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Accounting for the canopy drag effects on wildland fire spread in coupled atmosphere/fire simulations

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Abstract (237/500 words)

Since near-surface wind is the main influential parameter governing the rate of fire spread (ROS), its characterization remains key to simulate wildland fire behavior. The correct representation of the intensity and variability of the near-surface wind under complex terrain and vegetation remains an open problem but is essential to make a coupled atmosphere-fire model applicable to actual wildfires. In this work, we study the impact of canopy drag effects on the near-surface flow and the fire behavior simulated by the coupled Meso-NH/BLAZE model in the context of the FireFlux I experimental grass fire for which trees were located upstream and on the flanks. Drag effects can be activated in Meso-NH run in large-eddy simulation (LES) mode following work by Aumond et al. (2013) using SURFEX land surface platform. The drag approach formulation consists of adding drag terms to the momentum equation and subgrid turbulent kinetic energy dissipation as a function of the foliage density. This approach is compared to the standard roughness approach, where a different surface roughness coefficient is applied for the grass and tree areas. Results show the dynamical influence of the surrounding trees on the incoming atmospheric flow that is known to have a significant impact on the fire front propagation in the FireFLux I experiment following work by Costes et al. (2021). Results also indicate that the choice of drag effect parameterization, due to the difference in the represented physics, induces differences on the simulated fire front propagation. This encourages us to explore different options to accurately represent the surface boundary layer in presence of complex vegetation for coupled atmosphere-fire modeling in future work.

1. Introduction

Coupled atmosphere-fire models (Kochanski et al. 2013; Filippi et al. 2018; Costes et al. 2021) are both an efficient and representative way to simulate wildland fire behavior at landscape-to-meteorological scales. They can predict the fire front propagation at the land surface, the fire plume dynamics, and the different interactions they can have. The complex plume dynamics coming from the thermo-convective instability and its retroactive feedback can significantly modify the near-surface wind, enhancing the fire front propagation during a wildland fire event. In coupled atmosphere-fire models, the atmospheric model is run in large- eddy simulation (LES) mode at very high resolution (<100 m) and is coupled with a fire spread model that typically includes a rate of spread (ROS) parameterization and a 2-D front-tracking numerical scheme: see WRF/SFIRE (Mandel et al. 2011), WRF/FIRE (Cohen et al. 2013; Muñoz- Esparza et al. 2018), Meso-NH/FOREFIRE (Filippi et al. 2009) and more recently Meso-NH/Blaze (Costes et al. 2021). In a two-way coupling mode, the fire model requires from the atmospheric model the near-surface wind at a given height to evaluate the ROS and propagate the fire front. In return, it provides surface heat fluxes as surface boundary conditions to the atmospheric model. The counterpart is that parameterization of both the ROS (Rothermel et al. 1972; Balbi et al. 2009) and the surface heat fluxes is required and takes as input a large number of environmental factors related to biomass fuel properties, near-surface wind and terrain slope conditions. These input parameters are partially known (Jimenez et al. 2008) and thereby introduce uncertainties in the coupled model simulations. One way to deal with complex vegetation through these parameters would be either to adopt a stochastic viewpoint (i.e. to run an ensemble of coupled simulations), or to use a land cover database (e.g. ECOCLIMAP, (Masson et al. 2003)) to have a detailed description of the vegetation types and take advantage of the high-resolution simulations. The latter

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would allow us to represent both the influence of the vegetation on the wildland fire and on the atmosphere. The main issue addressed in this work is to integrate a land surface modeling approach to the already-existing coupled atmosphere/fire modeling framework so as to represent the dynamical effects of forest canopy on the atmospheric flow and their impacts on wildland fire spread. This is of first importance to extend the applicability of coupled atmosphere/fire models to forest environment and pursue their validation for different types of vegetation.

2. Coupled Atmosphere/Fire Modeling Framework

In the present study, we use the coupled Meso-NH/BLAZE model to simulate the FireFlux I experimental grass fire (Clements et al. 2007). We briefly present Meso-NH/BLAZE in this section. More details can be found in Costes et al. (2021).

2.1. Description of the coupled Meso-NH/Blaze model

Meso-NH (Lac et al. 2018) is a non-hydrostatic anelastic atmospheric model of the French research community, jointly developed by CNRM (Météo-France/CNRS) and Laboratoire d’Aérologie (Université de Toulouse/CNRS). It is used to simulate meso-scale (few kilometers to less than thousand kilometers) up to micro-scale (less than hundred meters) atmospheric flows. For the present wildland fire application, Meso-NH is run in LES mode to simulate the atmospheric flow in the surface layer at decametric horizontal resolution ($\Delta x = 25$m resolution in the present study as in Costes et al. (2021)). BLAZE (Costes et al. 2021) is a fire spread model that relies on i) Balbi’s ROS parameterization adapted for landscape-scale wildland fires (Santoni et al. 2011); ii) a two-dimensional level-set front-tracking numerical approach to propagate the fire front at the land surface; and iii) surface heat flux parameterization including flaming and smoldering contributions. A subgrid-scale fire front reconstruction is implemented in BLAZE to have a good localization of the surface heat fluxes without significantly constraining the fire model resolution ($\Delta xf = 5$m resolution in the present study as in Costes et al. (2021). In a two-way coupling mode, Meso-NH and BLAZE interact as follows: the near-surface wind simulated by Meso-NH at a given reference height (2 m above ground level as in Costes et al. (2021) is interpolated at BLAZE resolution, and is projected along the normal direction to the fire front; it is then given as input to the ROS parameterization. The surface heat fluxes simulated by BLAZE are given as surface boundary conditions to Meso-NH with a vertical distribution following an exponential decay over the first 30 m above the ground level as in Costes et al. (2021).

Figure 1 – Illustration of a coupled Meso-NH/BLAZE simulation of the FireFlux I experiment (without considering the trees near the burn plot).

2.2. Validation of the fire-atmosphere coupled modeling

The FireFlux I experiment (Clements et al. 2007) has been used to provide a first evaluation step of the coupled Meso-NH/BLAZE model. It corresponds to an experimental prescribed burn of 15 min on a flat terrain with tall grass. The burn plot of approximately 30 ha was instrumented with two towers equipped with thermocouples and anemometers at different heights (within the first 50 m above the ground level). In previous work, Costes et al. (2021) have simulated the FireFlux I experiment using the coupled Meso-NH/BLAZE model without considering the trees near the burn plot, i.e. the vegetation was considered as homogeneous tall grass for the whole computational domain and the impact of tall grass on the surrounding atmosphere was represented using the standard roughness approach (Figure 1). Simulation results (in terms of fire front positions and near-surface atmospheric variables such as the horizontal and vertical wind components at different heights) showed good agreement with the experimental measurements. In complement, Costes et al. (2021) have verified the validity of the anelastic approximation by developing a compressible version of Meso-NH to account for the three-dimensional density gradients in the vicinity of the fire front and by comparing results in anelastic and compressible modes for the FireFlux I experiment. Results in the two-way coupled mode have shown that the anelastic approximation for Meso-NH is suitable to represent wildland fire behavior, except for details of the plume if the atmospheric model horizontal resolution is of 10 m or finer. The anelastic approximation is therefore relevant to study canopy drag effects on wildland fire behavior at decametric resolution in the present study. Even though coupled simulations were reduced to a simple flat terrain with uniform vegetation in previous work, Costes et al. (2021) demonstrated the importance of atmospheric variability due to turbulence on the fire front propagation. This is a key result, which motivates the further development of the coupled Meso-NH/BLAZE model towards a more complex representation of the terrain surface and in particular of the vegetation. The objective in the present study is to account for the presence of trees upstream and on the sides of the burn plot (Figure 1), and to evaluate its impact on the near-surface flow and subsequently on the fire front propagation

3. Coupled MesoNH/Blaze/SURFEX simulations including canopy drag effects

To consider a more realistic fuel in the coupled atmosphere/fire simulations, it is of primary importance to have a better representation of the fuel behavior in response to the development of the fire but also of the fuel influence on the atmospheric flow. This implementation will be done via SURFEX (Masson et al. 2013), a surface modeling platform also developed by CNRM (Météo-France/CNRS). This model was originally aimed to better simulate energy and water exchanges between the land surface and the atmosphere to be integrated into Météo-France’s operational products. It is also of significant interest in research mode to study surface/atmosphere interactions. In the present study, we mainly use the ISBA (Interaction Soil Biosphere Atmosphere) vegetation scheme (Noilhan et al. 1996; Boone et al. 1999; Decharme et al. 2006) in SURFEX to have a more detailed description of the vegetation (grass and forest areas in the FireFlux I case study). Integrating the ISBA scheme into the already existing coupled atmosphere/fire modeling framework (Figure 2) will allow us to go one step further towards simulating actual cases of large-scale wildfires. To account here for the dynamical effect of the vegetation on the atmospheric flow, we first recreated the immediate vegetation close to the field experiment forming some kind of shelter from the atmospheric flow. We then implemented two different methods to account for the canopy’s drag effect on the the fire spread, namely, a roughness approach and a momentum/TKE drag approach.

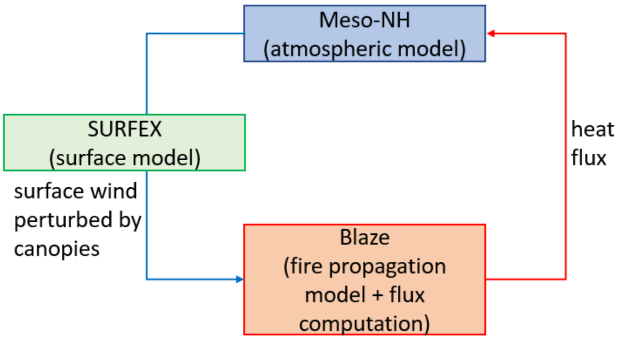


Figure 2 – Schematic of the coupling between Meso-NH, BLAZE and SURFEX with the additional component SURFEX to account for the tree's drag on the the fire spread.

3.1. Classical log-law parameterization

The classical approach, referred to as the standard roughness approach, in large-scale atmospheric models is to have a log-law with characteristics such as roughness length and zero plane displacement that depend on the surface type. This approach, initiated by Von Kármán (1930), revisited by Monin and Obukhov (1954) to take stability into consideration, supposes that the wind profile starts at a given height with a logarithmic profile. However, for LES, the fine horizontal resolution would allow us to represent the wake circulation behind obstacles (a tree barrier for example). Such complex flow feature cannot be fully accounted for using the classical log-law parameterization.

3.2. TKE and conservation of momentum parametrization

To include more physics into the LES, an alternative approach consists in incorporating a drag force directly into the atmospheric model dynamic equations. Using Kanda and Hino's (1994) parameterizations and following Aumond et al. (2013), an additional term is introduced to the momentum equation as follows:

$$\frac{\partial u_i}{\partial t} = A_{dv} + C_{or} + P_{res} + T_{urb}(u_i) - \; C_d A_f(z) u_i (u_1^2 + u_2^2)^{\frac{1}{2}} \quad i \in \{1,2\} \qquad (1)$$

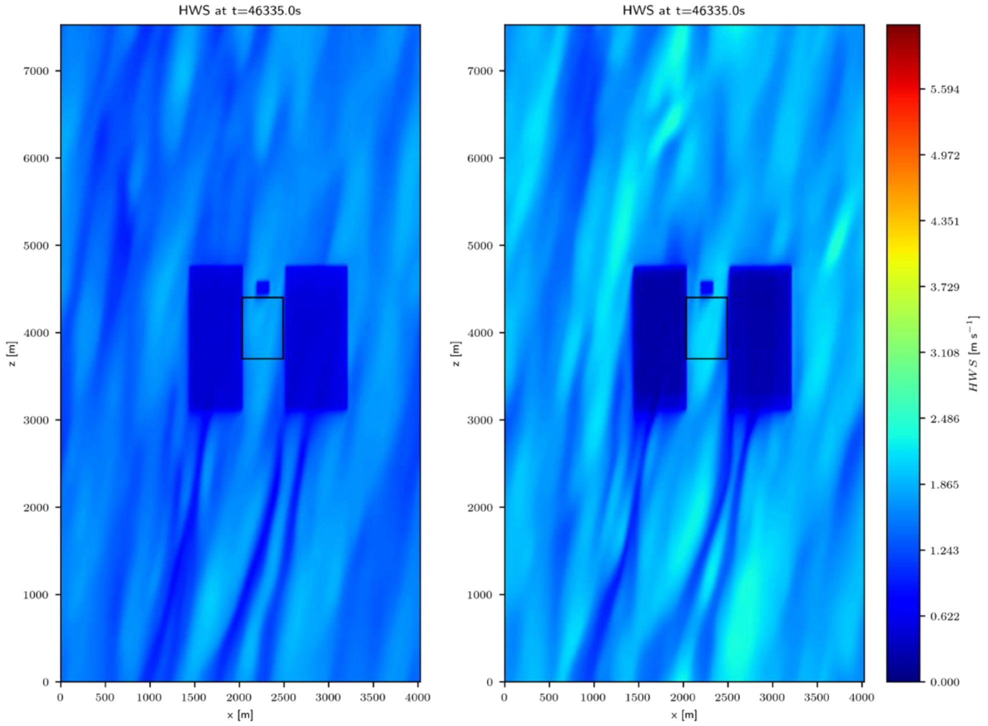
where (u_1, u_2) corresponds to the two horizontal wind components [*m/s*], A_{dv} is the advection term, C_{or} is the Coriolis force term, P_{res} is the the pressure gradient term, T_{urb} is the turbulence term, C_d is the canopy drag coefficient [-], and A_f (z) is the canopy area density $[m^{-1}]$ (this is a combination of the leaf area index (LAI), the fraction of vegetation in the grid cell and a function that represents the shape of the trees). To account for the subgrid-scale effect of trees on small-scale turbulence (trees have elements much smaller than the atmospheric grid mesh), additional dissipation is added into the turbulent kinetic energy (TKE) equation:

$$\frac{\partial e}{\partial t} = A_{dv} + D_{ynProd} + T_{hermProd} + T_{urbT}(u_i) - D_{iss-} \; C_d A_f(z) e (u_1^2 + u_2^2)^{\frac{1}{2}} \qquad (2)$$

where e is the subgrid TKE $[m^2/s^2]$, D_{ynProd} and T_{hermProd} are the dynamic and thermal productions, T_{urbT} denotes the turbulent transport and D_{iss} is the dissipation. This approach, referred to as the TKE/momentum drag approach, is particularly interesting for our wildland fire application since it directly links vegetation parameters, which can be inputs from a database, to drag force through the Cd and Af coefficients.

3.3. Results

We present a first comparison of the coupled Meso-NH/SURFEX simulations of the spin-up step of the FireFlux I case study that account for the forest canopy effect through either the standard roughness approach or the TKE/momentum drag approach (Figure 3). In Figure 3, the dark blue areas correspond to trees, while the rest of the domain is covered by tall grass. The burn plot is delimited by the empty black rectangle. It is worth mentioning that this spin-up step is required prior to the fire ignition to have realistic inflow conditions that correspond to in situ observation measurement statistics (Costes et al. 2021). This is a preliminary step before running the coupled Meso-NH/BLAZE/SURFEX simulations. The two approaches seemed to lead to very similar flow structures at first although the physics involved is very different but several differences can be spotted. The first main difference is that the momentum/TKE approach dissipates less compared to the standard roughness approach, leading to higher near-surface wind speed. This is of particular interest in the context of wildland fire behavior simulations. The second main difference in the case of the momentum/TKE approach, is the presence of more coherent structures coming from the wake of canopies, possibly due to a slightly better representation of the porosity of the vegetation than in the case of the classical log-law parameterization.



a) Roughness approach (b) Momentum/TKE parametrization

Figure 3 – Simulation of the horizontal wind speed [m/s] for the spin up step of the FireFlux I experimental grass fire, taking into account the immediate tree canopies around the burn plot with the two different approaches: (a) standard roughness approach; and (b) TKE/momentum drag approach. The burn plot is delimited by the black solid lines, and the trees are located in the dark blue areas (the rest of the vegetation, including the burn plot, is set as grass.

4. Conclusions

This study presents a prototype of a coupled atmosphere/fire model based on the coupled Meso-NH/BLAZE/SURFEX system, in which a vegetation scheme capable of representing the drag of forest canopies is integrated through the ISBA scheme of SURFEX. This study assumes that the immediate trees next to the FireFlux I experimental burn plot account for most of the vegetation dynamical influence on the incoming atmospheric flow. The results obtained for the spin-up step of the coupled simulations indicate that the canopy drag affects the overall regime of the atmospheric flow surrounding the burn plot. The canopy drag will therefore have an influence on the fire spread but the choice of parameterization for the turbulent boundary layer may also be decisive. In the short term, future work aims at extending the analysis of the canopy drag effects for the FireFlux I experimental grass fire and at investigating if the sensitivity of the fire spread to the inflow variability is stronger when considering canopy drag effects or not. In the long term, future work aims at enhancing the representation of the wake due to complex vegetation and shifting towards the simulation of large-scale wildland fire in forest environment. Other methods, such as the promising immersed boundary layer (IBM), recently implemented in Meso-NH (Auguste et al. 2019), could also be investigated.

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