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RandomFront - A Post-processing Routine for Including Fire-spotting in Regional-scale Wildfire Simulators: A Test Case with WRF-SFIRE

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Introduction

This research project is focused on the development of a step-by-step post-processing routine for including random phenomena, as fire-spotting, in operational forest fire simulators. The post-processing procedure allows for avoiding changes in the simulator code and for preserving the proprietary of the software as in the case of commercial tools. We present a response analysis of the post-processing routine RandomFront through the simple fire spread simulator LSFire+ and a test case with the fire simulator WRF-SFIRE (https://github.com/openwfm/wrf-fire/) which includes atmosphere-fire coupling.

The adopted modelling approach (*Pagnini and Mentrelli (2014), Kaur et al. (2016), Egorova et al. (2019), Trucchia et al. (2019a)*) is based on the idea to split the motion of the front into a drifting part and a fluctuating part. The drifting part represents the main front motion and it can be treated by any existing simulator based, for example, on both the Eulerian Level-Set method (LSM), in analogy with WRF-SFIRE, or on the Lagrangian Discrete Event System Specifications (DEVS), in analogy with ForeFire (http://forefire.univ-corse.fr/). The fluctuating part is the result of a comprehensive statistical description of the physics of the system and includes the random effects, that are here physically parametrized to include turbulent hot-air transport and firebrand landing distance [3].

The routine RandomFront has been already tested with LSFire+ (*Pagnini and Mentrelli (2014), Kaur et al. (2016)*), a simple solver based on the LSM, and with ForeFire (*Trucchia et al. (2019a)*). The resulting model emerges to be suitable for reproducing the effects due to turbulent convection, such as fire flank and backing fire, the faster fire spread because of the actions by hot-air pre-heating and by ember landing, and due to the fire overcoming a fire-break zone. As a novel part of the present work, following *Trucchia et al. (2019a),* we proceed with testing the proposed post-processing routine with the atmosphere-fire coupled simulator WRF-SFIRE, where the fire behavior module is fully integrated into the weather prediction model Weather Research and Forecasting (WRF).

The post-processing routine RandomFront v2.3 is freely available at the official git repository of BCAM – Basque Center for Applied Mathematics, Bilbao, https://gitlab.bcamath.org/atrucchia/randomfront-wrfsfire-lsfire already implemented in both the simple fire spread simulator LSFire+ and in WRF-SFIRE.

Modelling of Random Effects

For mathematical and physical details of fire-spotting and turbulence modelling we remind the readers to References *Pagnini and Mentrelli (2014), Kaur et al. (2016), Egorova et al. (2019), Trucchia et al. (209a)*. Here we briefly reported that for the downwind landing distance of the firebrands a lognormal distribution is chosen. Parameters of the distribution σ –the standard deviation– and μ –the ratio between the square of the average landing distance and its standard deviation– represent the transport of the firebrands rationally: μ is parametrized to characterise the lofting of the firebrands inside the convective column depending on the height of the Atmospheric Boundary Layer (ABL), σ is parametrized to reproduce the transport of the firebrands under the effect of the wind and the flame geometry. The parameters are derived from the assumption that the maximum landing distance can be represented by the p-th percentile of the lognormal distribution (*Kaur et al. (2016), Egorova et al. (2019), Trucchia et al. (2019a)*).

The turbulent hot-air transport is also considered as random phenomenon and it is modelled by a Gaussian distribution governed by a diffusion coefficient parametrised according to a convective cell where the height of the ABL and the temperature difference between the bottom (with fire) and the top of the ABL are considered in *Kaur et al. (2016), Egorova et al. (2019)*.

We observe that the proposed approach depends on several parameters, a Sensitivity Analysis (SA), to rank the inputs by their relevance, and an Uncertainty Quantification (UQ), on the main observables, are mandatory. The considered parametrisation emerged to be a nonlinear model with a remarkable range of variations in the size and topology of the fire due to uncertainties in its input parameters. There is a clear dominance of the lognormal parameter σ characterizing firebrand downwind transport and of the wind magnitude, in agreement with the fact that fire-spotting is a wind-driven phenomenon (*Trucchia et al. (2019b)*).

Response Analysis with LSFire+

The post-processing routine RandomFront includes effects due to turbulent hot-air transport and due to fire-spotting together. Both processes contribute towards the fire propagation. Here we perform a response analysis by using LSFire+, which is based on the LSM and then it can be understood as a simple version of WRF-SFIRE without the atmosphere-fire coupling. Since it is difficult to separate the effects of the individual processes, a comparison of the increase in burned area due to turbulence only and to turbulence with fire-spotting is performed.

The firebrands transportation is affected at the macro-scale by the mean wind and atmospheric conditions. Here we distinguish stable and unstable atmospheric conditions of the ABL. Stable atmosphere is characterised by the light wind and is usually observed during the night. Unstable atmosphere is characterised by higher boundary layer and erratic winds. At the meso-scale level, we consider the flame geometry that, affected by the fuel and the vegetation, causes changes in the fire-spotting characteristics. Figure 1 (left) shows the total number of burned points plotted at different elapsed times since the ignition and the contribution of fire-spotting to the simulated burned area increases in time providing a non-negligible and multiplicative effect. The effect of the height of the ABL is also studied. In Figure 1 (middle) the simulations show a dependence of the burned area on the height of the ABL that characterises both the turbulent diffusion coefficient and the lofting height of firebrands. In Figure 1 (right) the same is shown with fixed diffusion coefficient. This analysis reveals that atmospheric stability conditions affect the propagation of the fire front, but although they have a direct effect on the maximum landing distance of firebrands, their effects on the turbulent heat transport also governs the evolution of the wildfire. In particular, unstable conditions boost the number of fire-spotting generated fires at small elapsed times as well as the strength of turbulence leading to rapid merging separate fires in a synergetic dynamic. In Figure 2 the role of the flame length in the production of fire-spotting and the generation of independent fires is displayed. The plots show at the same elapsed time and different values of the flame length the case still without secondary fires, the case with merged independent fires and the case with effective fire-spotting.

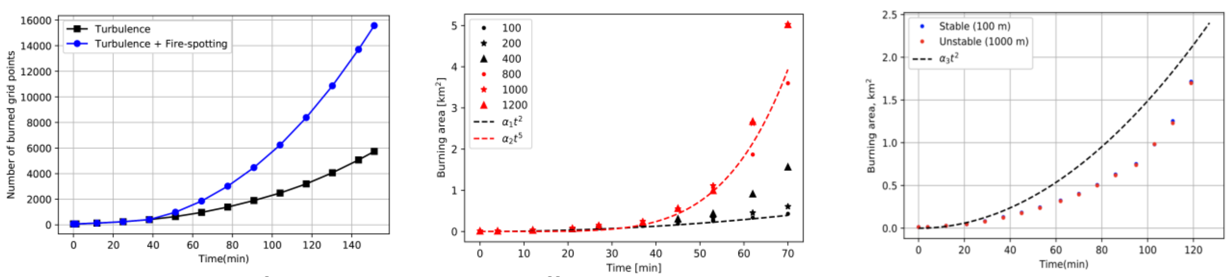

Figure 1.: Comparison of the total burned area at different elapsed times since the ignition when only turbulence is considered and when both turbulence and fire-spotting are included (left); and similar comparison for different height of ABL representing nocturnal (black) and diurnal (red) fires with turbulent diffusion coefficient dependent on (middle) and independent of (right) the height of the ABL.

A Test Case with WRF-SFIRE

As mentioned in the Introduction, the proposed post-processing routine has been already implemented and tested with LSFire+ (*Pagnini and Mentrelli (2014)*) and with ForeFire (*Kaur et al. (2016)*). Following *Trucchia et al. (2019a),* here we present a case study with the atmosphere-fire coupled code WRF-SFIRE. The fire module in WRF-SFIRE is a surface fire behaviour model that adopts a two-way coupling with the atmospheric model. That is, near-surface winds from the atmospheric model are interpolated to a finer fire grid and are used, with fuel properties and local terrain gradients, to determine the rate of spread of the fire. Fuel consumption, in turn, releases sensible and latent heat fluxes into the atmospheric model's lowest layers, playing a role in boundary layer circulations. The atmosphere-fire coupling is made through the weather model WRF.

In the present case study, we consider a slight modification of the hill test case (https://github.com/openwfm/wrf-fire/blob/master/wrfv2_fire/test/em_fire/hill/namelist.input.hill) where, in order to simplify the underlying dynamics, but keeping the fire-atmosphere coupling, the hill is suppressed. The fuel has been set equal to fire Type 9, i.e., FM 9 Hardwood litter according to Anderson classification this fuel type may represent a terrain covered by Pinus ponderosa trees.

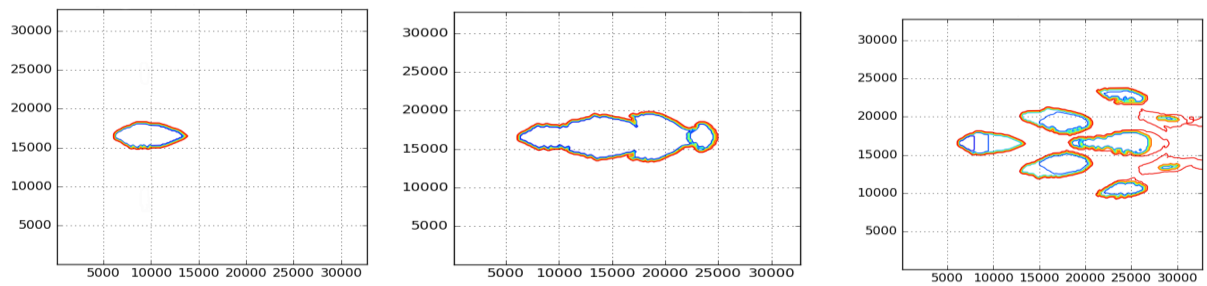

Figure 2.: Fire perimeter for different flame lengths reflected in σ=6.85, 7.74, 8.33, from left to right, with no fire-spotting, merging of independent fires generated by fire-spotting and effective fire-spotting.

The results of the implementation of the proposed post-processing routine in WRF-SFIRE are presented in Figure 3 by displaying the fire perimeters after 34 minutes of burning. This first implementation shows promising improvements with respect to previous simulations performed in more simple environmental conditions without atmosphere-fire coupling. In particular, the fire-spotting parameters σ and μ are now field variable due to the computed wind field that varies in space and time and to the spatial representation of the potential-fire characteristics (e.g., fire-line intensity) that comes embedded with WRF-SFIRE. It is worthy to observe that the fires generated by the fire-spotting are not in the main direction of the mean wind, and this suggests that also the geometrical shape of the burning surface may have a role in the production of fire-spotting phenomenon.

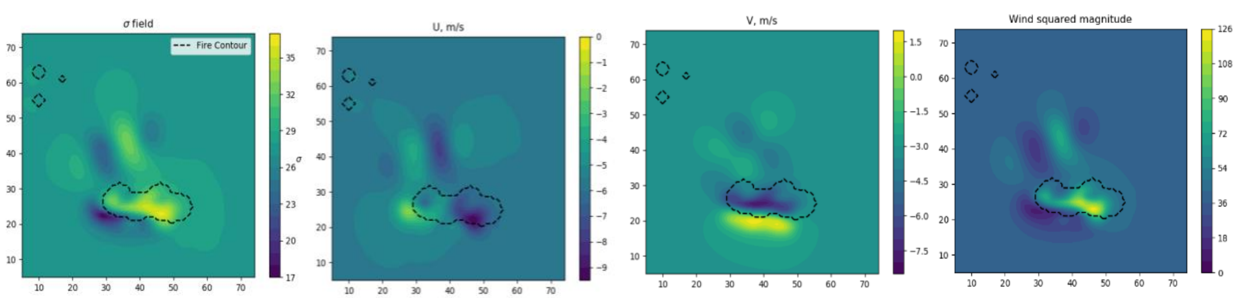

Figure 3: Test case of the post-processing routine RandomFront with WRF-SFIRE. Spotting phenomenon is observed after 34 minutes of burning in the top-left corner with the appearance of 3 secondary fires.

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