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Aplicação dos Modelos de Interação Atmosférica e de Incêndio Florestal BRAMS-SFIRE no sul de Portugal

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Resumo

O BRAMS-SFIRE é um novo sistema de modelação atmosférica com componente de propagação de fogo desenvolvido no Centro de Previsão de Tempo e Estudos Climáticos (CPTEC / INPE) no Brasil em colaboração com o Instituto Mediterrâneo de Agricultura, Ambiente e Desenvolvimento (MED) em Portugal. O presente artigo descreve a incorporação do modelo de propagação de fogo no Brazilian developments on the Regional Atmospheric Modeling System (BRAMS). Os principais objetivos foram desenvolver o acoplamento entre um modelo atmosférico e um modelo de propagação de fogo que simulasse os efeitos da circulação atmosférica sobre um incêndio florestal e vice-versa. Esta ferramenta tem como objetivo ajudar a entender as relações entre o fogo e a paisagem nas florestas de carvalho mediterrâneas, e avaliar os resultados das simulações deste acoplamento na escala fina no ecossistema do Montado na região do Alentejo. Para isso, três grades de alta resolução espacial ao longo de três incêndios foram configuradas com dados de caracterização de superfície realistas e propriedades dos modelos de combustível. Uma grade foi colocada sobre fogo em uma planície e as outras nas montanhas, para avaliar os diferentes tipos de propagação do fogo. Este trabalho demonstra que este sistema simula de forma consistente a interação entre o fogo, os modelos de combustível e a atmosfera, mostrando que o fogo altera a circulação local ao nível da superfície, intensifica as correntes de vento ascendentes e descendentes, alterando a estrutura da atmosfera.

Palavras-chave: interação entre incêndios florestais e circulação atmosférica, fluxos de calor, propagação do fogo, modelo atmosférico de mesoescala.

Application of the coupled BRAMS-SFIRE Atmospheric and Fire Interactions Models to the South of Portugal

Abstract

BRAMS-SFIRE is a new atmospheric modeling system with a fire spreading component developed at the Centro de Previsão de Tempo e Estudos Climáticos (CPTEC/INPE) in Brasil, in collaboration with the Instituto Mediterrâneo para a Agricultura, Ambiente e Desenvolvimento (MED) in Portugal. The present paper describes the incorporation of the

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fire model into the Brazilian development of the Regional Atmospheric Modelling System (BRAMS). The main objectives were to develop the coupling between an atmospheric and a spreading fire models which simulate the effects of atmospheric circulation over a wildfire and vice-versa. This tool is intended to help understand fire-landscape relationships in Mediterranean oak woodlands and evaluate the simulation results on a fine-scale in the Alentejo region's Montado ecosystem. For this purpose, three grids of very high spatial resolution over three fires were configured with realistic surface characterization data and fuel model properties. One grid was placed at a fire in the plains and the others in the mountains to evaluate fire propagation types. This work demonstrates that this system consistently simulated the interaction between the fire, the fuel models, and the atmosphere, showing the fire changes the local circulation at the surface level, intensify wind currents, and changes the atmosphere structure.

Keywords: interaction between forest fires and atmospheric circulation, heat fluxes, fire spread, atmospheric mesoscale model.

1. Introduction

Fire behavior models have been developed using mathematical approaches, which range from empirically to theoretically based, to describe the processes of fire and to overcome the computational and time limitations of specific applications. Empirical models use algebraic functions to describe the observed relationship between macro-scale fire behavior and environmental conditions. In contrast, theoretical or process-based models use differential expressions to explain individual processes that characterize the driving of fire behavior.

Forest fire behavior models have traditionally been used to predict fire spread and heat release for a prescribed set of fuels, slopes, and wind conditions and are designed primarily to assess surface fire risk behavior. Most of these models are not capable of evaluating the three-dimensional complex behavior of fire risk; they have a complete treatment of the chemical and energy processes of combustion in wildland fuels, but the fire spread progression is restricted to small distances in a two-dimensional plane (Grishin, 1997; Larini *et al*., 1998; Porterie *et al*., 2000; Movan and Dupuy, 2001; Rehm *et al*., 2003), and some systems used operationally are based on the empirical correlations developed by Byram (1959), Fosberg and Deeming (1971), Rothermel (1972, 1991), Van Wagner (1973) and Albini (1976).

Some operational fire spread models, like FARSITE (Finney, 1998) and BEHAVEPLUS (Andrews and Chase, 1989), are tools to estimate fire risk, fuel management treatments, and fuel-break networks and to prioritize firefighting strategies (Butler and Cohen, 1998) in a wide range of forest ecosystems. Others, used for research, include the three-dimensional FIRETEC model (Linn, 1997; Linn and Harlow, 1998; Linn *et al*., 2002; Linn and Cunningham, 2005) and the wildland-urban interface Fire Dynamics Simulator (WFDS) (Mell *et al*., 2007, 2009; Mueller *et al*., 2014). These systems simulate at a very high resolution and include a representation of fuel pyrolysis, the turbulent transport of combustion products, and the preheating of fuel products due to the approximation of the flame front. FIRETEC has been coupled to HIGRAD, a dynamic atmospheric model developed to describe the temperatures and speed gradients found in the vicinity of a forest fire (Reisner *et al*., 1998, 2000); that model allows a three-dimensional characterization of the fuel and responds to different types of fuel with a simulation capacity on flat and rugged terrain, and, due to the explicit treatment of forest fire combustion, incorporates in real time many explosive and unstable aspects of a fire. However, such models have a high computational cost and cannot be used for operational simulations.

For atmospheric/fire operational use, it is necessary to model the fire's behavior on the landscape scale - i.e., over large enough domains (distances of 200 m and greater) - where the fire environment typically spans several orders of magnitude, where it is not possible to detail the entire process between the atmosphere and the wildland fire behavior, and where significant approximations of chemical and physical processes of fire are made in order to represent the action of fire on the fuel structure. Several different three-dimensional approaches to simulation in high resolution at a synoptic scale have been presented in the recent literature. These are atmospheric models that make the weather forecasts coupled with semi-empirical surface spread fire models, have parameterizations of atmosphere-forest interaction, and are treated as a dynamic system in which it is possible to simulate, at a high-resolution synoptic scale, the interactions and feedback resulting from fire-induced forcing. These models started with basic approaches to describe several aspects of fire behavior described in observed fires (Clark *et al*., 1996a, 1996b, 2004) and incorporated subgrid-scale parameterization of combustion (Clark *et al*., 2003), leading to the development of the Coupled Atmosphere Wildland Fire Environment (CAWFE) (Clark *et al*., 2004). Advances in regional numerical weather prediction systems resulted in WRF-SFIRE, a coupled atmospheric and surface spread fire model (Mandel *et al*., 2009, 2011), and in WRF-SFIRE-CHEM, an integrated system able to predict fire progression, plume rise, smoke dispersion, and chemical transformations (Kochanski *et al*., 2016).

Herein, the authors demonstrate the applicability of Rothermel's (1972) surface fire formulation to the two systems, using the Eulerian moving interface method based on the level set method (LSM) for fire line propagation, and in this paper, the authors introduce BRAMS-

SFIRE (Menezes, 2015), which consists of a mesoscale atmospheric model - the Brazilian development on the Regional Atmospheric Modelling System (BRAMS) (Freitas *et al*., 2009, 2017) - coupled with the Spread Fire model (SFIRE) (Mandel *et al*., 2009, 2011). The resulting coupled model simultaneously combines weather simulation with fire spread in forestry fuel. BRAMS is a community-supported atmospheric model routinely used for weather forecasting and simulated from the mesoscale down to boundary-layer large eddies. The BRAMS-SFIRE system can realistically simulate fire propagation and feedback with atmospheric turbulence and may help with planning for and the mitigation of wildfires.

As inputs, the coupled code requires meteorological data, topography, and fuel model maps. The model is simulated on a logically quadrilateral three-dimensional grid on the Earth's surface. Only the refined atmospheric domain is coupled to the SFIRE model, and the SFIRE variables are represented at the centers of the cells of the SFIRE mesh. In this paper, the coupled model was applied to Montado, a characteristically Mediterranean landscape in the region of Alentejo in Portugal, but it can be used in other areas of the world, provided that a suitable fuel map is available.

The coupled BRAMS-SFIRE code is a fully consistent modeling system because both models exchange energy, momentum, and water fluxes. In particular, BRAMS provides the information needed for SFIRE to propagate and generate the combustion flames on the surface; SFIRE, in its turn, provides the latent and sensible heat fluxes, which enhances the turbulent airflow in the atmosphere allowing simultaneous weather and fire spread prediction. The code has open/free access, with competitive computational parallel and memory usage efficiency, allowing its operational application. The presented modeling system is particularly relevant to Portugal. From 1980 to 2017, rural fires' cumulative burned area was approximately 4.4 Mha, approximately 50 % of the continental area with estimated losses of € 9.5 billion both by combat costs and property loss. Additionally, if operationalized at the regional planning level, the present model can be useful to identify, by simulation, the high-risk areas (both in fire ignition and propagation risk) and plan the preventive silviculture operation to mitigate the risk of wildfires (Nunes *et al*., 2019).

2. Material and Methods

2.1. Spread fire model

SFIRE is an implementation of the semi-empirical fire propagation model developed by Clark *et al*. (2004), Coen (2005), and Mandel *et al*. (2009, 2011).

SFIRE gives the propagation of fire concerning spread J:

$$J(\psi) = -S\left(\vec{v}\cdot\vec{n}, \nabla z\cdot\vec{n}\right)||\nabla\psi|| + \varepsilon\Delta\psi \tag{1}$$

based on the spread rate $S = S(x, y, t)$ in the direction $\vec{n} = \vec{n}(x, y, t)$ normal to the boundary $\Gamma = \Gamma(t)$ of a fire area $\Omega = \Omega(t)$; the fireline, expressed as a function of the wind $\vec{v} = \vec{v}(x, y, z, t)$; the terrain height gradient ∇z; and the level set function ψ, which is based on the LSM of Osher and Fekiw (2003). During propagation, sensible and latent fluxes are released to the atmosphere following Eqs. (2)–(3), respectively:

$$Q_h = -c_p\rho_a T_* u_* + \frac{F(t) - F(t+\Delta t)}{\Delta t}\frac{1}{1+M_f}wh \tag{2}$$

$$Q_E = -\chi_*\rho_a u_* + \frac{F(t) - F(t+\Delta t)}{\Delta t}\frac{M_f + 0.56}{1+M_f}wL \tag{3}$$

Both Q_h and Q_E are functions of the properties of forestry fuel models (Anderson's (1982) categories) described by the user and dependent on the exponential decay of fuel, F, from the time of ignition. This fuel fraction decreases exponentially from the time start of ignition, computed over subcell C_j and during the burn (burn, $\psi(x, y) \leq 0$) by

$$\frac{area\{(x,y) \in C_j : \psi(x,y) \leq 0\}}{area(C_j)} \approx \beta = \frac{1}{2}\left(1 - \frac{\sum_{k=1}^{4}\psi(x,y)_k}{\sum_{k=1}^{4}|\psi(x,y)_k|}\right) \tag{4}$$

$$F(x,y,t) = \begin{cases} \beta \iint_{(x,y)\in\Omega(t)} e^{-\frac{0.8514(t - t_i(x,y))}{w(x,y)}} + [1-\beta] \\ 1 \quad otherwise \end{cases} \tag{5}$$

with

$$t_i = t + \frac{\psi(x,y,t)\Delta t}{\psi(x,y,t) - \psi(x,y,t+\Delta t)} \tag{6}$$

and

$$\psi = J(\psi)\Delta t \tag{7}$$

The sensible and latent heat fluxes from the fire (Eqs. (2)-(3)) pass to the boundary layer of the atmospheric model through the turbulence scheme. The chosen semi-empirical approach to fire propagation assumes that the fire spread rate is given by the modified Rothermel (1972) scheme (Mandel *et al*, 2011).

2.2. Coupling SFIRE with BRAMS

The coupling of SFIRE with version 5.0 of BRAMS, was done using variables of BRAMS of the basic state of the atmosphere (surface pressure, air moisture at 2 m, air temperature at 2 m, zonal and meridional wind of the lowest vertical model levels, geopotential height, air density, topography, etc.), of the microphysics, vegetation cover (roughness, vegetation type), and turbulent heat fluxes. When SFIRE is called, in one-time step, as defined by the user, the model run a step of initialization, starts to read the SFIRE list of parameters, makes the configuration flags, sets the grid spacing, and organizes the SFIRE grids inside the BRAMS grids. The model then allocates the pointer flags of SFIRE to BRAMS, allocates memory space to the variables, reads the file with the fuel models provided by the user, and fits these parameters into the grid. Next, it creates the relationships between the variables that BRAMS shares with SFIRE, sets the topography gradient, conducts SFIRE's scale reduction step, and calls the SFIRE main routine, which makes the model calls. Once SFIRE returns its results, the model corrects the data from BRAMS that introduce errors into the SFIRE model and starts the next time steps.

In the next step, the model guides the simulation of SFIRE grids within the BRAMS grids, the BRAMS variables will be entered into SFIRE, sets the topography gradient, calls the SFIRE main routine to perform its calculations, and corrects data errors. In each interaction, the calculated sensible and latent heat are combined with the turbulent heat flux coming from BRAMS, and this serial variable is passed in parallel, returned to BRAMS for atmospheric interaction, and returned again to SFIRE in a different atmospheric state. This coupling of models was constructed in a program for interaction between them, and the list of fuel property parameters was set to represent the Montado region.

The definitions of the compilation rules for this software project were created in the build folder of the BRAMS structure. These rules were defined in a file called "Makefile" that was used to compile, link, and assemble the files, with an option to include the fire modules (SFIRE) when needed for the simulations with BRAMS.

2.3. Model simulation in the Alentejo region

Simulations were conducted in three locations affected by forest fires:

- in the Ossa mountain range on 7th August 2006 (around 7.54° W, 38.73° N)
- close to Alcácer do Sal on 28th July 2010 (around 8.69° W, 38.35° N)
- close to Reguengos de Monsaraz on 4th July 2007 (approximately 7.59° W, 38.37° N)

that took place in Alentejo (Fig. 1), to analyze the results of BRAMS-SFIRE coupling. The grid domain at the three locations was defined by the fires' locations, which were provided by retrieving the temperature from the MODIS sensor aboard the TERRA satellite. The domains were defined by the limits of the fires' perimeters, and the center was defined based on the World Geodetic System (WGS 1984). The fuel models of the Northern Forest Fire Laboratory (NFFL) (Anderson, 1982) have been developed in the United States for the general description of potential forest fire behavior; of the 13 NFFL models, 10 apply to the Portuguese plant formations. A fuel model assignment to a particular spot of vegetation with roughly homogeneous characteristics is usually performed using photographic series. The fuel models of grid domain areas were characterized by cartography from the National Forest Inventory 6 (IFN6, 2015) and overlapped by orthometric (horto) arboreal coverage based on digital aerial photographs from 2004/2006 (Surový *et al*., 2004a, b). Fuel models of Montado (Table 1) were selected and quantified according to determinations of fuel stratum parameters characterizing these models' properties (Menezes, 2015). These parameters were incorporated into the list "namelist.fire" file of the BRAMS-SFIRE model. The SFIRE model has one parametrization based on Rothermel's (1972) mathematical model, and the parameters in list "namelist.fire" represent the variables of the Rothermel (1972) semi-empirical model.

The Alentejo includes the regions of Alto Alentejo and Baixo Alentejo corresponding to the districts of Beja, Évora and Portalegre, and the Alentejo Litoral. The Alentejo is constituted by a particular ecosystem, created by man, which he calls "Montado". Montado is an agro-silvopastoral system comprising pure or mixed stands of cork oak (*Quercus suber* L.) or holm oak (*Quercus rotundifolia* Lam.) woodlands in a complex system in conjunction with production activities (agriculture, pasture, grazing, animal stock, etc.) that share the same growing space (Ribeiro and Surový, 2011). The oak woodlands of southern Portugal (Montados/Dehesas) (Fig. 1) are a multifunctional landscape and occupied approximately 4 million ha in the south of Portugal and is characterized by scattered trees highly variable in canopy density result of wood-cutting and coppicing, shrub clearing, and burning, by annual crops or grasslands and to a lesser extent by evergreen shrubs (Guiomar *et al*., 2015). Its woodland fuel loads have low heat power and, due to management-related activities, take fires infrequently, although fires of considerable extent took place in the region in 2009, 2011, 2012, 2014, and 2015 (IFN6, 2015). Large and severe fires have affected these agroforestry systems in 2003-2005 (Silva and Catry, 2006). In the last years, the resilience decreasing in Mediterranean oak woodlands may be related to more frequent fire (Schaffhauser *et al*., 2011) or higher fire severity (Moreira *et al*., 2008), namely in sum-

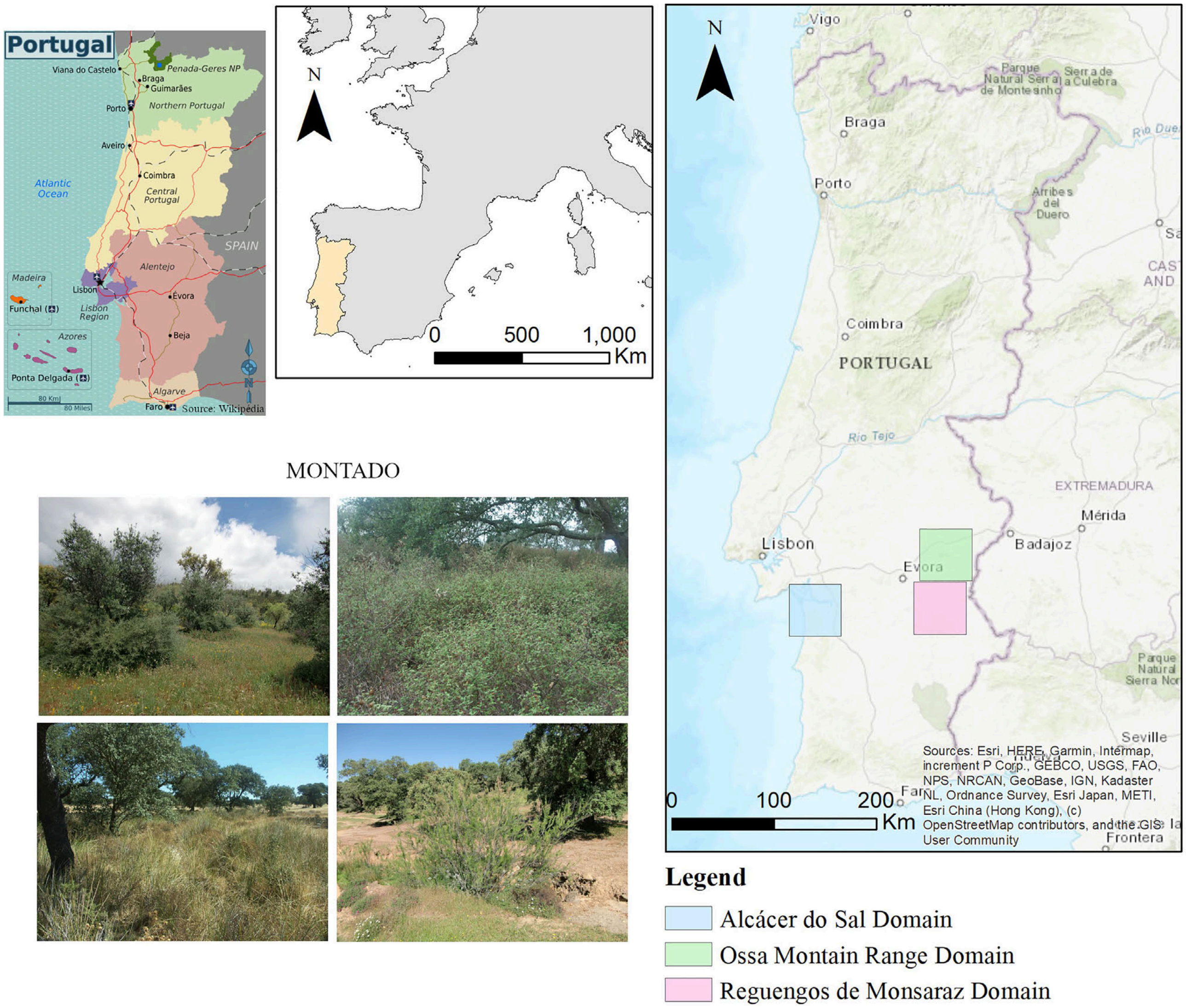

Figure 1 - Localization of Portugal country in Europe and localization of the three simulation domains, namely, Alcácer do Sal domain, Ossa mountain range domain, and Reguengos de Monsaraz domain, in Alentejo region in the Montado ecosystem.

Table 1 - Descriptions of the Northern Forest Fire Laboratory fuel models.

Fuel models	Description
M1	thin pasture, dry and low, with height below the knee, completely covering the soil, with scrubland or trees covering less than 1/3 of the surface
M2	continuous pasture, thin, dry, and low, with scrubland or trees that cover 1/3 to 2/3 of the surface
M3	continuous and thick pasture ($m \geq 1$), with 1/3 or more of dry grass
M4	scrubland or young trees, very dense, about 2 m high, with vertical and horizontal continuity
M5	dense scrubland with height less than 0.6 m, with slight load of leaves in the ground
M8	foliage in dense forest of conifers or hardwoods (no scrubland); the foliage forms a compact layer less than or equal to 5 cm
M9	foliage in dense forest of conifers or hardwoods (no scrubland); the foliage forms an airy layer with little compaction
M14	no fuel

mer-drought which could also affect the long-term viability of cork oak stands (Acácio *et al*., 2009). However, it needs further climate studies based on the relation of atmosphere and the fire and the biome to understand how wildfire characteristics influence the synergistic factors of dynamics of the Montado and to assess the transition to other land cover types, namely, evaluate positive feedbacks among landscape fragmentation, shrub encroachment, fire and tree density decrease (Acácio *et al*., 2007) and with this way can doing adaptive management to make possible the transition towards late-successional communities, as well as to reduce the effects of new disturbances (Baeza *et al*., 2007).

2.4. Model configuration

2.4.1. Initial processing settings and initial conditions of SFIRE

High-resolution (in this case, 25 m) fuel data on a regular grid was generated using the NFFL fuel models (Anderson, 1982) of the Portuguese National Forest Inventory 6 (IFN6, 2015), applied using the ArcGIS system, interpolated using Euclidean allocation, and exported to ASCII (see instructions for simulating with the BRAMS / SFIRE model in the topic "Run BRAMS-SFIRE model" or in Anexo E of Menezes (2015)). In addition to this initial data, the SFIRE model was started with fire-related information (using the file input "namelist.fire") described in Menezes (2015), containing the characteristics of the physical, thermal, chemical, and mineral fuel models of the Alentejo region in Montado.

2.4.2. Initial conditions and boundary conditions for atmospheric simulations

To establish the initial atmospheric state, the simulations used data for land cover type, soil type, the normalized difference vegetative index (NDVI), weekly sea surface temperature, daily soil moisture, and soil temperature. The NDVI is a product derived from 15-day MODIS images from 2001 to 2002 (Moreira *et al*., 2013), the weekly sea surface temperatures are distributed by Reynolds *et al*. (2002), and daily soil moisture is an operational product of CPTEC/INPE based on estimated rainfall from TRMM (Gevaerd and Freitas, 2006). The soil temperature was initialized with the air temperature at the first level of the BRAMS atmospheric model. We used topography data available through the United States Geological Survey's Earth Resources Observation Systems data center with 30 arc seconds (approximately 1 km) of latitude-longitude resolution (Gesch and Verdin, 1999).

The atmospheric fields for initialization and boundary conditions were obtained from the ERA-Interim global atmospheric reanalysis at 26 vertical pressure levels at intervals of 6 hours (ERA, 2011). The zonal and meridional wind, air temperature, geopotential, and relative humidity fields on a regular grid were extracted and interpolated to the BRAMS model grid, providing data for the initial and boundary conditions.

The BRAMS-SFIRE simulations were performed using a downscaling procedure (one-way interaction), which started from a model grid of 64 km resolution (with the model domain covering Europe). The data from this simulation was then used to feed another model run with a grid of 16 km resolution (covering continental Portugal), which in turn fed another grid of 4 km resolution (covering Alentejo), which fed yet another grid of 1 km resolution (covering the area being studied). The finer grid with 200 m resolution (in the area of the forest fire) was applied to the SFIRE model with atmospheric fields provided by the 1 km resolution grid model run.

2.4.3. Grid specifications and numerical aspects

The BRAMS physical parameterizations were configured according to Table 2. The simulations were conducted with the non-hydrostatic equations on a vertical grid with 55 levels. SFIRE was configured (in its configuration file "sfire.in") as in Table 3, with 200 m of horizontal grid spacing, updating the fuel moisture calculation every 30 s, with a reaction velocity (parameter fire reac-

Table 2 - Parameterization of the BRAMS 5.0 simulations for 64 km, 16 km, 4 km, 1 km, and 200 m resolution grids.

BRAMS grid	64 km, 16 km, and 4 km resolution	1 km resolution	200 m resolution
Topography scheme	Silhouette orography	Silhouette orography	Silhouette orography
Lateral boundary conditions	Klemp/Wilhelmson	Klemp/Wilhelmson	Klemp/Wilhelmson
Shortwave radiation	Carma	Carma	Carma
Longwave radiation	Carma	Carma	Carma
Radiation trend update frequency (s)	900	900	900
Convective parameters	Grell 3D formulation	Not used	Not used
Convection frequency (s)	900	Not used	Not used
Shallow cumulus parameters	Grell/Deveny	Not used	Not used
Shallow cumulus frequency (s)	1,200	Not used	Not used
Microphysics (moisture level of complexity)	Complexity level 3 (Flatau *et al*., 1989)	Complexity level 3 (Flatau *et al*., 1989)	Complexity level 3 (Flatau *et al*., 1989)
Surface model/soil/ vegetation	JULES (Moreira *et al*., 2013)	LEAF (Walko *et al*., 2000)	LEAF (Walko *et al*., 2000)
Turbulent diffusion coefficient	Mellor e Yamada (Mellor and Yamada, 1982)	Mellor e Yamada (Mellor and Yamada, 1982)	Isotropic deformation

Table 3 - Parameterization of the grid in which the forest fire would be propagated and parameterization of the simulation.

Parameters	Ossa mountain range domain	Alcácer do Sal domain	Reguengos de Monsaraz domain
Resolution in x (m)	200	200	200
Resolution in y (m)	200	200	200
Latitude of grid center	38.734° N	38.354° N	38.368° N
Longitude of grid center	−7.543° W	−7.687° W	−7.589° W
Refinement of the fire grid in x in relation to the atmospheric grid	1	1	1
Refinement of the fire grid in y in relation to the atmospheric grid	1	1	1
fmoist_run	.true.	.true.	.true.
fmoist_interp	.true.	.true.	.true.
fmoist_only	.false.	.false.	.false.
fmoist_freq (s)	0	0	0
fmoist_dt (s)	30	30	30
Number of ignitions	3	2	2
Focus point 1 longitude	−7.492000° W	−8.643000° W	−7.585000° W
Focus point 1 latitude	38.724998° N	38.312000° N	38.356000° N
Focus point 2 longitude	−7.532000° W	−8.652000° W	−7.594000° W
Focus point 2 latitude	38.713001° N	38.310000° N	38.355000° N
Focus point 3 longitude	−7.589000° W		
Focus point 3 latitude	38.734001° N		
Ignition 1 radius (m)	15,000	15,000	15,000
Ignition 2 radius (m)	15,000	15,000	15,000
Ignition 3 radius (m)	15,000		
Ignition 1 start time (s)	180	180	180
Ignition 2 start time (s)	180	180	180
Ignition 3 start time (s)	180		
Propagation speed imposed on focus 1 (m s^{-1})	7 (unrealistic, but imposed by CPU time constraints)	7 (unrealistic, but imposed by CPU time constraints)	7 (unrealistic, but imposed by CPU Time constraints)
Propagation speed imposed on focus 2 (m s^{-1})	7 (unrealistic, but imposed by CPU time constraints)	7 (unrealistic, but imposed by CPU time constraints)	7 (unrealistic, but imposed by CPU time constraints)
Propagation speed imposed on focus 3 (m s^{-1})	7 (unrealistic, but imposed by CPU time constraints)		
fire_print_msg	1	1	1
fire_atm_feedback	1	1	1
fire_upwinding	Eno	Eno	Eno

tion, defined by the user of the SFIRE model) of 7 m s^{-1}, with a 15 km radius prescription fire, and with a fire initiation time of 180 s after starting the atmospheric simulation.

2.5. Run BRAMS-SFIRE model

Figure 2 presented the framework of BRAMS-SFIRE, explaining how to run a simulation between coupled models. However, some extra details need to be explained to run SFIRE in the coupling. The user must create the following folder in the root folder of the simulation:

./data.

Inside this must be placed the file with the data of the classes of the fuel models distributed spatially over the study region.

The fuel model class data file should be created in a geographic information system, such as ArcGIS. A Euclidean allocation must be applied for high resolution, e.g., 25 m. The data must then be exported to ASCII and should have a structure like the following example:

```
ncols      14776
nrows      11452
xllcorner  -9.5170506754081
```

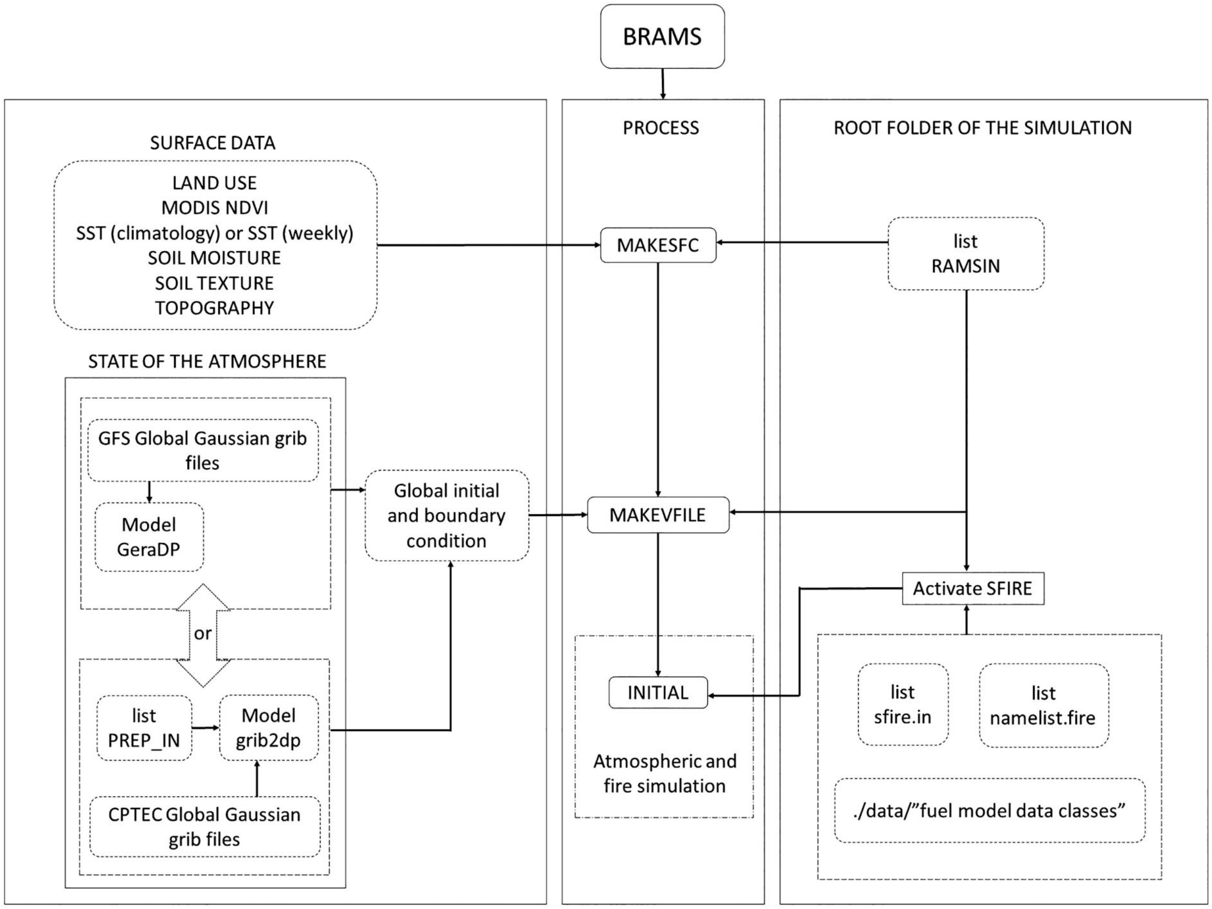

Figure 2 - The framework of the BRAM-SFIRE system, explaining the necessary processes to run a simulation between the atmospheric model and the fire spread model.

yllcorner 37.201733972025
cellsize 0.00022522522522523
NODATA_value -9999
-9999 -9999 -9999 -9999 -9999 -9999 -9999 11 11 11 11 11 11 11 11 11 6 6 6 6 6 6 6 6 6

The user should then go to the SFIRE root program, sfclyr_sfire.f90, and, in the routine combinit_user, should change the value of the parameters described below for the user's own model and only after compiling it:

```
integer. parameter :: nlinhas = 11452
integer.parameter :: ncolun = 14776
real.parameter :: distan = 0.00022522522522523
real.parameter :: lat0 = 37.201733972025
real.parameter :: lon0 = −9.5170506754081
filename="./data/alen25_clip.asc"
```

The user must verify whether the missing value −9999 is the same as usual; if not, it must be changed in the code:

```
if(idclass(i.s).eq.(−9999))then
```

The BRAMS-SFIRE executable should be in the root folder of the simulation; the "RAMSIN" list, the "sfire.in" list, the "namelist.fire" list, and the simulation initialization data files should all be in your directory. These are available at http://brams.cptec.inpe.br/.

The user must parameterize the "RAMSIN" list (atmospheric parameters) and the "sfire.in" list (parameters of SFIRE), as described in the document BRAMS Input_Namelist_Guide at http://brams.cptec.inpe.br/ and in Menezes (2015) in the Table in Anexo D.

To simulate, three processes must be executed:

1) assimilation of boundary condition initialization data: MAKESFC
2) assimilation of atmospheric data from the global model at sigma-z levels and preparation of the data set for reading at BRAMS: MAKEVFILE
3) simulation: INITIAL

The model simulates by downscaling one way, and the fire scheme is triggered at the last, highest resolution grid.

3. Results and Discussion

Ossa montain range, Alcácer do Sal, and Reguengos de Monsaraz have very smooth topographies (Fig. 3). Ossa montain range has a maximum altitude of approxi-

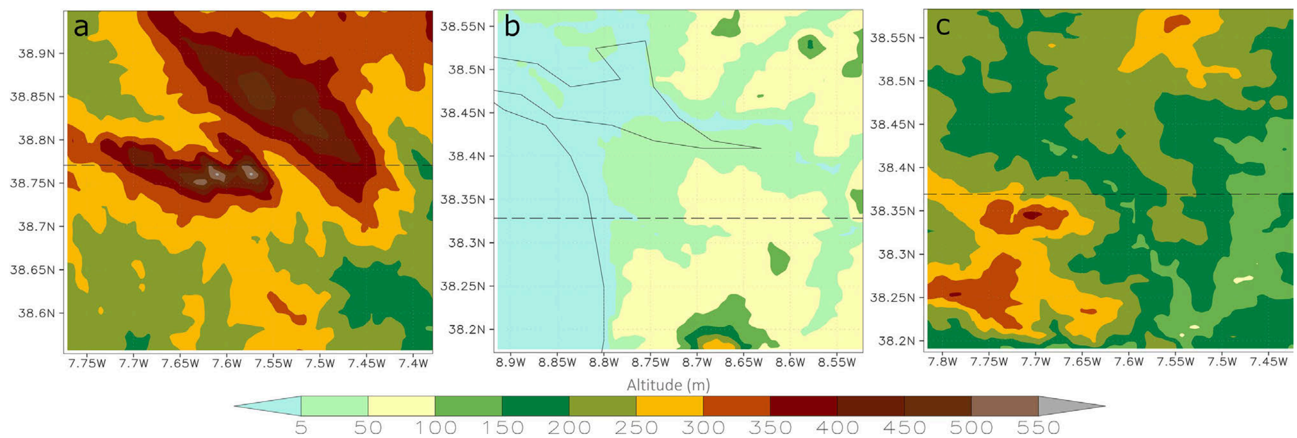

Figure 3 - The topography of the mountain ranges in a) the Ossa region and c) the Reguengos de Monsaraz region and of the open land in b) the Alcácer do Sal region.

mately 550 m, while Alcácer do Sal - the region where the fire was triggered - is nearly flat, with a maximum elevation of 100 m. In the Reguengos de Monsaraz region, the mountain range has a maximum altitude of 350 m and is surrounded by valleys of 200 m depth. Figure 3 shows the orographies of the three areas.

The prevailing fuel models in the three regions are M1, M2, M3, M4, M5, M8, and M9 (Table 1). The dotted lines in Figs. 3 and 4 indicate the zones in which vertical profiles were conducted on the areas where the fires occurred. The NFFL fuel models M1, M2, M4, and M5 were found over the zone of the vertical profile in the Ossa mountain range; fuel models M2, M3, M4, M8, and M9 over the zone of the vertical profile in the Alcácer do sal region; and M1, M2, and M4 over the zone of the vertical profile in the Reguengos de Monsaraz region (Table 1 and Fig. 4).

Over the Ossa mountains, the wind was anabatic with a weak intensity of about 2.5 m s^{-1}. The fire began from three locations (Fig. 5 a), and the fire lines took the form of three ellipses, which collapsed further into a single ellipse pattern. Sensible heat fluxes up to 28 kW m^{-2} were produced and moved down the mountain. During the propagation of the fire, the fuel types burned in several ways, releasing differentiated fluxes, depending on the time of consumption and the fuel's characteristics. As shown in Figs. 5 b and c, the fire front spread, burned fuel models M1 and M2 quickly, consumed model M4 with more difficulty, and released more intense fluxes. The fire altered the local wind field, making it more turbulent and intensifying it to 8 m s^{-1}.

In the Alcácer do Sal region, the northwest sea breeze had an intensity of 2.5 m s^{-1} to 6 m s^{-1} and was confronted with a southeast continental wind of an intensity of 4 m s^{-1} (Fig. 6 a). The fire began in two locations very close to one another and spread in an ellipse pattern at the plateau with a differentiated intensity of heat flux and consumption time, taking more time to burn fuel models M8, M9, and especially M4, while releasing different values of flux orders for each and losing intensity while burning the fuel (shown in Figs. 6 b and c). Again, the local horizontal wind field in the burned area became very chaotic and accelerated to 8 m s^{-1} up to 10 m s^{-1}. This clearly verifies, in both this region and in the Ossa mountain range region, that the wind did not influence the drift

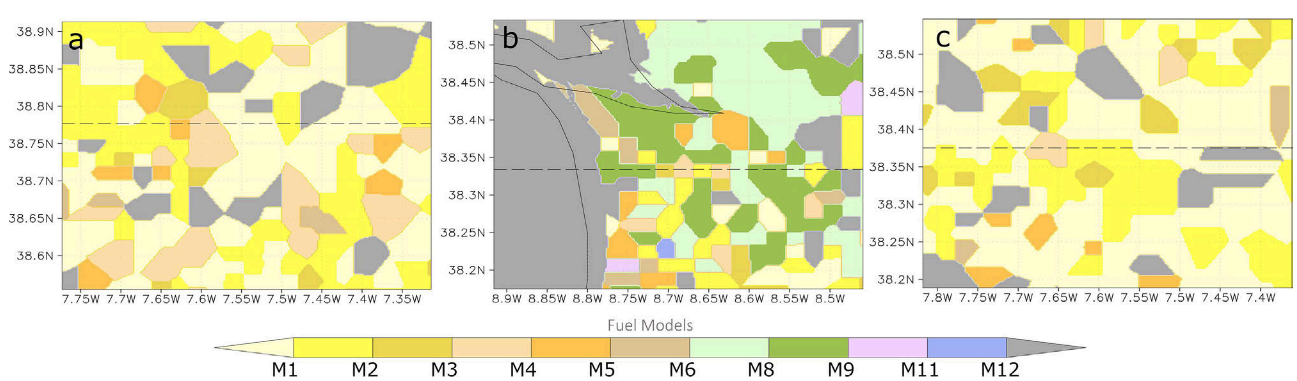

Figure 4 - Maps of fuel models interpolated by BRAMS-SFIRE in a) the Ossa mountain range, b) the Alcácer do Sal region, and c) the Reguengos de Monsaraz region.

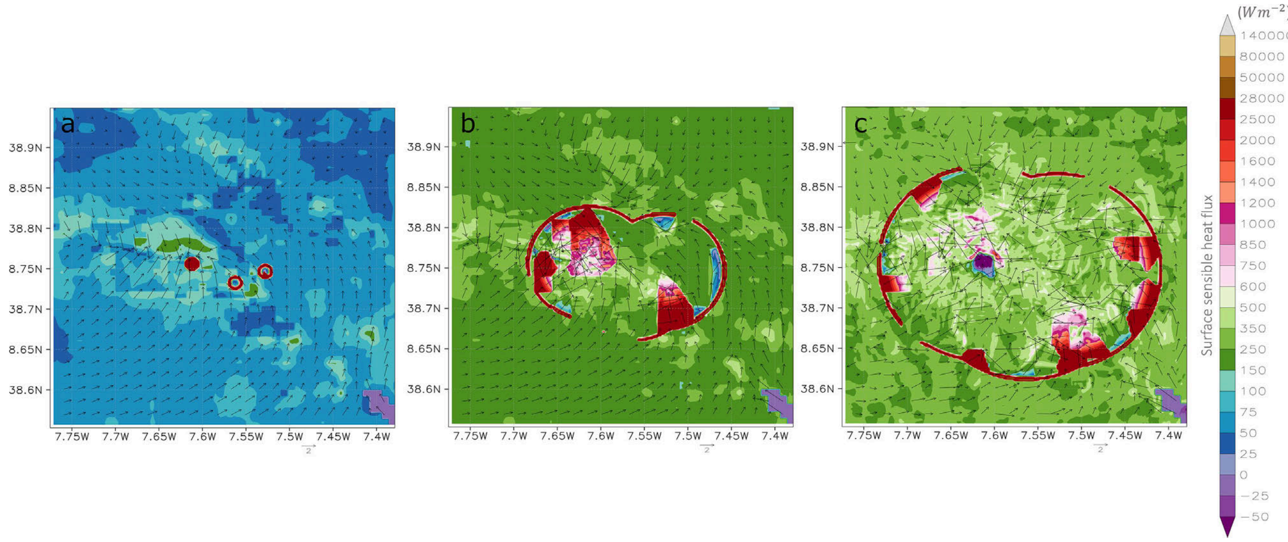

Figure 5 - Sensible heat fluxes (W m^{-2}) released during the spread of the fire front and the surface horizontal wind field (m s^{-1}) simulated by BRAMS-SFIRE for the Ossa mountain range a) start fire and b) & c) active fire.

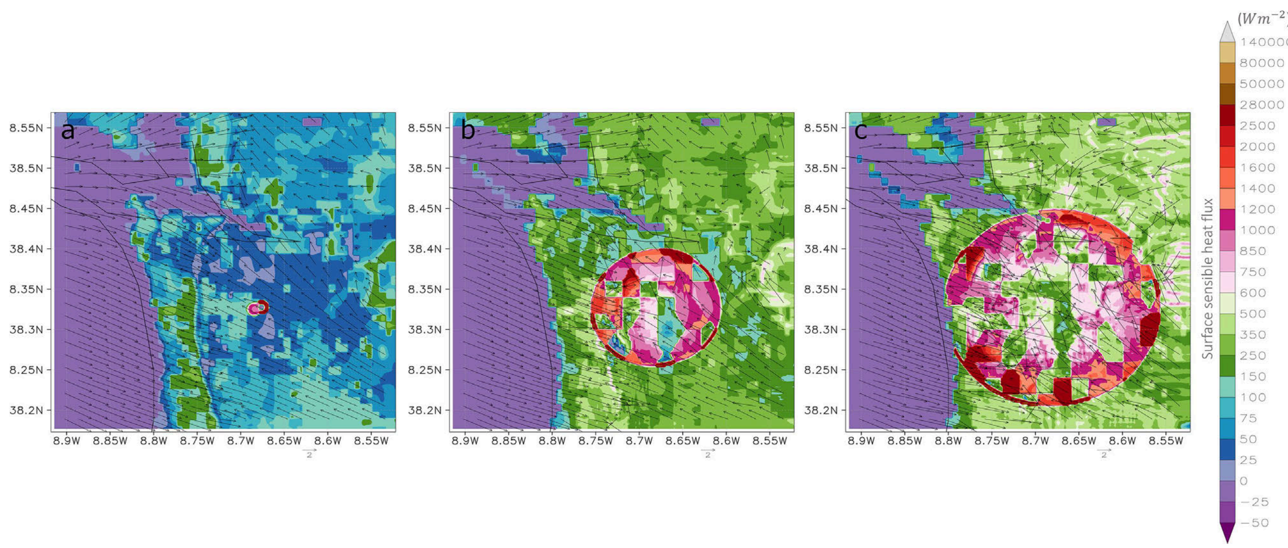

Figure 6 - Sensible heat fluxes (W m^{-2}) released during the spread of the fire front and the surface horizontal wind field (m s^{-1}) simulated by BRAMS-SFIRE for the Alcácer do Sal region a) start fire and b) & c) active fire.

of the fire because it was weak, yet the area still burned due to the type of fuel and the slope of the topography.

In the Reguengos de Monsaraz region, the wind gusts from the north and northwest had an intensity of 4 m s^{-1} to 5 m s^{-1}. A fire front spread along the valley and went up the mountain. In the region in which there was continuous pasture, thin, dry, and low, with some scrub-land or trees (fuel model M2; see Figs. 7 b and 4 c), the wind intensified (7 m s^{-1} up to 12 m s^{-1}) and caused a drift of the fire front toward the direction of the valley. The fire front burned this pasture region quickly. Only fuel model M4 remained until it was entirely consumed by fire (Figs. 7 b and c).

Figure 8 shows the vertical profile over the dotted line that was shown in Figs. 3 and 4. This profile shows the flame temperature, altitude reached, and wind caused by the spread of the fire fronts in the three regions studied. In Both 7th August 2006 (in the Ossa mountain range region) and 28th July 2010 (in the Alcácer do Sal region) temperatures reaches 36 °C and 38 °C, respectively, at 24.4 m height (Figs. 8 a) and b)). On 4th July 2007 (in the Reguengos de Monsaraz region), air temperature reaches 28 °C at 24.4 m height (Fig. 8 c). The first level of the BRAMS model is at 24.4 m above the surface, and the flames in the Ossa mountain range region and the Alcácer do Sal region raised hot air plumes with a temperature of 40 °C at altitudes of 200 m and 300 m, respectively

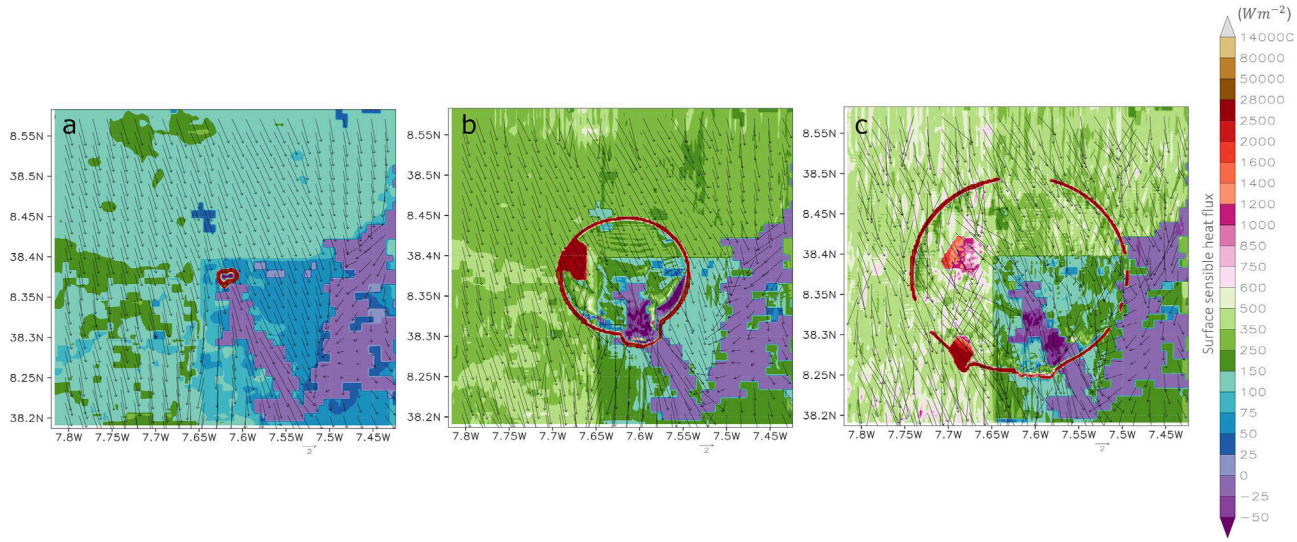

Figure 7 - Sensible heat fluxes (W m^{-2}) released during the spread of the fire front and the surface horizontal wind field (m s^{-1}) simulated by BRAMS-SFIRE for the Reguengos de Monsaraz region a) start fire and b) & c) active fire.

(Figs. 8 a and b) and hot air plumes at 36 °C for altitudes above 600 m. In the Reguengos de Monsaraz region, the flames raised hot air plumes of 34 °C and 32 °C at altitudes of 80 m and 100 m, respectively (Fig. 8 c).

Simulations both with the activation of forest fires and without fire were conducted in these three regions - in Alentejo in the Ossa mountain range on 7th August 2006, close to Alcácer do Sal on 28th July 2010, and close to Reguengos de Monsaraz on 4th July 2007. Atmospheric sounding was conducted over a point of the Ossa mountain range region (38.77° N, 7.68° W), the Alcácer do Sal region (38.33° N, 8.75° W), and the Reguengos de Monsaraz region (38.37° N, 7.62° W), both with the forest fire developed and with no fire. The air parcel thermodynamic evolution ascending on boundary layers, is described by state curves and the evolution curve on the nomogram SkewT-LogP. The following paragraphs describe the simulations' results and atmospheric soundings.

On 7th August 2006, the Azores anticyclone was located north of the Azores Islands and extended to the Gulf of Biscay; there was also a thermal depression over the Iberian Peninsula. The sky was clear, and the wind was blowing from the east quadrant with weak-to-moderate intensity in the morning. By the afternoon, the wind was blowing from the west quadrant on the western coastline and in southern Portugal (Bulletin no. 4482 of the Instituto Português do Mar e da Atmosfera (IPMA)). Over the Ossa mountain range, the atmosphere was thermodynamically neutral up to 700 hPa, becoming stable until 420 hPa, neutral up to 350 hPa, and stable at higher levels. There was no significant potential for convection due to the stability of the atmosphere (convective inhibition of about 155 J kg^{-1}). Stratiform clouds were present, of type stratocumulus (Sc) with a base at 750 hPa and extending up to 700 hPa (Figs. 9 c and d, with fire and without fire). The vertical profile image in Fig. 8 shows that the fire caused

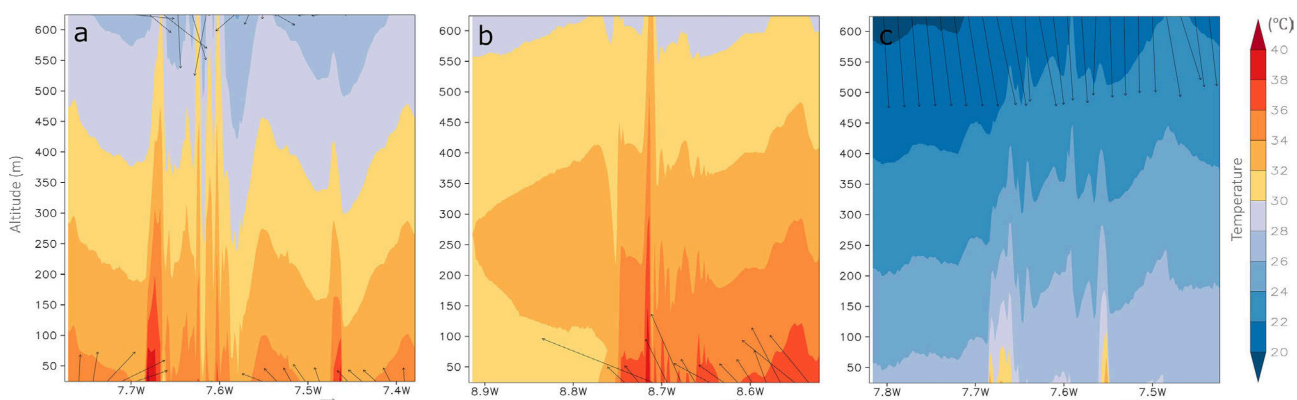

Figure 8 - Vertical profile of flames (°C) and wind fields (m s^{-1}) during the fires in a) the Ossa mountain range region, b) the Alcácer do Sal region, and c) the Reguengos de Monsaraz region simulated by BRAMS-SFIRE.

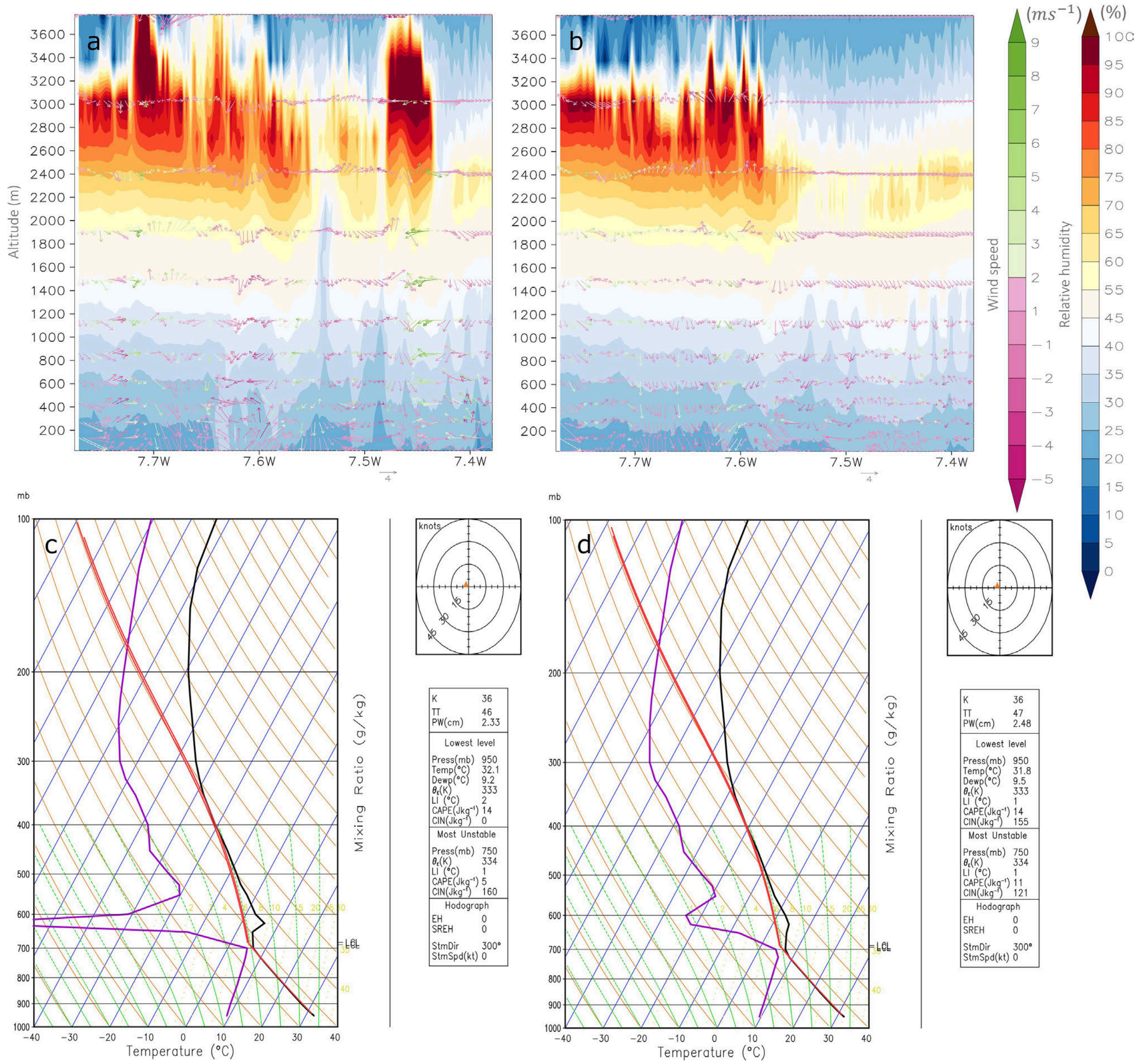

Figure 9 - Relative humidity (%) and horizontal and vertical wind (m s^{-1}) in the Ossa mountain range region a) with fire and b) without fire. State curves and evolution in Skew-T Log-p nomograms in the Ossa mountains range region on 7th August 2006, simulated by BRAMS-SFIRE at latitude 38.77° N and longitude 7.68° W c) with fire and d) without fire.

hot and dry air intrusion (30 % relative moisture) at altitude and caused the rising of the stratocumulus cloud top and its horizontal dispersion. The fire disturbed the local wind currents and intensified the upward, downward, and horizontal circulation, especially over fuel model M4 (Figs. 9a and b, with fire and without fire).

On 28th July 2010, the Azores anticyclone was located northwest of Galicia and stretched in crest to the western Mediterranean and North Africa. A thermal depression was located on the Alto Alentejo. In the morning, the sky was generally clear, with the wind blowing from the east quadrant with light-to-moderate intensity, which turned to the northwest in the afternoon. In the morning, in Algarve in the southern region of Portugal, light showers occurred, accompanied by thunderstorms (Bulletin no. 5933 of the IPMA). In the Alcácer do Sal region, the atmosphere was thermodynamically stable up to 620 hPa, unstable from this level up to 250 hPa, and stable at higher levels. The level of free convection was situated at 640 hPa, and the isotherm zero temperature of the wet thermometer was at 590 hPa. The equilibrium level was situated above 100 hPa. The fact that the convective available potential energy (CAPE) (528 J kg^{-1}) was about two times the convective inhibition (CIN)

(253 J kg^{-1}) suggests that the instability of the atmosphere was latent (Figs. 10 c and d, with fire and without fire), and a more significant potential for convection existed, derived from the trade wind zone along the maritime coast, between sea breezes and continental wind from the southeast. Figures 10 a and b, with fire and without fire, show that, on this day, there was more humidity in the air at the surface than on the day of fire in the Ossa mountain range, and this fire injected a layer of dry air at the 1.6 km level. More intense upward and downward currents were generated over the fire, especially in the trade wind zone over the area covered by fuel model M4 (Fig. 4), causing enlargement of this trade wind zone. The fire increased the available potential energy (633 J kg^{-1}), potentiated the appearance of cloud in the troposphere derived from the instability of the atmosphere, and forced convection columns.

On 4th July 2007, the Azores anticyclone was located in the Azores Islands and stretched in crest to the Bay of Biscay and the archipelago of Madeira. The sky was generally clear, being cloudy and foggy in the coastal region north of Cabo da Roca until the early morning, where drizzle or light rain occurred. The wind was blowing from the north quadrant with a generally weak inten-

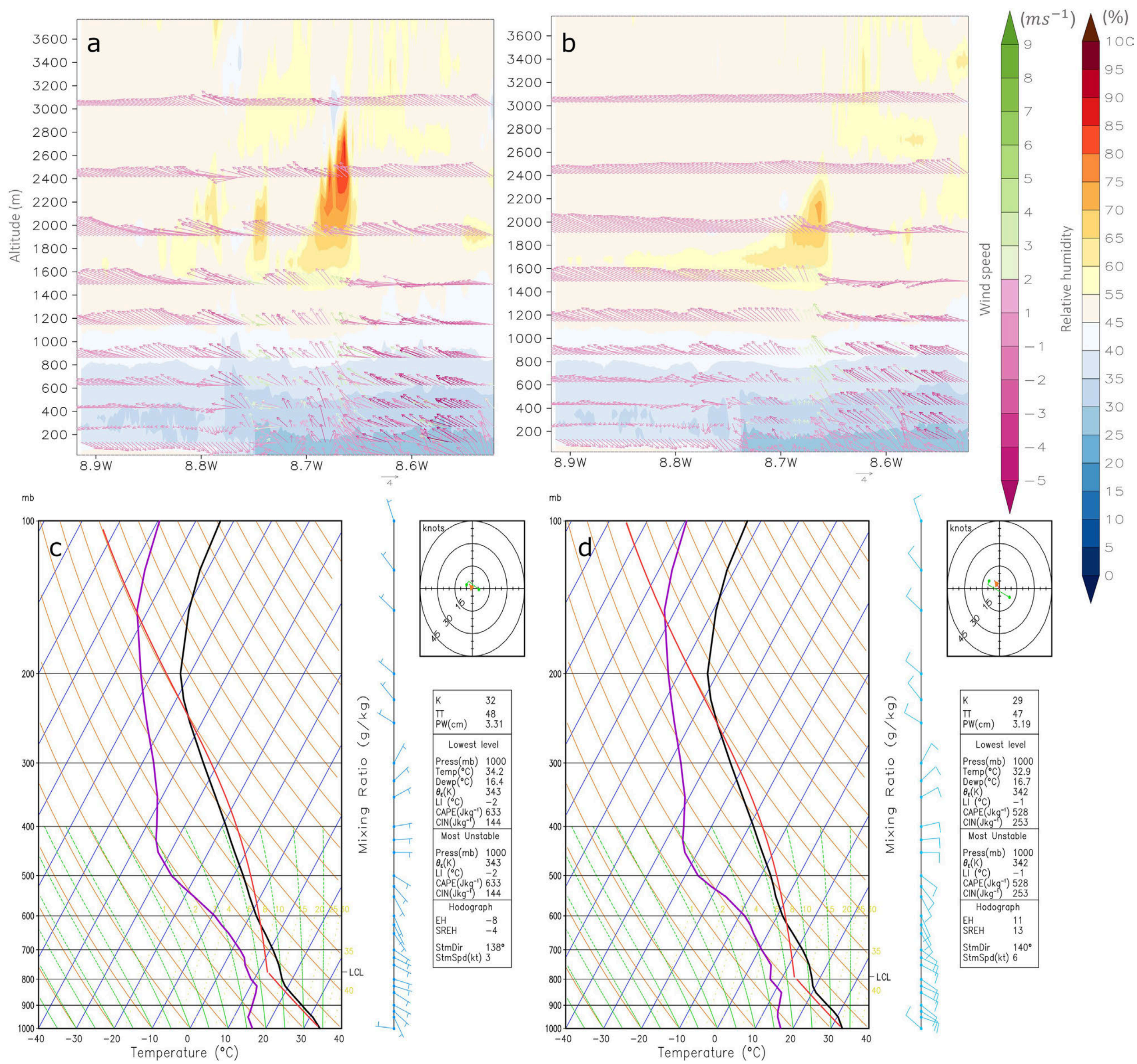

Figure 10 - Relative humidity (%) and horizontal and vertical wind (m s^{-1}) in the Alcácer do Sal region a) with fire and b) without fire. State curves and evolution in Skew-T Log-p nomograms in the Alcácer do Sal region on 28th July 2010, simulated by BRAMS-SFIRE at latitude 38.33° N and longitude 8.75° W c) with fire and d) without fire.

sity; over high land, it was blowing from the northwest with moderate intensity gusts of around 50 km h^{-1}; and, over the coast, it was blowing with strong to moderate gusts of around 75 km h^{-1}, especially in the center (Bulletin No. 4813 of the IPMA). In the Reguengos de Monsaraz region, the atmosphere was thermodynamically stable (Figs. 11 b and d, with and without fire). Figures 11 a and b, with fire and without fire, show that the wind blew from the north and was katabatic. Burning of model M4 fuel (Fig. 4) changed the horizontal and vertical local circulation at the surface level, intensifying it and causing the rise of a dry air plume without repercussions at altitude due to a katabatic circulation of wind in the region. As the area is covered by pastures, with little bush or trees, the fire front and the rear of the fire did not have enough power to overcome the large-scale dynamics of local winds and to produce effects at higher altitudes.

The vertical intrusions of the fire plumes differ between the three episodes simulated by the model. The weak-to-moderate atmospheric wind speed during these episodes shows that the drift of fire took place mainly due to drainage of the terrain slope and the fuel in the regions. It is evident from the simulations that an interaction of the ambient atmosphere and fire buoyancy generated turbulence, originating at its intrusion altitude, and drove the dispersion of clouds. It is clear from the size of the total

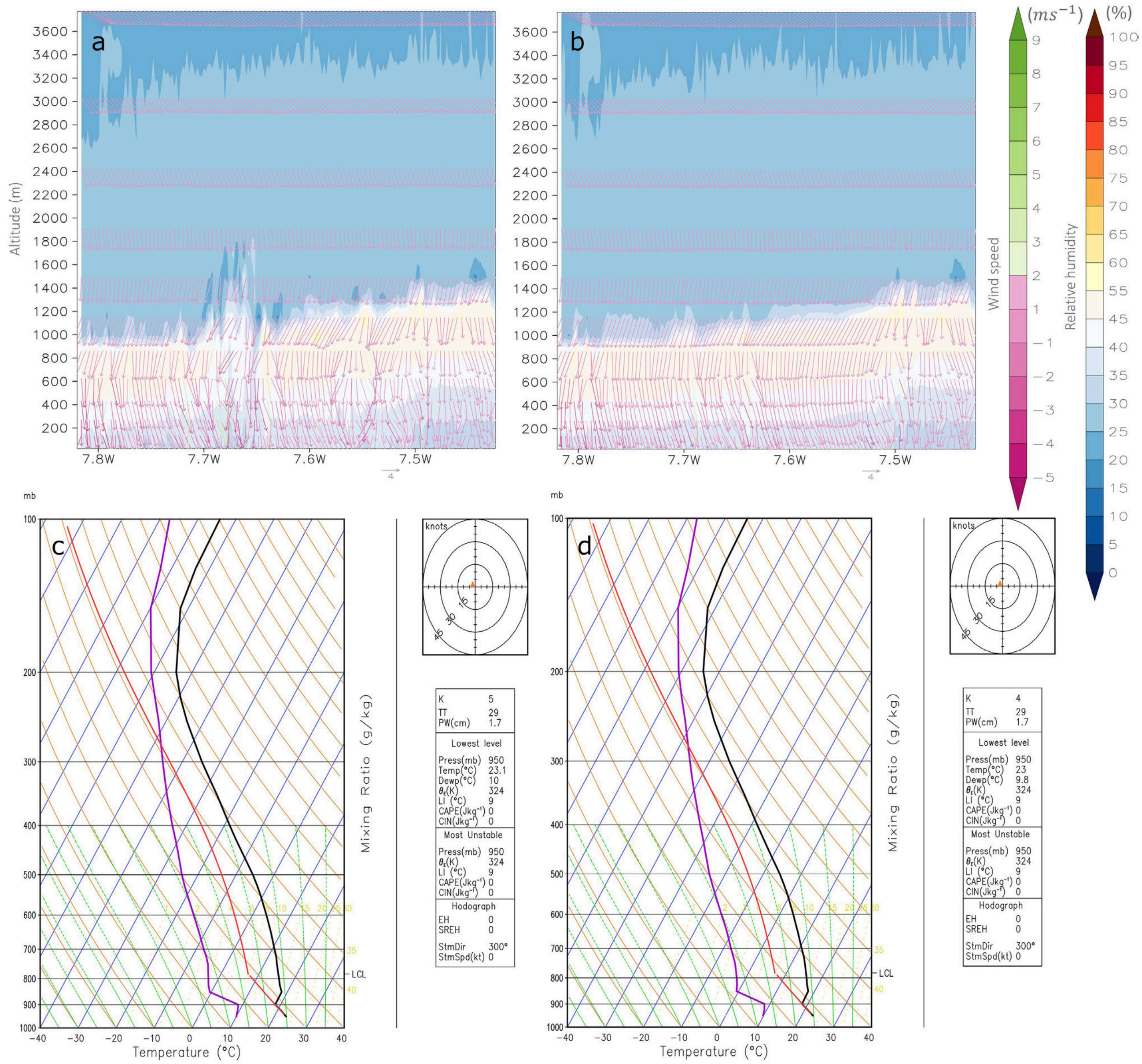

Figure 11 - Relative humidity (%) and horizontal and vertical wind (m s^{-1}) in the Reguengos de Monsaraz region a) with fire and b) without fire. State curves and evolution in Skew-T Log-p nomograms in the Reguengos de Monsaraz region on 4th July 2007, simulated by BRAMS-SFIRE at latitude 38.37° N and longitude 7.62° W c) with fire and d) without fire.

burn area that a large number of sub plumes were generated by the drift of fire, the updraft intensity decreased as the fuel models burned, and the number of sub plumes in the fire line increased.

The simulations show a dynamic interaction of heat fluxes during the convection of the fire plume, bringing drier ambient air into the convective column and increasing the upward and downward circulations. The associated atmospheric perturbation reaches high levels of approximately 2 km above the boundary layer. Horizontally, the fires move elliptically at the surface, driven by anabatic atmospheric winds of moderate intensity or gusts from the north quadrant or other direction. However, observational measurements of the heat transport are needed to assess whether this realistically represents the actual vertical heat transfer and how the vertical decay scale depends on the type of fire and its intensity. The model's ability to resolve this turbulent mixing should therefore be assessed based on observational measurements of turbulent fluxes of heat and momentum; the thermodynamic state of evolution of ambient air must also be evaluated through a sounding balloon, to define the properties of the air being entrained into the smoke column.

The lateral fire spatial patterns show an elliptic progression in the simulations, but the rates at which the fuel mass is consumed during the burn and the topographic accidents seem not to exert a striking influence on the fire's progression. It is therefore necessary to conduct simulations on days with higher intensity winds to evaluate whether this result persists; to validate burn duration and evolution, fuel consumption, and area burned, with observations and measurements of the fire line; and to improve the burn model algorithms. In the burn evolution, it is vital to assess observations of surface heat distribution and release rates - an essential process for determining fuel consumption.

The BRAMS was implemented to run on the same high-resolution grid as SFIRE, and it is important to assess how well the model can resolve fire changes when the burning area becomes small relative to the size of the atmospheric grid cell. An observational estimate of the stand structure that remains after the fire line passes is also needed to determine the drag of the fire, especially for lower-intensity fires, to infer the effect of the indrafts and plume velocities near the ground (Liu *et al*., 2019). Basing the start of ignition on weather risk must also be implemented in the model. Radiation and temperature observations of fire heat fluxes are further needed to implement the interaction within the coupled fire-atmosphere model.

4. Conclusions

This work demonstrates that the BRAMS-SFIRE coupled model system consistently simulated the interaction between the fire, the fuel models, and the responses of the atmospheric thermodynamic and dynamic processes. It also shows that the type and nature of the fuel greatly impacts the intensity of a forest fire and its interaction with the dynamics and thermodynamics of the atmosphere above. Regions in which the shrubland or young trees are very dense, about 2 m high, and with plenty of dead wood fuel (branches) under cover of mature trees are potentially dangerous. They produce a large release of sensible and latent heat fluxes and, after burning for an extended period, can transfer a surface fire to an intensely lethal crown fire, which could be avoided with preventive measures, such as cleaning scrubland. This coupled model can simulate the susceptibility of forest stands to fires and establish itself as a support tool for fire risk management decisions, with the advantage of allowing both highly accurate risk mapping and planning for the impact of actions and vegetation control at critical points, thus significantly reducing the costs associated with the prevention of fire risk. However, combustion experiments in the field are needed to validate the simulations presented, develop the model, and introduce prediction of the behavior of crown fires and incidents of spotting in order to represent the whole effect of a forest's structure on fire and not just the surface phenomenon.

List of symbols

u_*: scale friction velocity
ρ_a: air density
T_*: scale of temperature
χ_*: scale of specific moisture
c_p: specific heat at constant pressure
M_f: fuel particle moisture content
w: total fuel load per unit area
h: low heat value
L: specific latent heat of water condensation
t: time
Q_h: sensible heat fluxes
Q_E: latent heat fluxes

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