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Comparison of the effect of one-way and two-way fire-wind coupling on the modelling of wildland fire propagation dynamics

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Wildland fire, WFDS Level-set, static wind field, two-way coupling.

Abstract

Operational wildland fire propagation models are typically uncoupled from the wind field or they rely either on estimations extracted from an atmospheric model or on meteorological observations. This leads to a frozen wind field (one-way coupling) with a high degree of uncertainty, thus drifting away from the ground truth. In contrast, fully-coupled models (two-way coupling) comprise more accurate representations of the real phenomena, although they are not viable for operational use due to the hefty computational effort they entail. This article investigates and compares the effects of one-way and two-way wind-fire coupling on the predicted propagation of wildfires. The models are validated against experimental data obtained from grassland experiments carried out by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia. Simulations are carried out on a flat surface and for different wind speeds. Two scenarious are considered, one with and the other without an obstactle affecting both the wind flow and the wildfire propagation. Results from the simulations indicate that the burnt area and the rate of spread (RoS) are both smaller in two-way coupled than in one-way coupled models.

1. Introduction

Wildfire propagation modelling is remarkably challenging due to the complexity that results from its multi-physics and multiscale characteristics (Grasso and Innocente 2020). Chemical energy is converted into thermal energy during combustion as a result of a high-temperature (exothermic) chemical reaction between a fuel and oxygen. This energy is then transferred to the surrounding unburnt fuel, which ignites if a sufficiently high temperature is reached (ignition temperature). Whilst combustion is a chemical phenomenon, energy transfer is a physics phenomenon that occurs on domains ranging from millimetres to kilometres (Sullivan 2009a). Sullivan classified techniques for modelling wildland fire spread into three categories: *physical models* (Sullivan 2009a), *empirical models* (Sullivan 2009b), and *mathematical analogue models* (Sullivan 2009c). In turn, Innocente and Grasso (2019) classified wildfire propagation models into *theoretical models* (mechanistic, possibly physics-based), *data-driven models* (constructed from or fitted to actual or synthetic data), and *mechanistic surrogate models* (mechanisms not directly related to the phenomena being modelled).

A forest fire substantially affects the wind patterns in the immediate area. Rather than regular wind patterns, localised flow structures are generated by the interaction of atmospheric wind and the convection caused by the flaming combustion front. Thus, precisely forecasting fluctuations in wind velocity components produced by the presence of the fire in the boundary layer around its location is critical for effective fire behaviour prediction (Lopes et al., 2017). Several physics-based models such as FIRETEC (Linn et al. 2002), WFDS (Mell et al. 2007), CAWFE (Clark et al. 1996a; Clark et al. 1996b), WRF-FIRE, ForeFire/Mesho-NH (Filippi et al. 2010), and others have been developed and utilised to model wildfire propagation at various scales. However, these models have not been used within operational settings (Marino et al., 2012; Lopes et al., 2017) due to the computational resources required and the resulting slower-than-real-time simulations. Conversely, operational models such as FARSITE (Finney 1996) produce fast simulations at the expense of removing or weakening their links to the laws that govern the underlying physics. These are characteristically data-driven or mechanistic surrogate models, which only provide information on the propagation of fire lines. Furthermore, they are usually decoupled from or partially coupled with atmospheric models and therefore do not capture the effect of complex wind patterns on the fire dynamics (Bakhshaii and Johnson 2019). They simulate fire propagation using inputs from an atmospheric model and/or meteorological observations resulting in a frozen wind field unaffected by the fire (Bakhshaii and Johnson 2019). These static wind fields are typically calculated by diagnostic models such as WindNinja (Wagenbrenner et al. 2016) and Nuatmos (Ross et al. 1988). The immediate effect of using these models is an increase in the uncertainty of their output (Bakhshaii and Johnson 2019). A more recent study on the effect of two-way fire-wind coupling in (Lopes et al. 2017) suggests that this results in a significantly smaller burnt area than the one obtained with one-way coupled simulations. Later, Lopes et al. (2019) performed simulations with one-way and two-way coupling and reported that, even though both models over predict the fire area, two-way coupling performs better and provides values which are closer to the real data.

To the best of the authors' knowledge, limited research has focused on the effect of one-way and two-way fire-wind coupling on the simulated propagation of wildfires. Since this may differ depending on the combination of fuel, wind and topography, this paper is limited to flat lands covered with short grass. Two scenarios are considered, one with and the other without obstacles to the wind flow and wildfire propagation, aiming to investigate the effect of the formation of complex wind patterns. Simulations are performed using the WFDS level set model for point fire ignition in both two-way and one-way coupled conditions, and results are compared at different times from ignition.

2. WFDS Level-set method

An extension of the structural Fire Dynamics Simulator (FDS) for vegetative fuels developed by the National Institute of Standards and Technology (NIST) in the United States is the so-called Wildland-Urban Interface Fire Dynamics Simulator (WFDS). The governing equations for buoyant flow, heat transfer, combustion, and the thermal degradation of vegetative fuels are solved using computational fluid dynamics techniques. Solving gas-phase equations on computational grids that are too coarse to directly resolve precise physical events requires large-eddy simulations (LES). WFDS offers three models for simulation of wildland fires, including (1) particle mode, (2) boundary fuel model, and (3) level set method. The *Particle Mode* and the *Boundary Fuel Model* rely on physical principles and may employ grid resolutions as fine as 1 m in their basic implementations (Vanella et al. 2021). They require the thermo-physical parameters of the vegetative fuels whilst they calculate the fire rate of spread (RoS). Conversely, the propagation of the fire front in surface wildfires is modelled based on empirical principles only in the *Level Set Method*. A model for vegetation deterioration is not included, and the no-wind no-slope fire rate of spread (RoS_0) for various kinds of vegetation and wind speeds must be set (Vanella et al., 2021). Variations in the way wind and fire interactions are modelled allow for more than one version of this method. In this paper, we adopt the *Level Set Method* due to its capability of carrying out simulations with both one-way and two-way fire-wind coupling.

3. Results and Discussion

3.1. Validation of results

Simulation results are compared to experimental data obtained from grassland experiments carried out by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia (Cheney et al., 1998). The selected experiment is the C064, which was performed in the midlle of summer with fully dried kerosene grass on a 100×100 m^2 field with wind gusts of 4.6 m/s, grass height of 0.21 m, and a measured RoS of 1.2 m/s.

For the validation of the two-way coupled model, the class 1 Albini fuel models is used with some modifications, including the height changed from 0.3 m to 0.21 m and and Surface Area to Volume Ratio changed form 11500 to 9770. The resulting fire front position for three different mesh sizes of 1, 3 and 5 m is presented in figure 1, which shows that the *Level Set Method* underpredicts the fire propagation when compared to experimental data. Besides, reducing the mesh size appears to decrease the RoS of the simulated fire.

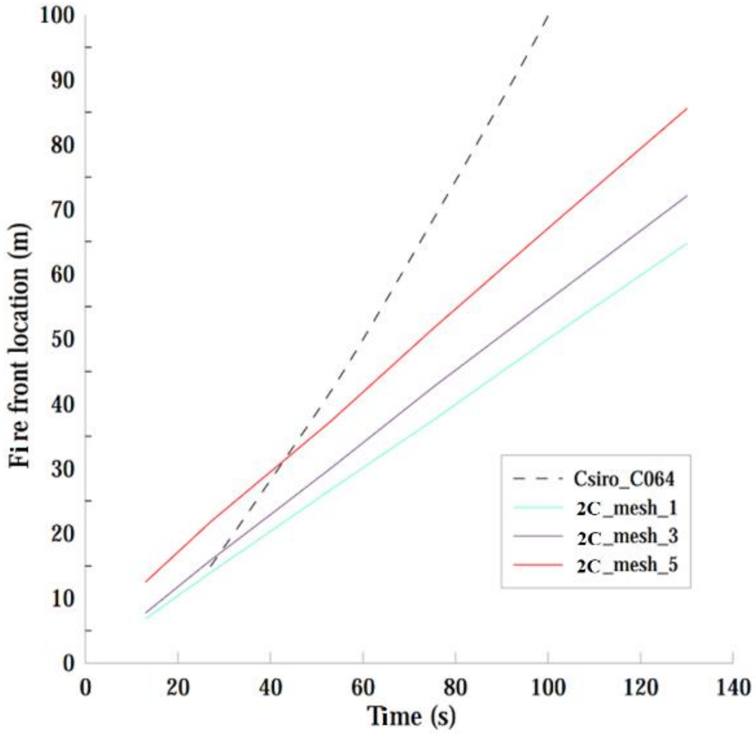

Figure 1- Comparison of fire front position with experimental data of CSIRO-C064 for different mesh sizes.

3.2. Simulations results

The WFDS *Level Set Method* in its two modes, namely one-way (1C) and two-way (2C) fire-wind coupling, is utilised to perform simulations under different conditions to assess the effect of the type of coupling on the prediction of the wildfire propagation. Fire simulations are performed in a 100×100×20 m^3 (x,y,z) domain with a uniform mesh size of 1×1×1 m^3. This results in 100 cells in the x-, 100 cells in the y-, and 20 cells in the z-direction. The fuel is modelled by the type 1 Rothermel-Albini fuel model called "short grass", with a fuel depth of 0.3 m and no-wind no-slope RoS_0 = 0.03 m/s (McGrattan et al. 2019). Fire is ignited at the centre of the fuel area after the wind field has developed. The first mode consists of using a frozen wind field, which is the one developed by the time the fire is ignited. The wind field remains constant for the duration of the simulation. The second mode is a fully coupled simulation, in which the wind is affected by the fire latent heat as it propagates. Figure (2) presents the burnt area 100 s after the fire is ignited, over plain vegetation, for four wind speeds between 1 m/s and 10 m/s, and for both coupling modes: figures (a-d) for one-way coupling or static wind field (1C), and figures (e-h) for two-way coupling or dynamic-wind field (2C). Figure (3) shows the same but in the presence of an obstacle to study the effect of the formation of complex wind structures on the fire propagation.

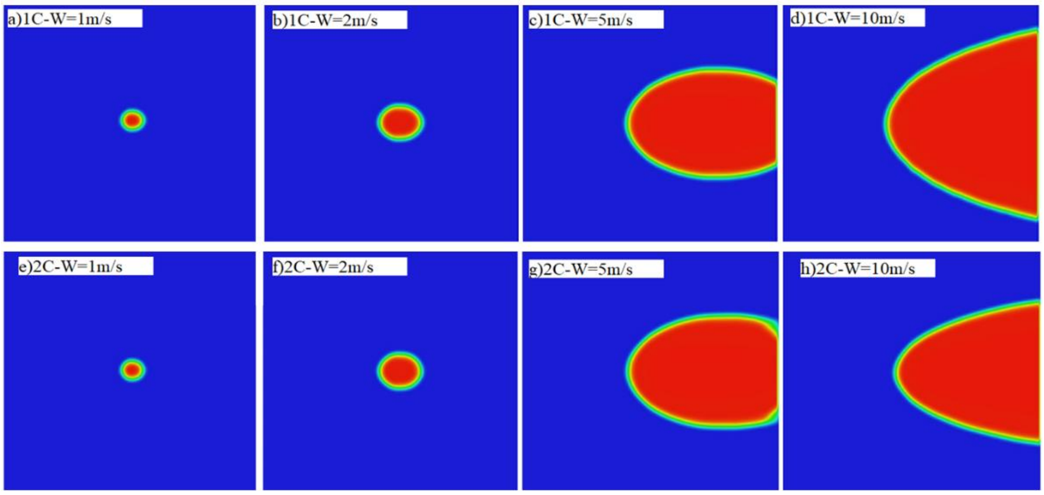

Figure 2- Burnt area at plain surface vegetation in one-way coupling (1C) and two-way coupling (2C) modes.

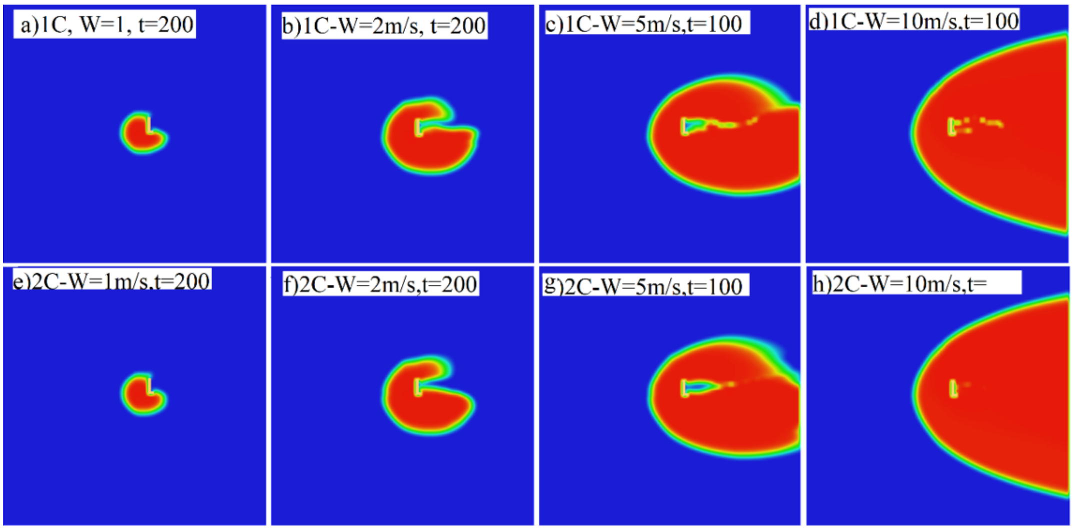

Figure 3- Burnt area at the plain surface with obstacles in one-way coupling (1C) and two-way coupling (2C) modes.

Results indicate that the burnt area is smaller for fully coupled simulations than for frozen wind field, and this difference appears to increase as the fire front propagates. In fact, the RoS is slower in two-way than in one-way coupling, which agrees with (Lopes et al., 2017). For the case with an obstacle, the wind field is highly dynamic, and the fire lines differ significantly depending on the coupling. Furthermore, increasing the wind speed (especially above 5 m/s), the fire intensity increases significantly and the RoS increases exponentially.

Figure (4) presents the fire area for a wind speed of 5m/s at different stages of fire propagation in 1C and 2C modes. As can be seen, the area and shape of the burnt area and fire front at different times of the fire propagation differ substantially. The fire front in two-way coupling is affected significantly by the wind structure. This is directly related to the in-draft flow caused by the convection column, which is not accounted for in the frozen wind field approach and becomes more dominant as the fire propagates over a larger area.

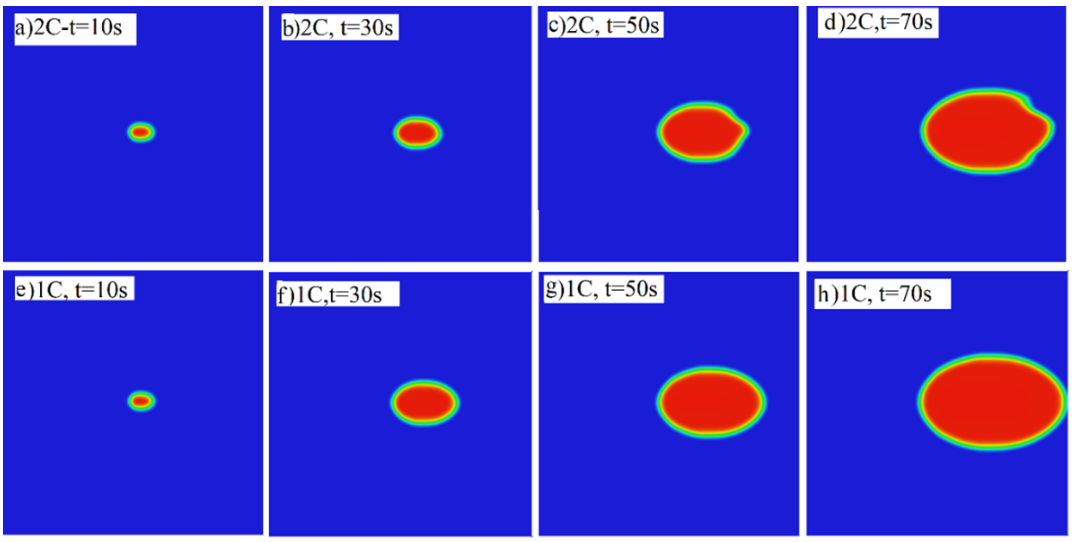

Figure 4- Burnt area at plain surface vegetation in one-way coupled (1C) and two-way coupled (2C) modes at different times.

Figure (5) presents the wind field around and above the fire, which induces the shape of the fire front. The wind which passes above the fire is heated by the latent heat and moves upwards (updraft column). This induces an inward wind field (indraft flow) from the flanks towards the centre line of the fire (green lines), which in turn induces the new shape of the fire front and reduces its RoS compared to the one-way coupling. Figure (6) presents the wind field at different times of the fire propagation for the cases with and without obstacles in wind speed equal to 5 and 4.6 m/s, respectively, with the fire line depicted in white. The indraft flow at the rear sides of the front fire is clearly visible (figure 6 a-e). Besides, a low-speed zone which turns to recirculation flow forms in front of the fire. This seems to be responsible for reducing the fire RoS in two-way coupled simulations. Variations of the vortex area and structure behind the obstacle is depicted in figure (6 f-j). It is indicated that the area of the vortex behind the obstacle is reduced as the fire front propagates, yet it is the main responsible for the slow propagation of the fire front behind the obstacle, especially in two-way coupled simulations.

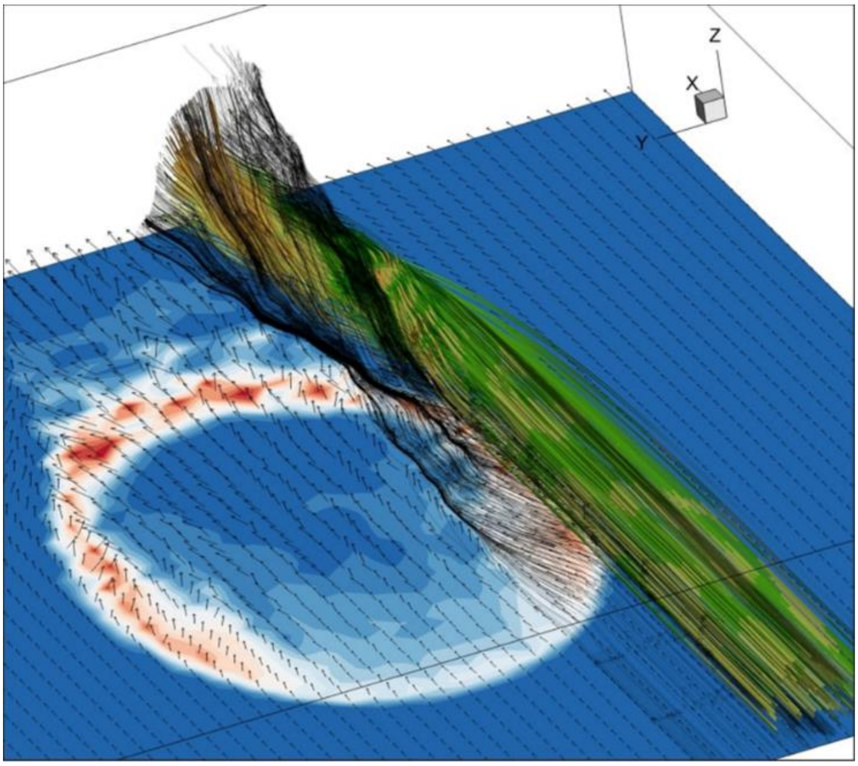

Figure 5- Wind field around and above the fire line.

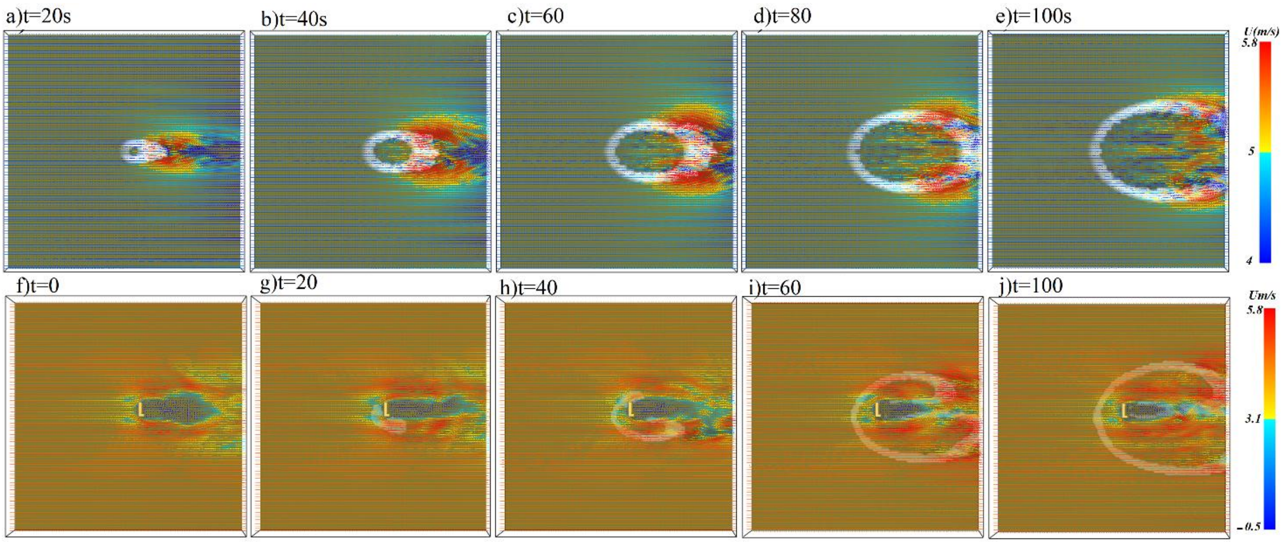

Figure 6- Wind field at z = 1m above the ground in different stages of fire propagation.

4. Conclusion

This paper discusses the effect of utilising one-way and two-way fire-wind coupling strategies on the simulation of wildfire propagation on a flat land covered with short grass, with and without the presence of obstacles. It is observed that the rate of spread (RoS) of the front line in the two-way fire-wind coupling is lower than that for one-way coupled simulations. It is hypothesised that the main reason for this behaviour is the formation of the indraft flow from the back front and flanks of the fire front caused by the updraft column convection, as well as the formation of wind recirculation (vortex) zones in front of the fire line. It is also observed that the vortex structure behind the obstacle becomes smaller as the fire spreads behind the structure, and yet it reduces the fire propagation speed and its intensity in these areas.

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