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Assessment of ForeFire/Meso-NH for wildland fire/atmosphere coupled simulation of the FireFlux experiment

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Abstract

Numerical simulations using a coupled approach between Meso-NH (Non-Hydrostatic) LES (Large Eddy Simulation) mesoscale atmospheric model and ForeFire wildland fire area simulator are compared to experimental data to assess the performance of the proposed coupled approach in predicting fine-scale properties of the dynamics of wildland fires. Meso-NH is a non-hydrostatic, large eddy simulation capable, atmospheric research model. ForeFire insures a front tracking of the fire front by means of Lagrangian markers evolving on the earth's surface according to a physical rate-of-spread model. The atmospheric model forces the fire behavior through the surface wind field, whereas the fire forces the atmosphere simulation through surface boundary conditions of heat and vapor fluxes. The FireFlux experiment, an experimental 32 Ha burn of tall grass instrumented with wind profilers and thermocouples, was designed specifically to estimate the atmospheric perturbation introduced by wildland fire. Comparisons of the simulations at different resolutions with the large-scale experiment validate the chosen coupling methodology and the choice of a coupled approach with a meso-scale atmospheric model for the prediction of wildland fire propagation. Distinct fire propagation behavior is simulated between coupled and non-coupled simulation. While the simulations did not reproduce high frequency perturbations, it is shown that the atmospheric model captures well atmospheric perturbations induced by combustion at the ground level in terms of behavior and amplitude.

Keywords: Wildland fire; Atmosphere; Simulation; Plume; Coupled model

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1. Introduction

Although a natural process in most parts of the world, wildland fires represent a constant threat wherever there exists an interface with human activities. Whereas it is well known that large wildland fires can create their "own weather," many earlier studies on wildland fire behavior neglected the feedback from the fire to the atmosphere, until more recently when several numerical studies on atmosphere/fire coupled behavior [1–3] showed the strong influence atmospheric coupling has on the behavior of the fire.

When simulating large wildland fires the user first has to choose the accuracy of the models depending on the computational framework (what

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computation power? how much time?) and available data. The variety of models at hand ranges from physically detailed, fire/atmosphere coupled and computationally intensive models such as FIRETEC [2] or WFDS [4] to more behavioral models that can work at real scale such as FARSITE [5].

The proposed approach has been developed to enable numerical fire/atmosphere coupling between available meso-scale atmospheric models (WRF, MesoNH, ...) with the family of fire area simulators. Numerical fire/atmosphere coupling has already undergone numerous studies, starting from the static fire simulations of [6] to more recent works where a simplified fire spread model of Rothermel [7] type is coupled with the so-called Clark–Hall atmospheric model [1] or the WRF mesoscale model [3]. While efforts at simulating coupled effects were fruitful even at the scale of large fires (several square kilometers), and with a relatively high degree of fire front precision, the use of Rothermel model may be subject to limitations as effects of wind and slope on the rate of spread is expressed through coefficients that are experimentally fitted to wind values. Wind predictions are then to be issued as if the fire was not there and no local heterogeneous change in the fire/atmosphere coupling can be taken into account.

In an effort to tackle these problems, a fire area simulator, named ForeFire, based on the propagation speed model of [8] has been developed. In order to investigate fire/atmosphere coupling while aiming for operational use, the ForeFire simulation code has been coupled with the Meso-NH model [9]. In an approach similar to [1], the mesoscale atmospheric model is coupled to a reduced front-tracking, wildfire model. This setup allows investigations of the differences induced by the atmospheric feedback in terms of propagation speed and behavior. The uniqueness of this configuration resides in the fact that Meso-NH is run in a Large Eddy Simulation (LES) mode and that the rate of spread model used in ForeFire provides a physical formulation to take into account effect of wind and slope.

2. Presentation of the models

The effects of the atmosphere on fire behavior (wind, humidity, ...), while not always well documented, are taken into account in most fire simulators. In our case, these phenomena are embodied in the theoretical model for the propagation velocity of [8]. Concerning the feedback from the fire on the atmosphere, one should take into account several phenomena such as mass, momentum and energy injection, and even modification of the roughness of the canopy and so on. In these preliminary studies we will limit ourselves to first order phenomena influencing the dynamics of the atmosphere, *i.e.* water vapor and heat fluxes.

2.1. Meso-NH atmospheric model

Meso-NH is an anelastic non-hydrostatic meso-scale model [9], intended to be applicable to all scales ranging from large ($\sim$1000 m) to small scales ($\sim$10 m) and can be coupled with an on-line atmospheric chemistry module [10]. A joint effort of the Centre National de Recherche Météorologique and Laboratoire d'Aérologie. it comprises several elements; a numerical model able to simulate the atmospheric motions, ranging from the large meso-alpha scale down to the micro-scale. Primary meteorological variables (pressure, velocity and temperature) are advected with a centered 4th order scheme, while scalars and other meteorological variables (such as water vapor fraction) are advected with a so-called monotonic Piecewise Parabolic Method [11]. Temporal derivatives are computed following the so-called leapfrog algorithm.

In this study Meso-NH is run in Large Eddy Simulation configuration as the typical size of the structures stemming from the fire forcing is typically several hundreds of meters. Due to the lack of chemical observations, and the computational cost of simulating chemistry ($\sim$500% augmentation), the authors chose to overlook the chemical issues and focus on the effects of the fire forcing on the atmospheric flow in the lowest layers.

2.2. Fire propagation model and simulator

The propagation model for the fire front is based on the assumption that the front propagates in the normal direction to the front. To obtain an analytical formulation for the rate of spread the fire is considered as the sum of a "conductive" part (vegetation under pyrolysis) and a flame heating the vegetation in front of it [8]. The model accounts for slope, atmospheric properties (wind velocity $\vec{v}$, air density ρ_a and temperature T_a), spatial characterization of the fuels (mass loading σ, height e, emissivity ϵ_v and moisture content m (fraction of water over total weight)) and the fuel combustion properties (ignition temperature T_i, calorific capacity $c_{p,v}$, combustion enthalpy Δh, stoichiometry s and mass exchange rate due to pyrolysis $\dot{\sigma}$). It is assumed that only a given portion χ_0 of the total combustion energy is released as radiation, and that the flame can be modeled as a tilted radiant panel with 2 parameters: flame tilt angle towards the unburnt fuel γ and front depth λ. The equation governing the propagation velocity of the front reads [8]:

$$R = R_0(\epsilon_v, T_i, e, \sigma, m, T_a) + \chi_0 \Delta h \dot{\sigma} f(\lambda, \gamma), \qquad (1)$$

where $R_0 = \epsilon_v B T_i^4 e / 2\sigma[c_{p,v}(T_i - T_a) + m\Delta h_w]$ is the contribution of the vegetation undergoing pyroly-