Meteorological condition and numerical simulation of the atmospheric transport of pollution emitted by vegetation fires

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Abstract

The objective of this study is to investigate the atmospheric transport of gases and particles emitted by forest fires occurring on the Iberian Peninsula, affecting Continental Portugal during the period from 7 to 12 August 2003. The simulations were implemented using the on-line 3-D transport model CATT-BRAMS (**C**oupled **A**erosol and **T**racer **T**ransport to the **B**razilian developments on the **R**egional **A**tmospheric **M**odeling **S**ystem) coupled to an emission model. The results generated by CATT-BRAMS allow one to describe the local and synoptical condition at the target area. The wind direction from the northeast varying to east over the Iberian Peninsula favored the dislodgment of the smoke plume toward the Atlantic Ocean, distant from the regions with forest fire emissions.
Keywords: atmospheric modeling, biomass burning, summer 2003, long-distance transport.

1 Introduction

Biomass burning is a major source of regional and global scale air pollution, and the smoke plumes interact with both solar and terrestrial radiation, sometimes

WIT Transactions on Ecology and the Environment, Vol 137, © 2010 WIT Press
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/FIVA100141

exerting significant regional-scale forcing of climate. Wildfire initiation and spread are known to be heavily influence by wind (Clements *et al* [1]). Direction spread, propagation speed and smoke plume are result of strong interactions between wildfire and atmosphere occurring at different scales (turbulent mixing in the front, large eddies forming near the front, fire induced winds). Fire emissions are mainly concentrated in the tropics, and are an important regulator of the oxidizing capacity of the global atmosphere. To move forward, fire science needs to go beyond observation and description to provide increased understanding of the interactions between fire and forests so that effective policy, management, modeling and monitoring efforts can be created.

Through this route, biomass burning affects the global budgets of many chemistry species, including the second most important emitted greenhouse gas, methane. There are also important post-fire effects on soil and vegetation emissions. A variety of carbon and nitrogen species are released into the atmosphere from vegetation fires. Carbon monoxide, methane and nitrogen oxides lead to the photochemical production of ozone (O_3) in the troposphere (Crutzen [2]). Particulate material, such as smoke or soot particles, are also produced during the burning process and released into the atmosphere. These solid particles absorb and scatter incoming sunlight and hence impact the local, regional and global climate. In addition, particulates with diameter of about 2.5 micrometers or smaller can lead to various human respiratory and general health problems when inhaled.

The objective of this work is to study the atmospheric transport of gases and particles emitted by biomass burning, due to forest fires affecting large areas over the European continent (Iberian Peninsula and France), during the occurrence of heat wave that affected Europe and in particular continental Portugal on the period from 7 to 12 August 2003. The synoptical situation responsible of the heat wave event was also studied. These studies were accomplished through the use of numerical simulations with the on-line 3-D transport model CATT-BRAMS (**C**oupled **A**erosol and **T**racer **T**ransport to the **B**razilian developments on the **R**egional **A**tmospheric **M**odeling **S**ystem) coupled to an emission model (Freitas *et al* [3]).

2 Methods

2.1 Fires description

According to the European Forest Fires Information System [4], during the 2003 summer heat wave in Europe over 25,000 fires in Portugal, Spain, Italy, France, Austria, Finland, Denmark and Ireland were observed. The total area of forest burnt was 647,069 hectares – four times the size of Greater London. More than half (390,146 hectares) were in Portugal, making it the worst forest fire season the country had faced in the last 23 years with a total area burned of almost five times the average area and an impressive amount of natural resources affected. Spain registered during the same period extreme temperatures of 46°C in the south and 51°C in the city of Sevilla. Forest fires burning 70 kilometers east of

Madrid and in Salamanca destroyed about 2.000 hectares of forest. Southern France saw its share of forest fires in the region of the Var, near the Mediterranean Coast and in the Tarn.

Portugal's forest area is about 3.3 million hectare, of which 87% corresponds to private property. In terms of the monthly distribution the year of 2003 was characterized by a remarkable concentration of burned area in August, where 66% of total burned area took place, which is about 2.7 times greater than the annual average value of the last 10 years. It was also in this month that the highest number of fires was registered, according to the authorities; forest fires have affected 15 of the country's 18 districts, with most of fires occurred in the Northern Region (69%).

This region is characterized by a large density of population on the forestland, associated with small dimension land properties. According to the European Forest Fire Damage Assessment System (EFFDAS) evaluation the distribution of the forest fires covering areas larger or equal than 50 ha recorded in 2003 in Portugal represented only 2% of the total number of fires (327 fires) but responsible for 95% of the total burned area. The higher number of fires occurred mostly over Guarda district representing 32% of the total incidents (see table 1). However the higher values of burned area were in the districts of Castelo

Table 1: Total burned area as distributed through the Portuguese administrative districts in August 2003. The districts most strongly affected by the fires were Castelo Branco (21% burned area), Portalegre (16%), Santarém (15%) and Faro (14%), August 2003.

Start date	Districts	Area burned (ha)
07/08/2003	Bragança	1677
	Guarda	10842
	Castelo Branco	892
	Leiria	1785
	Faro	25900
08/08/2003	Bragança	1376
	Portalegre	2530
09/08/2003	Faro	950
	Guarda	700
10/08/2003	Guarda	700
12/08/2003	Guarda	3618
	Castelo Branco	1560
	Faro	14850

Branco and Portalegre, where 10% belongs to agriculture areas mainly located in Alentejo, of which Portalegre represents 37% of the total.

In Portugal, there were 21 deaths during 2003 fire season, 18 of them only in three weeks (between July 29 and August 14). Most of the reported deaths were located in the centre region of Portugal (districts of Castelo Branco, Portalegre and Santarém) and occurred during the critical period where several forest fires created a continuous burned area. Most of the victims (17) were civilians trying to save goods or escape from fire. There were also reports of more than one thousand people (mainly civilians) needing medical assistance due to smoke intoxications, burns and wounds. Total amount of damages has achieved a value of more than 1000 M€. Over 2.000 buildings were affected, causing almost 200 homeless. Additionally, more than two thousand km of electrical cables were destroyed, leaving over half- million people without electricity. Telephone network was also destroyed in some areas, leading to absence of communication with more than 10 thousand homes (National Service for Fire and Civil Protection and Technological Hazards Division).

2.2 Description CATT-BRAMS model

The on-line 3-D transport model follows the Eulerian approach and was coupled to the Brazilian developments on the Regional Atmospheric Modeling System (B-RAMS). The RAMS is a multipurpose, numerical prediction model designed to simulate atmospheric circulations spanning in scale from hemispheric scales down to large eddy simulations (LES) of the planetary boundary layer. The equation set used is the quasi-Boussinesq nonhydrostatic equations described by Tripoli *et al* [5]. The model is equipped with a multiple grid nesting scheme which allows the model equations to be solved simultaneously on any number of interacting computational meshes of differing spatial resolution. It has a complex set of packages to simulate processes such as: radiative transfer, surface-air water, heat and momentum exchanges, turbulent planetary boundary layer transport and cloud microphysics. The initial conditions can be defined from various observational data sets that can be combined and processed with a mesoscale isentropic data analysis package (Tremback [6]). For the boundary conditions, the 4DDA schemes allow the atmospheric fields to be nudged towards the large-scale data. New deep and shallow convective schemes based on the mass flux approach and with several types of closure (Grell and Devenyi [7]) were also implemented.

The CATT-BRAMS explores the B-RAMS tracer transport capability using slots for scalars. The on-line transport model solves the mass conservation equation for carbon monoxide (CO) and particulate material $PM_{2.5}$, considering a tracer mixing ratio, $\boldsymbol{s}$ ($=\rho/\rho_{air}$) where ρ stands for the concentration of the tracer. This equation is solved taking in account the following processes:

$$\frac{\partial s}{\partial t} = \left(\frac{\partial s}{\partial t}\right)_{adv} + \left(\frac{\partial s}{\partial t}\right)_{\substack{PBL \\ turb}} + \left(\frac{\partial s}{\partial t}\right)_{\substack{deep \\ conv}} + \left(\frac{\partial s}{\partial t}\right)_{\substack{shallow \\ conv}} + W_{PM2.5} + R + Q \qquad (1)$$

where ***adv, PBL turb*** and ***deep (shallow) conv*** stand for grid-scale advection, sub-grid transport in the planetary boundary layer (PBL) and sub-grid transport associated to moist and deep (shallow) convection, respectively. ***W*** accounts for the convective wet removal for $PM_{2.5}$, ***R*** is a sink term associated with generic process of removal/transformation of tracers (dry deposition for $PM_{2.5}$ and chemical transformation for CO), and ***Q*** is the source emission associated to the biomass burning process.

The tracer mixing ratio ***s*** is updated in time using the total tendency given by Equation (1) and a constant inflow is applied as a tracer boundary condition. A complete description of the terms of the Equation 1 is given in Freitas *et al* [3]. The advection and PBL turbulent transport schemes are obtained from the B-RAMS. The sub-grid transport associated with deep and shallow convective transport is coupled to the Grell cumulus scheme.

The biomass burning source emission parameterization (for CO, CO2, CH4, NO_x and $PM_{2.5}$) is based on the MODIS (Moderate Resolution Imaging Spectroradiometer) fire as well as field observations. For each fire detected by remote sensing, the mass of emitted tracer is calculated and its emission in the model follows a diurnal cycle of the burning (Freitas *et al* [3]). The type of vegetation that is burning is obtained from the IGBP 1km vegetation map, thus allowing an appropriate selection of the vegetation dependent factors in Equation 1.

The sources are spatially and temporally distributed and daily assimilated according to the biomass burning spots defined by the satellite observations. The carbon monoxide emission associated to the anthropogenic processes (industrial, power generation, transportation, etc) is provided by EDGAR database (http://arch.rivm.nl/env/int/coredata/edgar/). All biomass burning emissions are added with the EDGAR "agricultural waste burn" and "fuelwood burning" emissions with 1x1 degree horizontal resolution and 1 year time resolution. For $PM_{2.5}$, the tracer convective transport scheme accounts also for the wet (in and below cloud) deposition based on the work of Berge [8].

2.2.1 Model configuration, initial and boundary conditions

The main options and parameterizations used in these simulations, for our goal, are described as follows:

- For this study the initial and boundary conditions necessary to drive CATT-BRAMS were provided by the twice daily Aviation run of the National Centers for Environmental Prediction Global Spectral Model (AVN) with a resolution 1.25 x 1.25 degrees. The analyzed fields include geopotential, temperature, wind (u,v), and relative humidity at 11 isobaric levels, and the surface pressure every 6 hours intervals (00, 06, 12 e 18 UTC);
- The model is set up with three tri-dimensional grids. The coarse grid specification was defined with 80 km grid spacing, the other two with 20 km and 5 km horizontal resolutions respectively, both centered at 38.8°N; 9.28°W (Lisbon, with altitude reaching 104 m a.s.l). The vertical resolution starts at 150 m near the surface, stretching at a rate of 1.10 to a final resolution of 850 m, with the model top at about 21 km. The coarse grid

covers Europe, Atlantic Ocean and North Africa. The simulation covered 91 days, beginning July 01 at 00:00 UTC;

- The B-RAMS full microphysics package was activated for all the grids. This scheme includes the use of generalized gamma distributions as the basic function for all hydrometeor species; the use of a heat budget equation for hydrometeor classes, allowing heat storage and mixed phase hydrometeors; partitioning hydrometeors into seven classes (including separate graupel and hail categories); the use of stochastic collection rather than continuous accretion approximations and the extension of the ice nucleation scheme to include homogeneous nucleation of ice from haze particles and cloud droplets (Walko *et al* [9]);
- Grell cumulus parameterization scheme improved by Grell and Devenyi [7], radiation parameterization from Chen and Cotton [10], turbulence and diffusion parameterizations were handled using the Mellor and Yamada [11] was activated in three grids;
- Topography, vegetation type, land percentage and sea surface temperature were read onto the grid from USGS (U.S. Geological Survey at 1km horizontal resolution) datasets. The simulation utilized silhouette-averaged topography (Bossert [12]) in order to incorporate the desired terrain effects.
- A soil model was assumed, using seven levels with 50% saturation moisture for all depths (Tremback and Kessler [13]) and constant inflow conditions are used to the tracer boundary condition.

3 Results

Meteorological conditions: The southeast region of Iberian Peninsula Southeast registered extreme conditions on August 2003, with very high temperatures and unstable atmosphere which favoured fire raged out of control through several parts of Spain and Portugal. The synoptic configuration during the period verified a wide anticyclone system over North Atlantic Ocean as the averaged streamlines at 850 hPa (fig.1(a)) and at 200 hPa (fig. 1(b)) shows, characterizing atmospheric circulation associated with blocking anticyclone. The wind is practically zonal in the south flank of the anticyclone at 200 hPa extending through a quite considerable longitudinal area, with the persistence of the anticyclone over North Atlantic Ocean, which confirms the stationary location of blocking. This anomalous anticyclone is also seen in the anomalies of geopotential height at 500 hPa under the form of an extensive area of positive anomalies (fig. 1(c)). Situation of negative anomaly of relative humidity (fig. 1(d)) is observed in the whole region with positive temperature anomalies extending from Atlantic Ocean to Iberian Peninsula (fig. 1(e)) with negative core pressure anomalies in this area (fig. 1(f)). The persistent anticyclonic conditions characterized by exceptionally high temperatures low values of relative humidity, mainly for the first two weeks of August 2003, with an average flow primary from northwest over Iberian Peninsula, had a significant impact in what respects to the number of forest fires and extension of the burned areas and the development of a large-scale pollution episode.

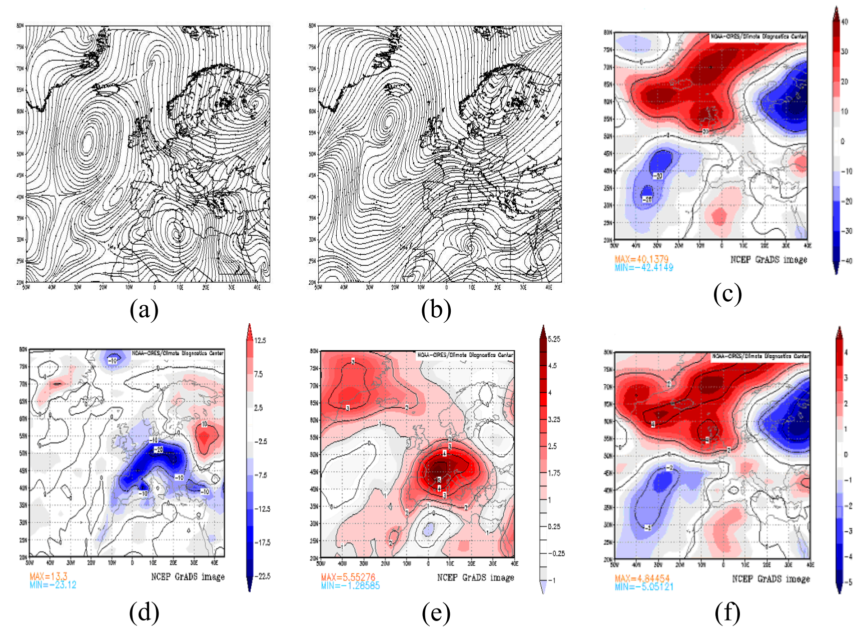


Figure 1: Averaged streamlines at 850 hPa (a) and at 200 hPa (b), geopotential height anomalies (c) at 500 hPa; relative humidity (d) and temperature (e) at 1000 hPa and atmospheric pressure (f) at 850 hPa, August 2003.

Simulation of smoke plume: The analysis correspond to the average carbon monoxide (CO) concentration values (ppb) at two different depths, 53 and 1100 meters, above the surface and of the total column content $PM_{2.5}$ ($\mu g.m^{-2}$) aerosols during the period 7–12 August 2003. The wind fields for the three tri-dimensional grids: 80 km (grid 1), 20 km (grid 2) and 5km (grid 3) are used in the previous simulations. The transport is conditioned by two anticyclones one located over the British Islands and the other one over Azores involving practically all grid domains. Both originate a wind confluence zone along the European continent and North Africa. The wind over Iberian Peninsula, varying from northeast to the east, influences the transport smoke plume. Hence the transport is firstly across the Portuguese continent from Spain, where forest fires occur at different places and then there is a predominant drainage of a part plume towards the south Atlantic Ocean leaving the continent around latitude 37°30'N. A part smoke plume from Galiza in Spain and from north Portugal is transported directly towards the Atlantic Ocean due to the influence of meridional wind flow. An anticyclone over Mediterranean Sea conditions the export of the smoke plume observed over Africa and east Europe. A part plume is displaced towards the southeast of the European continent, including the Mediterranean area, whereas the other part is advected over North Africa mixing with the plume and transported to the Atlantic Ocean. A part smoke plume from France moved to Bay of Biscay and then is redirected to the Atlantic Ocean (fig. 2).

The use grid 2 allows the nesting-grid to higher-resolution simulations of the CO and $PM_{2.5}$ concentrations (grid 3) over Iberian Peninsula. The CO concentrations detailed over the continent show values about 3000 ppb and a maximum core of 5000 ppb mainly in north and centre-south regions of Portugal at both altitudes. In Spain, the maximum values are located along the northern regions as well as at Extremadura, Andalusia and Madrid regions with concentrations of about 100 ppb. The transport is conditioned by two

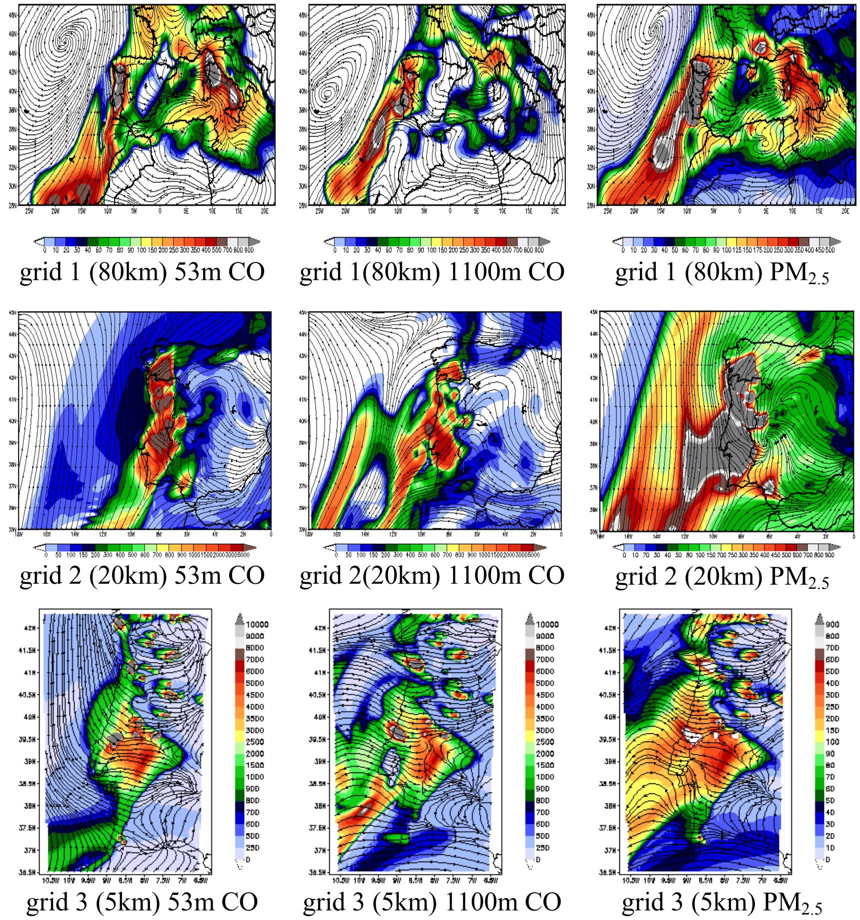
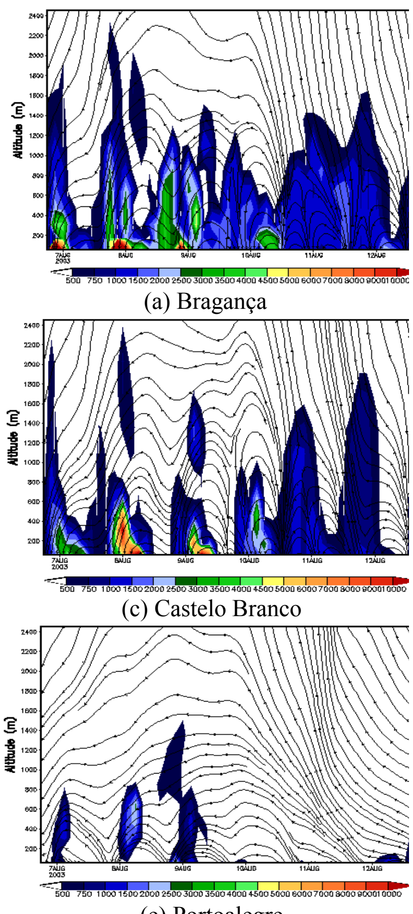


Figure 2: The average smoke plume values of the $PM_{2.5}$ total column content in ($\mu g.m^{-2}$) and CO concentrations in parts per billion (ppb) at two different altitudes , 53 and 1100 meters, with wind field simulated by CATT-BRAMS for grids 1 (80km), 2 (20 km) and 3 (5km), during the period 7–12 August 2003.

anticyclones one located over Atlantic Ocean and the other one over Mediterranean Sea with exports predominantly smoke plume over the Atlantic Ocean reaching the proximity African continent. For grid 3 (5 km) the transport from the fires in the Portugal was influenced by oscillation wind confluence zone over the country, causing two main different exports patterns of plume, one for the interior continent reaching bordering Spain and other to the Atlantic Ocean.

Fig. 3 shows the times series of simulated CO concentrations during the period 7–12 August 2003, for different districts in Portugal, due to forest fires classified according to EFFDAS system, using the higher-resolution wind simulations grid 3 (5km). The CO evolution within planetary boundary layer

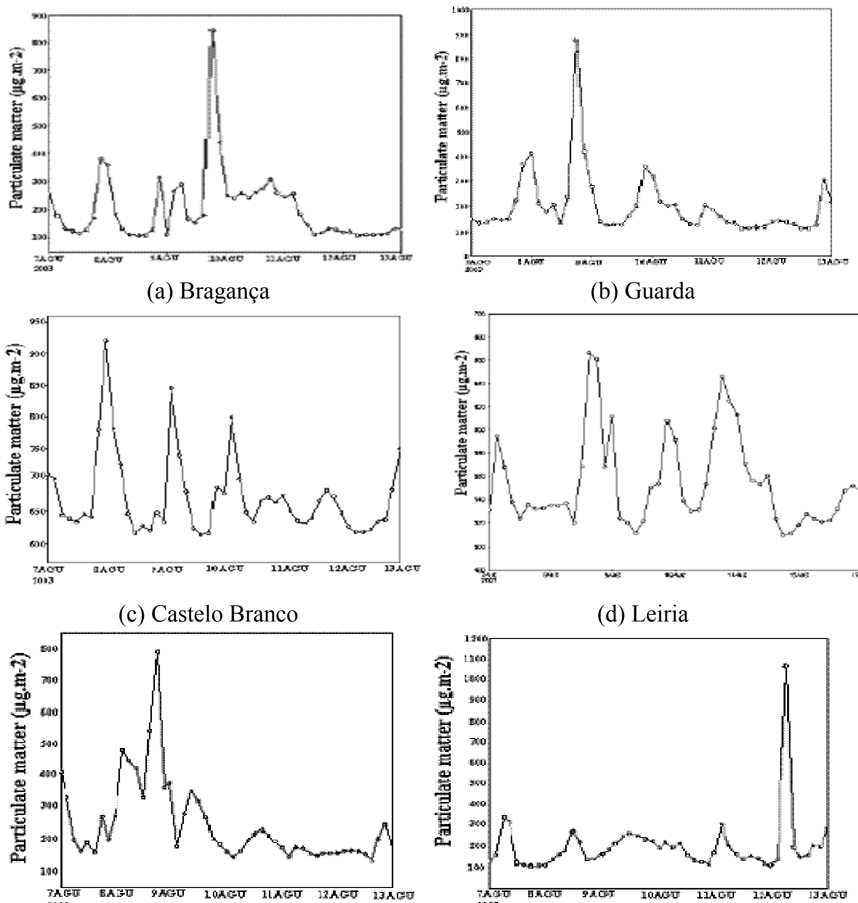


(a) Bragança (b) Guarda

(c) Castelo Branco (d) Leiria

(e) Portoalegre (f) Faro

Figure 3: The time series of concentration monoxide carbon (CO), in ppb, with wind field simulated by CATT-BRAMS for grid 3 (5 km), during the period 7–12 August 2003 to districts in Portugal.



(a) Bragança (b) Guarda

(c) Castelo Branco (d) Leiria

(e) Portalegre (f) Faro

Figure 4: The time series of particulate matter ($PM_{2.5}$), in $\mu g.m^{-2}$, simulated by CATT-BRAMS for grid 3 (5 km), during the period 7–12 August 2003.

(PBL) shows, in all districts, values of about 4.500 ppb confined to an altitude of approximately 2000 meters, with the exception of Portalegre where the values are confined up to 1500 meters. The gas is transported vertically and homogenized inside the mixture layer decreasing in intensity. The export and expansion of the pollutant in horizontal direction and relight the fires (as described in the EFFDAS) can provide high concentrations of pollutant in the atmosphere. The times series simulated particulate matter $P.M_{2.5}$ concentration profile in $\mu g.m^{-2}$ is shown in Fig 4. The modeled results showed maximum concentration values of 950 $\mu g.m^{-2}$ and are obtained mainly for the forest fire event of 09/08/2003. The Faro district shows a maximum on the 12/08/2003 corresponding to a series of forest fire events of great intensity according to the

Forest Portuguese Authorities well as Castelo Branco with higher value record during period.

4 Conclusions

The numeric simulations of the atmospheric transport of gases and particles emitted by forest fires during the occurrence of a heat wave that affected Continental Portugal on the period from 7 to 12 August 2003 were performed using the on-line 3-D transport model CATT-BRAMS (**C**oupled **A**erosol and **T**racer **T**ransport to the **B**razilian developments on the **R**egional **A**tmospheric **M**odeling **S**ystem) coupled to an emission model, which explores the B-RAMS tracer transport capability of using slots for scalars. It is an on- line transport model fully consistent with the simulated atmospheric dynamics. The results show the large-scale circulation may be responsible for transporting of smoke plume to distant regions away from the burned sites and covering thousands of square kilometers. The general performance of the model simulations lead to believe that the mesoscale models are a useful tool to describe the atmospheric transport of pollutants over the region. Moreover, the long time permanence of adverse meteorological conditions conjugated in some areas with a high vegetable cover density and a pronounced irregular topography as occurring in the north and center of continental Portugal, have contributed to live sceneries (high temperatures and low relative humidity of air characterizing he environment hot and dry). The biomass combustion emits gases and aerosol particles that interact efficiently with the solar radiation affecting the microphysical processes, dynamics of cloud formation and air quality. The contamination caused by fires can reach distant areas from the burned region and increase the atmospheric pollution of urban and industrial areas. Therefore, the understanding of the evaluation and progress of fires, through numeric modeling simulations contributes to identify the interrelations between biosphere and atmosphere and help authorities to prevent human lost.

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