

Computing Wildfire Behaviour Metrics from CFD Simulation Data

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Abstract

In this article, we demonstrate a new post-processing methodology which can be used to analyse CFD wildfire simulation outputs in a model-independent manner. CFD models produce a great deal of quantitative output but require additional post-processing to calculate commonly used wildfire behaviour metrics. Such post-processing has so far been model specific. Our method takes advantage of the 3D renderings that are a common output from such models and provides a means of calculating important fire metrics such as rate of spread and flame height using image processing techniques. This approach can be applied similarly to different models and to real world fire behaviour datasets, thus providing a new framework for model validation. Furthermore, obtained information is not limited to average values over the complete domain but spatially and temporally explicit metric distributions are provided. This feature supports posterior statistical analyses, ultimately contributing to more detailed and rigorous fire behaviour studies.

Introduction

Computational Fluid Dynamics (CFD) are increasingly being used to study fire behaviour. In the field of enclosure fires, CFD models have successfully been used for quantitative fire risk assessment and they constitute a key tool in Performance-Based Design (PBD) methodologies. In the area of wildland fires, CFD simulation has a significant potential for fire risk assessment at the Wildland-Urban Interface (WUI) (Mell *et al.* 2010, 2011) and for fuel management (Ziegler *et al.* 2017; Parsons *et al.* 2018). In recent years, several 3D CFD simulators have been specifically designed to model forest fire behaviour. Two examples of these are FIRETEC (Linn *et al.* 2002) and the Wildland-Urban Interface Fire Dynamics Simulator (WFDS) (Mell *et al.* 2009), both of which are still undergoing active development and validation. Favourable comparisons with experimental data from lab and field studies (Menage *et al.* 2012; Mueller *et al.* 2014; Hoffman *et al.* 2016) suggest that their output is reliable under certain circumstances. These successes have spurred an interest in the development of wider modelling frameworks that include the modelling of fuels inputs. In this sense, systems such as FuelManager (Pimont *et al.* 2016) and STANDFIRE (Parsons *et al.* 2018) facilitate the quantitative evaluation of how fuel treatments and other fuel changes modify fire behaviour.

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Despite the wide range of research opportunities available in this context, the analysis of wildfire physics-based model outputs poses significant challenges. CFD simulators provide a wide range of quantitative data, including 2D and 3D fields of air temperature, air velocity and heat release rate, among others. However, they do not directly compute fire behaviour metrics such as rate of spread, flame height, fire front depth or fire line intensity. These metrics are essential to study fire dynamics and fire effects on soil and vegetation, and they are necessary to analyse the efficacy of different fuel treatments as well as to assess fire risk at the WUI. Differences in model architecture and data formats currently constrain such post processing to be model specific, making direct comparison between models somewhat complicated. Similarly, measurements on field fire experiments rarely cover the same set of variables or have similar detail in output, making direct comparison between field fire data and simulation output challenging. These constraints pose a barrier to advancement of this field and refinement of such models, either through comparisons with other models, or with experimental data.

In an attempt to overcome these restrictions, we propose a post-processing framework that facilitates the computation of fire behaviour metrics from CFD simulation data. Our methodology is not aimed at any particular simulator but it was designed as a model-independent tool. This entails the additional advantage of providing a common framework for inter-model comparison. Furthermore, the methodology employed to process simulation outputs is similar to the approach usually followed to analyse experimental infrared (IR) imagery (Valero *et al.* 2018). Therefore, the proposed framework also constitutes a valuable third-party tool for model validation against experimental data.

Methodology overview

In order to compute wildfire behaviour metrics, the proposed methodology relies on the 3D visualization of the simulated fire. This is a common output provided by the vast majority of existing simulators, usually through third-party tools such as Smokeview or Paraview. Our approach relies on the assumption that this view approximately corresponds to what a visual camera would see in the simulated fire scenario. If this statement holds true, then image processing and computer vision algorithms developed for video fire analysis can be applied to the virtual rendering. The fact of using 3D fire visualization as the only needed input simplifies the application of our methodology. No additional simulation output variables must be recorded and already completed simulations must not be re-run. Furthermore, simulated scenarios provide exceptional flexibility to select the most convenient views of the fire, acquire simultaneous views from different perspectives and remove undesired objects from the scene, among others.

For the quantitative study of wildfire behaviour, each virtual video sequence is rendered twice: firstly, from a nadir view to measure the fire rate of spread; secondly, from a front view to obtain flame height distributions. After selecting the view and exporting all video frames, the footage is geometrically corrected in order to retrieve physical dimensions from image coordinates. This is achieved through a 2D geometric transformation commonly used in remote sensing to georeference oblique imagery (Paugam *et al.* 2013; Valero *et al.* 2018). Furthermore, original colour footage is transformed into greyscale video using a transformation similar to the one recommended by the International Telecommunication Union to calculate luminance in digital television (International Telecommunication Union 2011).

After the necessary pre-processing, the nadir view is used to reconstruct the fire perimeter evolution during the fire, which allows the computation of spatially explicit values of rate of spread. These tasks are accomplished using the methodology proposed by (Valero *et al.* 2018), which was originally developed for infrared video and is completely automatic. On the other hand, the frontal view is used to measure flame height distributions within each video frame. Fire contours are detected by grey level thresholding and object border tracking. Thresholds are computed automatically using Otsu's method (Otsu 1979).

Sample results and utility demonstration

Two example WFDS simulations were analysed to illustrate the applicability of the presented methodology. The first simulation reproduced a laboratory test and derived metrics were used to assess the similarity between simulation and experimental results. The second simulation was designed using example STANDFIRE simulation output and exemplifies how this methodology may support fuel management and fuel treatment assessment.

Study case 1: comparison of simulation and experimental data

One of the main applications of our post-processing approach is the detailed comparison of simulated results with experimental data. A measurement strategy that works similarly with infrared video and outputs provided by different simulators has a great applicability as a model-independent tool for model validation.

In order to assess the suitability of our approach for this goal, we reproduced a laboratory test using WFDS. The laboratory burning was performed over a horizontal combustion table of about 1.5 meters in width and 3 meters in length, with no wind and using straw as fuel. It was recorded with a thermal infrared camera from an overhead perspective in order to track the fire perimeter and compute its rate of spread. The same experimental setting was reproduced in WFDS and the simulation output was analysed following the methodology proposed in this article. The resulting fields of rate of spread are displayed in figure 1.

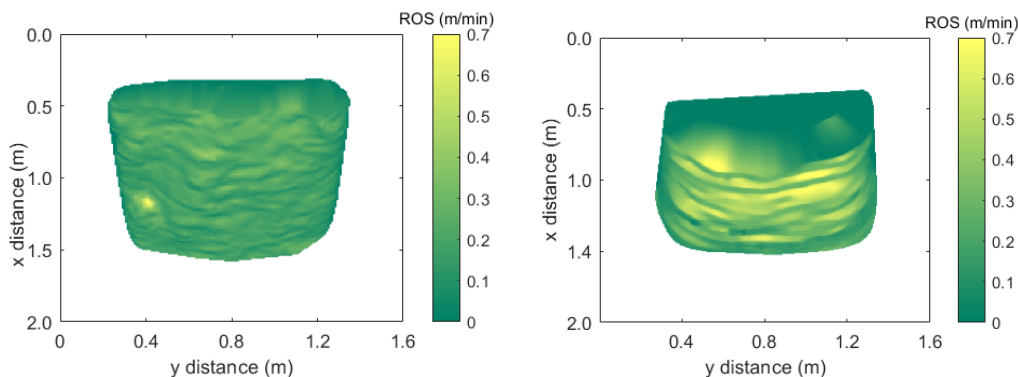


Fig. 1. Spatially explicit fire rate of spread. Left: experimental test (from Valero *et al.* 2018). Right: WFDS simulation, analysed with the proposed methodology.

Figure 1 demonstrates how simulation results are now directly comparable to experimental information, which is not the case with the standard output produced by WFDS. In this particular case, significant dissimilarities can be observed between simulation and experiment. A probable cause of these differences in ROS is the inaccuracy of simulation input parameters. In a real study, parameters' accuracy should be properly quantified and sensitivity analyses should be performed to further assess the reliability of simulation data. Our methodology may also assist in such analyses.

Study case 2: fuel treatment analysis

Another relevant application of this approach may be the quantitative assessment of fuel treatment effects on fire behaviour. STANDFIRE (Parsons *et al.* 2018) was developed with the aim of unifying and simplifying this task through the integration of fuel modelling and physics-based fire simulations. It works successfully with two of the most powerful wildfire CFD simulators available at present, i.e. WFDS and FIRETEC.

This section presents the potential improvements that our methodology brings to this framework. In addition to rate of spread fields as those showed in figure 1, measured rates of spread can be analysed statistically both in time and space. This provides additional tools to investigate potential relationships between rate of spread and fuel properties, weather conditions or terrain characteristics. Similar studies can be performed on flame height data, which is furthermore essential to estimate crown effects and the probability of crown ignition.

As a proof of concept, sample results were obtained for a medium scale WFDS simulation designed with STANDFIRE (fig. 2). Dimensions of the computational scenario were 160m x 90m x 50m (length x width x height). Surface fuels were represented as a homogeneous litter bed, while canopy fuel consisted of a series of trees of different species, each with different fuel loads. Figures 3 and 4 show average and standard deviation values for the fire rate of spread and flame height, respectively, whereas figures 5 and 6 include histograms of the measured values.

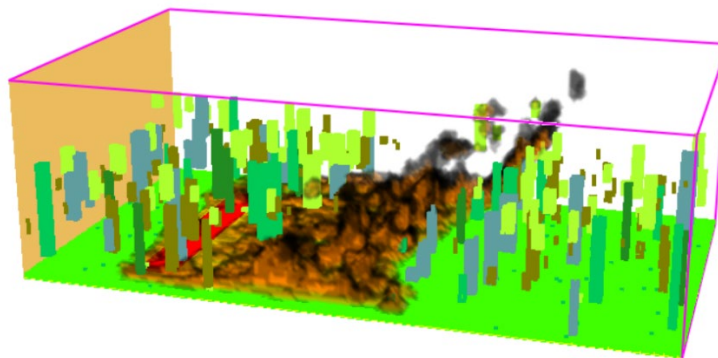


Fig. 2. Example WFDS simulation output from STANDFIRE, analysed using the proposed methodology.

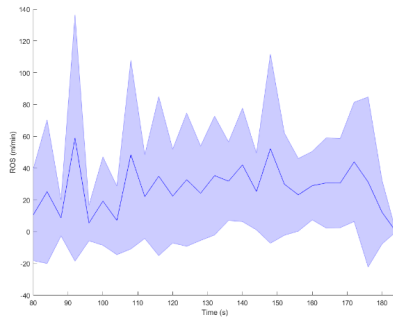


Fig. 3. Average rate of spread along the fuel burning interface, and its evolution with time. Shadowed area represents spatial standard deviation.

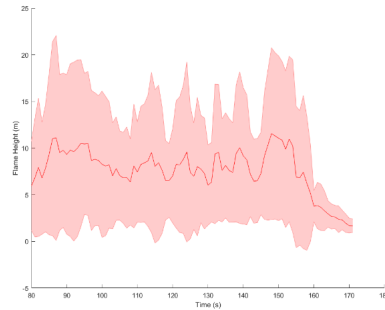


Fig. 4. Average flame height along the fuel burning interface, and its evolution with time. Shadowed area represents spatial standard deviation.

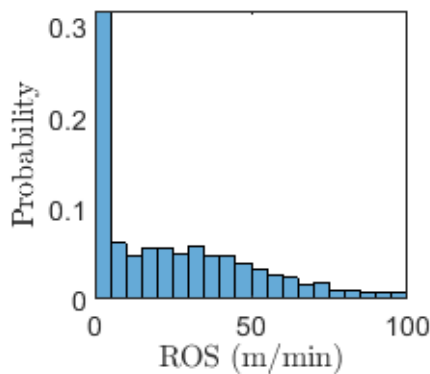


Fig. 5. Probability distribution of rate of spread measured from simulation data using the proposed methodology.

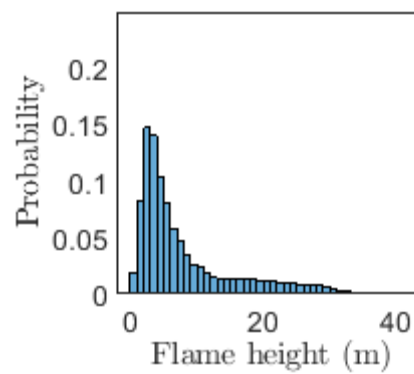


Fig. 6. Probability distribution of flame height measured from simulation data using the proposed methodology.

Discussion and future work

The proposed methodology for CFD output post-processing showed promising preliminary results. An automatic tool capable of computing probability distributions such as those displayed in figures 5 and 6 may support rigorous statistical analyses, which are essential for model validation, yet not always conducted. This tool is model independent, thus facilitating quantitative inter-model comparisons as well as validation against experimental data. Furthermore, it is decoupled from the models themselves, which brings advantages and drawbacks. Because it can be used a posteriori and it does not introduce requirements in simulation inputs, it is versatile and can be used by non-modellers. On the other hand, this fact also makes it prone to errors and misuse. Losing track of model input parameters or parameters used for 3D rendering would invalidate any subsequent analysis.

Based on this discussion, we acknowledge a series of development steps that should be completed before this tool fully achieves its intended use. First, the workflow described in this article must be automated to ensure a standardized process. Second, data transparency must be ensured during the complete workflow so that the system keeps track of all parameters used to obtain a certain result. Finally, further tests must be conducted on diverse simulation platforms as all results shown here were obtained using WFDS and Smokeview. Additionally, we expect to extend the range of computed fire metrics including fire line intensity and fire radiative power, among others.

Acknowledgments

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