland Fire Sciences Laboratory, Seattle, Washington, USA, wemell@fs.fed.us

Nicholas Skowronski
USDA Forest Service, Northern Research Station, Carbon, Fire, and Climate Sciences, Morgantown, WV 26505, USA, nskowronski@fs.fed.us

Kenneth L. Clark, Michael Gallagher
USDA Forest Service, Silas Little Experimental Forest, New Lisbon, NJ 08064, USA, kennethclark@fs.fed.us, michaelgallagher@fs.fed.us

Rory Hadden
University of Edinburgh, Institute for Infrastructure and Environment, Edinburgh, EH9 3JL, UK, r.hadden@ed.ac.uk

Albert Simeoni
Exponent Inc., Natick, Massachusetts 01760, USA, asimeoni@exponent.com

Introduction

Fire behavior models have shown utility in understanding and predicting the progression and impact of wildland fires for both research and management applications. Detailed discussions of the different types of existing models can be found in the reviews by Pastor et al. (2003) and Sullivan (2009a; b). Each group of models has strengths and weaknesses that dictate the uses to which they are suited. However, of all of these groups, detailed physics-based models are the only which aim to include all of the relevant physical phenomena. These provide a number of advantages, such as allowing their use in a more flexible predictive capacity. Detailed physics-based models can also be used to develop or parameterize simplified models, such as fire spread or smoke transport models, where experimental data may not be readily available. However, a common criticism of these models, beyond computational demand, is the relatively limited extent to which they have been evaluated against experimentation, particularly at the field-scale. Such testing is a necessity given the significant number of input parameters required to run such a model, some of which may not be well characterized. Therefore, our project is designed to test model predictions against a set of experimental fire behavior measurements conducted in a forested environment.

Here, we focus on the application of one particular detailed physics-based fire behavior model, The Wildland-urban interface Fire Dynamics Simulator (WFDS), to describe a spreading fire in a forested environment representative of the Pinelands National Reserve (PNR) in New Jersey, USA, with an ultimate goal of understanding how environmental conditions and fuel characteristics can modify potential fire behavior. Such information can be of use to managers and firefighters.

Wind is a key driving variable in wildland fire behavior, and therefore the drag coefficient, which appears in the momentum equation as a sink term due to vegetation drag, is an important parameter. However, the approach for defining this parameter has not been rigorously tested for physics-based fire behavior models. There are two different formulations commonly used to model this momentum drag within the raised fuel layer (shrubs and canopy), and these are described in more detail below. We tested both approaches with the objective of simulating fire behavior in a pine-dominated stand, and find that this choice varies the predicted quasi-steady spread rate by a factor of 1.6. This difference is linked to heat transfer ahead of the fire front, which in turn is related to the flame height.

Methods

Experimental methods

In order to provide the requisite data for model testing, measurements were made of experimental fires carried in the Pinelands National Reserve (PNR) in New Jersey. The overstory of the experimental blocks was predominantly pitch pine (Pinus rigida Mill.), and the shrub layer in the understory was composed of huckleberry (Gaylussacia spp.), blueberry (Vaccinium spp.), and scrub oaks (Quercus spp.). Measurement techniques included both remote sensing, yielding quantities such as spread rate from aerial IR and pre- and post-fire canopy bulk density (CBD) from aerial LiDAR, and point-based measurements, yielding quantities such as wind speed (both at and below canopy height), temperatures, and radiative heat fluxes. A full treatment of all experimental measurements is beyond the scope of this presentation, though an example of some early analysis can be found in Mueller et al (2014). The present simulations focus on one of the experimental fires, conducted in March 2014.

Numerical methods

WFDS is a Computational Fluid Dynamics (CFD) model that uses Large Eddy Simulation (LES) to directly resolve turbulent eddies that are larger than grid scale, and includes submodels for combustion, radiative transport, subgrid-scale turbulence. It is built upon the Fire Dynamics Simulator (FDS) (McGrattan *et al.* 2010), and employs a multiphase formulation for the description of subgrid-scale vegetation elements, originally developed by Grishin (1997) and Larnini et al. (1998). Details specific to the WFDS formulation can be found in Mell et al. (2007, 2009), and only aspects relevant to the problem formulation are discussed here.

The simulations presented focus on a sub-section of interest from the full experimental burn block, as shown in Figure 1. This choice was made in order to reduce run times and thus facilitate the study of a number of parameters that are not well defined experimentally, before moving on to larger scale simulations. The area encompassed by the numerical domain was 240 m x 225 m x 76.5 m. The horizontal grid resolution was 0.5 m x 0.5 m, while the vertical resolution was 0.5 m at ground level and, starting at a height of 2*h* (where *h* is canopy height), was stretched progressively to 1.5 m. A north wind was specified by a fixed velocity profile at the maximum y-boundary. The magnitude at canopy height was 3.9 ms^{-1} (following measured values), and a logarithmic profile was used above canopy and an exponential profile below. Key input parameters related to the vegetation are based on experimental measurements, and are given in Table 1. A vertical profile of CBD for live needles, considered to be the main

Table 1: Key vegetation input values for surface-to-volume ratio (σ), bulk density (ρ_b), element density (ρ_e), and moisture content (M). Subscripts refer to live canopy needles (ln), dead litter layer needles (dn), and fine woody shrub fuels (s1-3). Shrub fuels are subdivided into diameter categories of 0-2 mm (s1), 2-4 mm (s2), and 4-6 mm (s3).

Parameter	Value	Parameter	Value	Parameter	Value
σ_{ln}, σ_{dn}	4661 m^{-1}	$\rho_{e,dn}$	615 $kg\cdot m^{-3}$	$\rho_{b,s1-3}$	0.181 $kg\cdot m^{-3}$
$\rho_{b,ln}$	see Figure 2	M_{dn}	20 %	$\rho_{e,s1-3}$	512 $kg\cdot m^{-3}$
$\rho_{e,ln}$	787 $kg\cdot m^{-3}$	σ_{s1}	4000 m^{-1}	M_{s1-3}	61 %
M_{ln}	114 %	σ_{s2}	1333 m^{-1}		
$\rho_{b,dn}$	20.6 $kg\cdot m^{-3}$	σ_{s3}	800 m^{-1}		

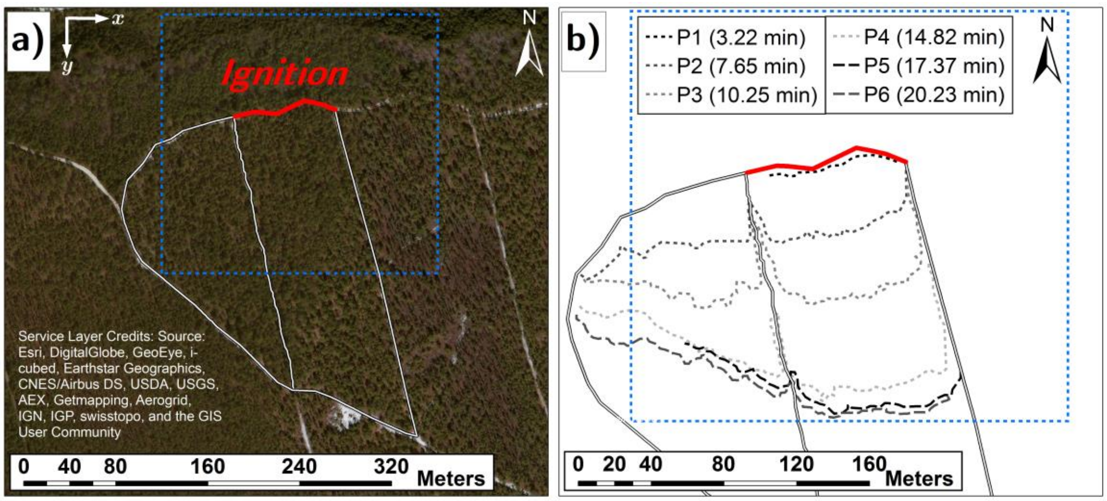

Figure 1: (a) Satellite imagery and (b) close up of fire progression contours (obtained from aerial IR imagery) of the experimental burn block. The numerical simulation domain is overlaid (dotted blue line), and the simulated ignition line is shown in red.

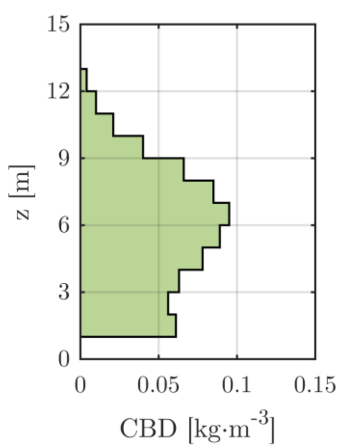

Figure 2: Block average of live needle CBD used for the simulations, as determined from calibrated LiDAR data. Note that as shrub fuels dominate below 1 m, the bulk density within this volume is specified from field sampling values (see Table 1) and are not included here.

contributors of fire intensity and momentum drag, in the forest canopy (Figure 2) was obtained from an average over the whole region of 10 m x 10 m raster data generated from the LiDAR measurements (Skowronski *et al.* 2011). The vertical resolution is 1 m. CBD in the shrub layer (lowest 1 m) and the litter layer of dead needles was obtained from destructive sampling pre-fire (Table 1).

In many LES-CFD studies of flow through forest canopies, a drag force is represented in the form of Equation 1, which is dependent on the one sided leaf area density (a_f) and the drag coefficient (c_d) set as a fixed value, depending on the vegetation characteristics.

$$\langle F_{d,i} \rangle_{V_b} = -\rho c_d a_f u_i |\mathbf{u}| \quad (1)$$

This approach has been used to test WFDS for canopy flow previously (Mueller *et al.* 2014), and has also been applied to FIRETEC, another physics-based fire behavior model (Pimont *et al.* 2009). However, a number of studies employing the multiphase formulation for wildland fire modeling consider the bulk influence of the many subgrid particles by summing the contribution of each (e.g. Morvan and Dupuy 2004; Mell *et al.* 2009), resulting in a form following Equation 2. Here, c_d is a Reynolds number-dependent quantity based on the assumed particle geometry (cylinders, in our case), c_s is a shape factor ($1/(2\pi)$ for cylinders), and the other quantities are defined based on the vegetation (see Table 1).

$$\langle F_{d,i} \rangle_{V_b} = -\rho c_d c_S \sigma_e (\rho_b / \rho_e) u_i |\mathbf{u}| \quad (2)$$

These two formulations are tested for modeling drag forces in both the canopy and shrub layer in the numerical simulation described above, with $c_d = 0.25$ for Equation 1. With this choice, for a given vegetation type, Equation 2 will result in greater drag, particularly at low velocities. For example, for live pine needles at a CBD of 0.05 $kg \cdot m^{-3}$ and a velocity of 0.1 ms^{-1}, the drag from Equation 2 will be 10 times greater. With increasing velocity, the ratio of the relationships reaches an asymptote at a value of 2.5.

Results and Discussion

A logical starting place for analyzing the simulation results is with broad fire behavior descriptors such as progression, or spread rate. Figure 3 shows that static drag coefficient progresses more rapidly during the initial stages (during which a surface fire was observed), but has a good match to the experimental spread rate from P2-P4 (during which a period of crown fire occurred). The dynamic formulation matches quite well initially (P1-P2), but under-predicts the more rapid spread following P2. In general, the time for the fire to reach 100 m increases by nearly 1.6 for the dynamic drag coefficient. In neither case is the simulation able to predict the sudden drop in fire spread following P4. However, this steady spread is expected as the modeled fuel loading is spatially homogenous and the wind speed is temporally homogenous, giving no reason for a sudden change in fire behavior.

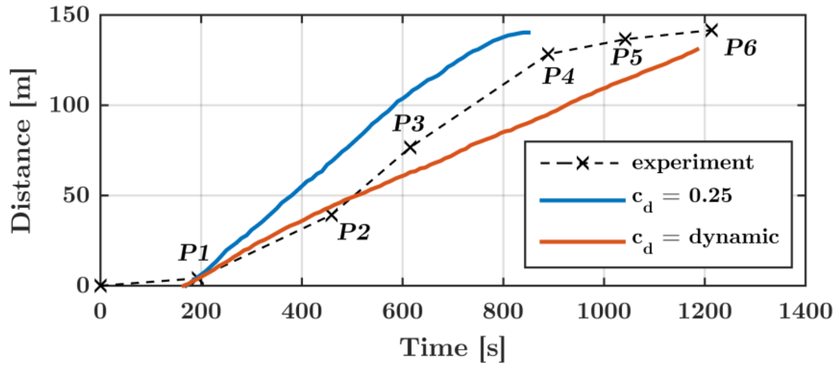

Figure 3: Simulated fire front progression (solid lines) compared with experimental progression (symbols). In both cases, the progression is determined by evaluating the distance traveled from the ignition line along a transect halfway between the center and rightmost road in Figure 1. Due to uncertainties associated with modeling the ignition process, the simulation times have been shifted so that the time of the fire at P1 is consistent for all cases and only the progression following this point is considered.

In order to better understand the reasons for these different predictions, an investigation of some more detailed aspects of the fire behavior was carried out. Figure 4 shows an example assessment of flame structure (T > 300 °C) and the characteristic radiative heat flux to the needle litter bed. It is clear that the higher air flow from the lower drag values result in taller flames (though the flame angles appear similar) with a greater depth, and thus higher heat fluxes (with a peak value roughly 1.7 times that for the dynamic drag coefficient). This increased thermal transfer to the fuel results in the more rapid fire spread observed in Figure 3. An investigation of the simulated fuel bulk density and consumption will help reveal which fire behavior (and thus drag formulation) is more in line with expectations, given that average values are used compared to the range of bulk densities observed in the experiments.

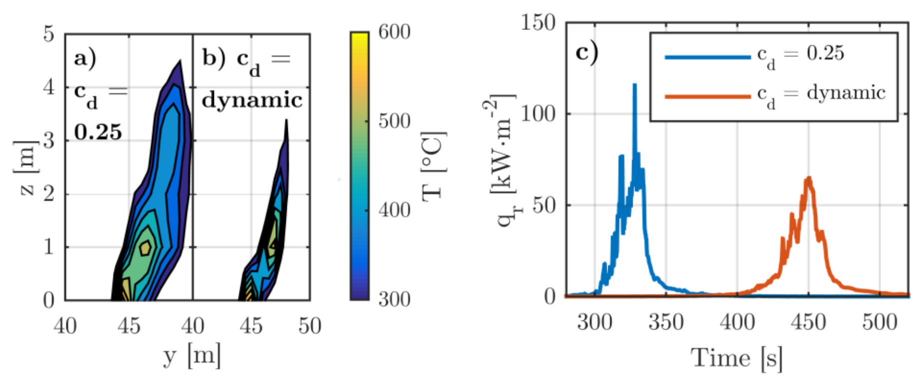

Figure 4: Examples of simulation difference in terms of (a) 5-s average of flame front temperatures along a transect on the y-axis (bisecting the flame front), and (b) incident radiative flux onto the needle litter fuel bed. Both figures represent the fire after traveling 45 m, or close to P2.

Conclusions

In this work, it is shown that WFDS is capable of giving a reasonable prediction of fire progression when compared to the experimental data. However, for this scenario, the results are sensitive to the formulation of the drag coefficient. The differences in broad fire behavior are linked to more fundamental characteristics of the flames, with a static drag coefficient tending towards larger flames and faster spread. Ongoing experimental analysis of these types of characteristics (such as temperatures and heat fluxes) will shed more light on the quality of the two different approaches, but ultimately a more robust characterization of drag within these types of fuel beds is recommended. Finally, implementation of heterogeneous descriptions of wind and vegetation will help assess the ability of the model to capture the dynamic fire behavior observed in the experiments.

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