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Effect of Spatiotemporally Varying Fuel Moisture Content on Turbulence Statistics During Fire Propagation

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Abstract

Prescribed burns are valuable tools utilized for land management. They serve the purpose of reducing the risk of wildfires by lowering the build-up of dry fuels, improving forest health, and controlling the growth of plants and insects. One of the crucial components that affects the execution of prescribed burns and controls the fire behaviour and smoke dispersal thereafter is the fuel moisture content, which needs to be considered when planning prescribed burns. The fuel moisture content variation is dependent on the meteorological variables, fuel properties, and the local turbulent fire dynamics, and so varies spatially and temporally over the land area before and during the fire advancement. In previous studies, the fuel moisture content was treated based on average properties, independent of the effect of local turbulence. In this study, the spatiotemporally varying fuel moisture content is obtained by a physics-based model that considers the coupled energy and moisture balance dynamics inside the fuel layers. This moisture model is implemented into the Wildland-urban Interface Fire Dynamics Simulator (WFDS) by means of a two-way coupling. Along with the local fuel properties, the model uses the instantaneous solar radiation and relative humidity, together with the instantaneous turbulent wind velocity and ambient air temperature at the boundary of each fuel sub-surface (grid) in the simulation domain. The coupled model is employed to study the effect of the dynamic variations of the fuel moisture on the turbulent evolution of the fire plume during a line fire propagation over a flat grassland. The findings of the study will provide insights into the effect of the fuel moisture content on the plume dynamics and smoke dispersal during prescribed burns and will assist in planning these burns.

1. Introduction

Prescribed fires, also known as controlled burns, are planned and controlled applications of moderate to low intensity fires under specific atmospheric conditions. In addition to mitigating wildfires, prescribed fires are essential for maintaining the health of fire-dependent ecosystems. In fire-dependent ecosystems, prescribed fires serve the purpose of: (1) regulating the buildup of dry fuel, (2) controlling the growth of plant species, insects, and parasites, and (3) improving the health of the soil (Heinselman and Wright, 1973). In addition, prescribed fires help with training firefighters and prepare them for the required actions during wildfires. The smoke from prescribed fires, however, may be troublesome for the neighboring communities. It may substantially impact the air quality and increase the risk of road accidents. When the plumes from prescribed fires penetrate the troposphere, they add smoke aloft, which impacts regional as well as global scale climate for instance by reducing insolation and altering the cloud microphysics (Lareau and Clements, 2017). Contradictory to this, when the plumes remain restricted to the atmospheric boundary layer, they affect the local population by posing health hazards in the nearby communities. These near-field plumes bring about persistent temperature inversions, unanticipated patterns of smoke transport, and could pose a travel risk by reducing visibility.

An important factor that influences the fire plume dynamics, as well as the fuel flammability, fire propagation behavior, and the burn plan is the fuel moisture content (FMC). FMC is influenced by the vegetation characteristics, the background atmospheric conditions, and the local fire-induced turbulent airflow and temperature during the fire. Therefore, as a result of the instantaneous variations in solar radiation, relative humidity, and the local turbulent wind velocity and air temperature the FMC varies both spatially and temporally at the fuel boundary. While there are studies that investigate temporal variations of the FMC using empirical models (Alves, 2009; Slijepcevic, 2013) and physics-based models (Wittich, 2005; Matthews, 2006), an

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understanding of the spatiotemporal turbulent variations of the FMC at the fuel boundary during fire events is missing. In this study, we aim to examine the effects of the dynamically varying FMC on the turbulence statistics of the flow and plume dynamics during a line fire using a coupled fire-atmospheric interaction model that considers the spatiotemporal variations of the fuel moisture content.

2. Model Description and Simulation Setup

The change in the FMC is modelled by utilizing a physics-based FMC variation model (Matthews, 2006). The model represents the transfer of energy and water and their two-way interactions in a fuel bed, which is bounded between the atmosphere and soil surface. The fuel bed is comprised of multiple layers of fuel and each layer is made up of three components of the fuel solid, air, and free liquid water. The model is controlled by precipitation, diurnal solar radiation, the local wind speed and ambient air temperature, relative humidity, and the physical properties of the fuel (e.g., the surface to volume ratio, packing ratio, and height of the fuel bed). The energy and moisture balance equations (Eq. 1 and 2, respectively) are solved inside each layer in a coupled way to obtain the FMC (m).

$$C_{h,m}\frac{\partial T_m}{\partial t} = \frac{1}{V_m}\left(\frac{\partial R_{net}}{\partial z} + \frac{\partial H_C}{\partial z}\right) - \mu_{m,a}H_{ma} - \mu_{m,a}\lambda E_{ma} - \mu_{m,l}H_{ml} \tag{1}$$

$$\rho_{air}\frac{\partial m}{\partial t} = -\mu_{m,a}E_{ma} - \mu_{m,l}E_{ml} \tag{2}$$

Here, the energy budget equation (Eq. 1) models the variations of the fuel temperature (T_m) with time. In these equations, $C_{h,m}(Jm^{-3}K^{-1})$ and $V_m(m^3m^{-3})$ are the volumetric heat capacity and volume fraction of the fuel solid. $\mu_{m,a}(m^{-1})$ and $\mu_{m,l}$ (m^{-1}) are, respectively, the surface area-to-volume ratio at the interface between the fuel solid and air and at the interface between the fuel solid and the intercepted liquid water. λ (Jkg^{-1}) and ρ_{air} (kgm^{-3}) are the latent heat of vaporization of water and density of air. R_{net} (Wm^{-2}) is the net radiative heat flux, H_C (Wm^{-2}) is the heat flux due to conduction, H_{ma} (Wm^{-2}) is the sensible heat flux at the fuel boundary, E_{ma} $(kgm^{-2}s^{-1})$ is the moisture flux between the litter solid and air, H_{ml} (Wm^{-2}) is the heat flux between the fuel solid and the intercepted liquid water, and E_{ml} $(kgm^{-2}s^{-1})$ is the moisture flux between the fuel solid and the intercepted liquid water.

The FMC model is coupled with the Wildland-urban interface Fire Dynamics Simulator (WFDS) in a two-way manner to allow for the investigation of the FMC variation effects on the fire and plume dynamics. WFDS is a large-eddy simulation (LES)-based model that simulates the fire-atmospher interactions. In the two-way coupling, the FMC model utilizes the instantaneous information of the meteorological conditions and the fire-induced flow from WFDS and provides the instantaneous fuel moisture content to WFDS at each timestep.

In this study, the coupled model is used to investigate how the instantaneous changes of the fuel moisture due to the turbulent interactions at the fuel boundary affect the fire and plume behavior in a case of a line fire in a flat grassland. The domain size and grid resolutions are found through sensitivity analyses and the first and second-order turbulence characteristics of the flow and plume dynamics, as well as the fire propagation behaviour under the effect of dynamic FMC change is investigated. The results are also compared against cases with constant FMC and with no fuel moisture. Findings of this study provides a better understanding of the role of fuel moisture in fire behavior and near-field plume structure and dynamics.

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