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Development of a fire-smoke modelling system to integrate crown fire behaviour

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Abstract

Over the last decades, several real-time air quality forecasting systems have been developed worldwide to support decision-making to control and manage anthropogenic pollution and its impacts. However, the current forecast systems do not, in general, integrate wildfire emissions. In Portugal, from 1996 to 2021, a cumulative area of 3 Mha burnt by rural fires was registered, accounting for roughly half of Portugal's continental area, causing damage to infrastructure and lives, and in particular impacting the quality of the air and human health. The ability of modelling tools to predict the behaviour of fire smoke is fundamental to effectively improve the accuracy of air quality forecasting and preventing public health consequences. There is a wide variety of models available to simulate fire-smoke phenomena. Nonetheless, it is necessary to consider computational aspects, resources, and goals to choose a suitable model to fit the purpose. In the ongoing FIRESMOKE project, the weather forecast model BRAMS-SFIRE version 5.0 is implemented to be part of the new version 5.6.2 of BRAMS. The BRAMS-SFIRE model was coupled to simulate a broad integration between the surface fire fluxes and the atmospheric environment and presented a good accuracy in terms of the physics of the atmosphere and fire interaction. FIRESMOKE also aims to improve the SFIRE model by including the crown fire behaviour. A predictive model for surface fire spread adapted for the timber litter and understory fire behaviour fuel model and conceptual predictions for the behaviour and size of crown fires, including conditions for the crown fire starting and spreading, were incorporated in the SFIRE model by linking these models with the existent surface fire spread and the numerical scheme of propagation. Furthermore, the smoke emitted by the fire, which spread is estimated with the new approach, was entered into the chemistry module of BRAMS. The goal of this paper is to present the BRAMS-SFIRE developments oriented toward the creation design of a FIRESMOKE system for forecasting and monitoring forest fire smoke emissions that also incorporate anthropogenic and biogenic sources of air pollution, to provide a public access service in the scope of air quality over the domain of continental mainland Portugal.

1. Introduction

Smoke integrated framework modelling systems have been implemented worldwide using a combination of independent models, generally providing smoke transport and pollutant concentrations, forecasting air quality, and producing alerts for the risk of high pollution caused by wildland fires. There are three main framework systems in the United States of America, the BlueSky (Wheeler et al., 2010), the United States National Oceanic and Atmospheric Administration smoke prediction system (Stein et al., 2009), and the ClearSky (Jain et al., 2007). Australia has implemented the Australian Bureau of Meteorology Smoke Prediction System for wildfires and prescribed burning (Peace et al, 2020). In Europe, the Copernicus Atmospheric Monitoring Service (CAMS, Akritidis et al., 2020) monitors emissions from fires and atmospheric composition using satellite observations and numerical modelling. The Center for Weather Forecast and Climate Studies (CPTEC) at the National Institute for Space Research (INPE) in Brazil provides numerical air quality forecasts with the BRAMS modelling system, including emissions both from fires and urban/industrial sources (Freitas et al., 2017; Longo et al., 2013). In Portugal, modelling studies of air pollution from wildfires have been widely developed by the University of Aveiro (Miranda, 2004; Martins et al., 2012; Valente et al., 2007) which maintains the operational Portuguese air quality forecasting system. However, this system does not integrate wildfire emissions into the atmosphere.

Since Portugal is one of the Southern European countries with a higher number of forest ignitions (Rodrigues et al., 2013), the ability to predict the ignition and spread of forest fires, as well as the behaviour of emitted air pollutants, is important to improve resources management's effectiveness and efficiency, for operations of preventing, detecting and fighting forest fires and monitoring air quality, with repercussions on public health.

The application of a fire-smoke modelling system implies the selection of the models to be included that should take into account aspects, such as computational resources, the required accuracy, and physical phenomena representations. In many cases, the available models interact with each other through downscaling. Only a few models include a broad integration of the atmosphere's dynamic and thermodynamic concepts, comprising surface and soil phenomena interaction with the atmosphere's boundary layer. For high-resolution (meters) applications, this ability is limited to case-studies simulations and, still, with inefficient prognosis simulations of the weather state, and therefore, unsuitable for the fire-smoke forecast with high landscape resolution.

The BRAMS-SFIRE system (Menezes et al., 2016, 2021a; Freitas et al., 2017) aims at overcoming this challenge. BRAMS is continuously under development to better simulate atmospheric processes and the coupled SFIRE simultaneously simulates the interactions between the surface fire fluxes and the atmospheric environment, both on the mesoscale and micro-scale. The BRAMS-SFIRE system, which is the representation of fire spread, presented excellent results in terms of the physics of the atmosphere and fire interaction (Menezes, 2016, 2021a) promising a reliable performance for fire-smoke after the development of the crown fire spread model.

The ongoing FIRESMOKE project (Menezes et al., 2021b) aims to improve the meteorological weather forecast model BRAMS-SFIRE, which also integrates an atmospheric chemistry (CCATT - Eulerian Coupled Chemistry, Aerosol and Tracer Transport) model, with the development of a crown behaviour module. This modelling system operates from meso to local scale and in real-time conditions. The present work is part of this project and describes the incorporation in BRAMS, v5.6.2, of the crown fire propagation and fire smoke pollutants in the chemistry model CCATT.

2. Methodology

2.1. Overview of ongoing fire developments on BRAMS

The SFIRE model (Mandel et al., 2009, 2011) coupled to BRAMS (Freitas et al., 2017) by Menezes (2016, 2021a) allows the analysis of surface fire behaviour taking into account the type of fuel bed and its moisture, the topography and the atmospheric wind. Under the FIRESMOKE project, the developments of BRAMS-SFIRE comprise the up-grade for the last version of SFIRE, the introduction of a mathematical model for predicting surface fire spread (Rothermel, 1972) for fire behaviour fuel model 10 (timber litter and understory) (Anderson, 1982) and of the conceptual model for predicting behaviour and size of crown fires from Rothermel (1991), including conditions for the crown fire starting and spreading for coniferous forest fuel types (Van Wagner, 1977), based on the research of Scott and Reinhardt (2001). This new version of BRAMS-SFIRE, part of the current BRAMS model v5.6.2, would be suitable for the operational forecast of fire size and behaviour, weather, and air quality. This development was designed following the scheme in Figure 1. In this scheme, the crown behaviour introduced in the model is represented in the red boxes, in particular in: the "calculation of the fireline advance" and the "calculation of total fireline intensity".

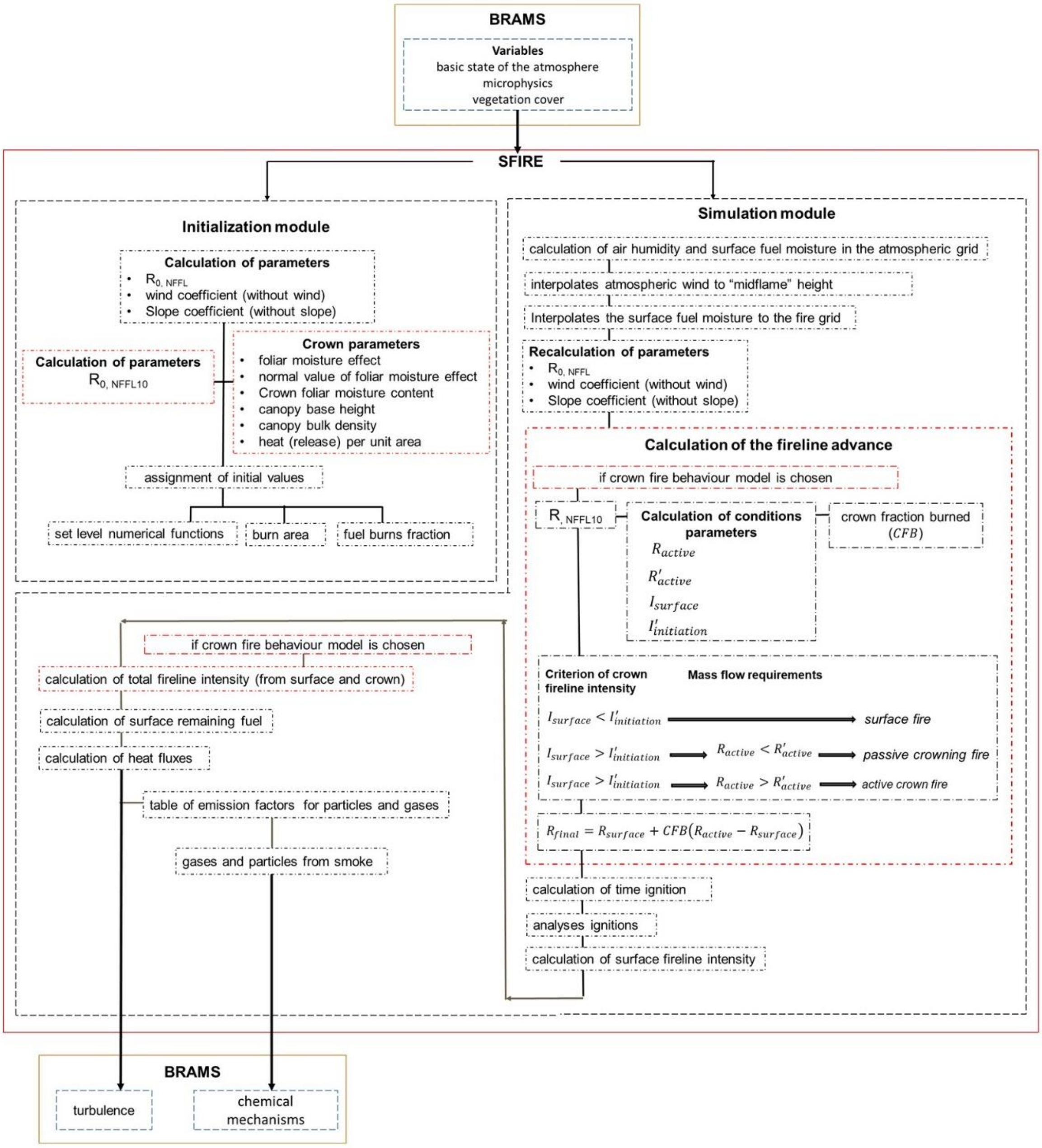

Figure 1- The framework of the BRAMS version 5.6.2 system, with the necessary developments for crown behaviour introduced in the SFIRE model. R is the rate of spread and I is the fireline intensity.

BRAMS-SFIRE, version 5.0, is a one-way coupled fire-atmosphere model. BRAMS injects data from variables of the basic state of the atmosphere, the microphysics, and vegetation cover into the SFIRE, which injects data from variables of sensible and latent heat fluxes from the fire into the boundary layer of the atmospheric model BRAMS, through the turbulence scheme, by carrying out a process of constant exchange during simulation. The SFIRE model uses as surface data high-resolution fuel data on a regular grid, generated using the Northern Forest Fire Laboratory (NFFL) fuel model (Anderson, 1982), and a table with physical and mineral properties, and dendometric measures of the thirteen NFFL fuel models. A new module was built to include the propagation of fire in crown trees by creating new routines and adapting the code of SFIRE's original routines. In this module, the parameters referring to no wind forward rate of spread for a surface fire for NFFL fuel model 10, and the forward rate of spread for NFFL fuel model 10 were programmed. Some considerations were implemented, namely for the crown ignition criteria of Byram's fireline intensity and critical fireline intensity for initiating a crown fire, and the requirements of mass flow, namely, the forward rate of spread for a fully active crown fire and a critical forward rate of spread for sustaining an active crown fire. Depending on the criteria met, a forward rate of spread for any type of fire - surface, passive crown, or active crown - was associated with the level set numerical method from the SFIRE model, which is the numeric propagation scheme (Osher and Fedkiw, 2003). The assessment of crown fire in SFIRE, requires other estimates of canopy fuel characteristics, namely, canopy bulk density (CBD), canopy base height (CBH), and crown foliar moisture content per cent (FMC) and foliar moisture effect (FME) data. The CBD and FME was programmed from a alometric equation and FMC trough read of data in a "namelist.fire" table, and CBH trough read of a map created from Forest Inventory data from 7964 field plots in Portugal, available from Portuguese Institute for Nature Conservation and Forests (ICNF).With the module "sfclyr_sfire", is made the interaction between BRAMS and SFIRE.

2.2. BRAMS and smoke modelling

Atmospheric emissions during fire events were estimated using the most suitable emission factors ($g.kg^{-1}$), the burning efficiency, the fuel load ($kg.m^{-2}$), and the burned area (m^2). Most of the studies reported in the literature include emission factors for American fuels (e.g. McMeeking et al. 2009; Akagi et al. 2011), savannas/pastures, tropical and extratropical forests (Van Der Werf et al. 2017). For this work, emission factors for Mediterranean conditions were chosen based on a bibliographic review considering values selected by previous studies (Miranda 2004; Alves et al. 2011; Van Der Werf et al. 2017; Vicente et al. 2017, 2012). For Eucalyptus, Acacia and Pinus pinaster species the emission factors were expressed as the average of the emission factors obtained experimentally by Alves et al. (2011) and Vicente et al. (2012, 2017). For the other hardwoods species, the emission factors reported by Van Der Werf et al. (2017) were used. For other resinous, Oak, Chestnut, Cork Oak and Stone pine species the emission factors were obtained by Miranda (2004). Finally, the emission factors obtained for each species were adapted to the NFFL classification considered by the model to update the emission factors parameterization for the Mediterranean conditions.

Within BRAMS concentrations of smoke pollutants are estimated using the species mass released by a fraction of biomass burned (emission factors) dispersed as fluxes, through buoyancy convection and vertical and horizontal advection in dry air along the vertical column in the BRAMS simulated boundary layer, and resolved by chemical mechanisms in the domain of simulation. The selected emission factors of gases and particulate matter from fires, in the domain of simulation, are included in the modelling system through an emission table.

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