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The EFFIS forest fire atmospheric emission model: Application to a major fire event in Portugal

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HIGHLIGHTS

- The new forest fire emission model developed for the EFFIS system is tested.
- A large forest fire event occurred in 2011 in Portugal was selected for study case.
- Hourly emissions were calculated for all gas and particulate pollutants.
- These fire emissions represent more than 90% of the total annual amount emitted.
- The impact of these forest fire emissions on air quality is also addressed.

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ABSTRACT

Forest fires are a major contributor of gaseous and particulate compounds to the atmosphere, impairing air quality and affecting human health. A new forest fire emissions module was developed and integrated into the European Forest Fire Information System (EFFIS), which systematically compiles, since 2000, series of burnt area statistics mapped from satellite imagery. This new forest fire emission model was built on classical methodologies of fuel-map based emission estimation that were improved, especially on burning efficiency, fuel consumption estimation and emission factors. It makes the best use of EFFIS near-real time and detailed information on forest fires, mainly concerning products with a high temporal resolution, which is needed to simulate smoke dispersion and chemical transformation in the atmosphere.

A case study of a forest fire event in the north of Portugal on October 14, 2011, with a total of 4400 ha of burnt area, was selected to test this forest fire emission model. The fine scale information used in this study included: (1) 3-h resolution meteorological fields; (2) daily evolution of the cumulative fire perimeter from the EFFIS rapid damage assessment system; and (3) a fine spatial resolution fuel map, forest type map and topography. The 3-h evolution of pollutant emissions was calculated for gas and particulate species based on the evolution of the burnt area increase and fuel consumption. The estimated forest fire emissions represent more than 90% of the total annual (anthropogenic and natural) emissions over the study region. The impact of these forest fire emissions was analyzed in terms of air quality, using observational data from the nearest air quality monitoring station. High peaks of NO_2 and SO_2 were registered simultaneously during the period 06–09 a.m. and a later peak of PM from 07 a.m. to 15 p.m.

1. Introduction

Biomass burning events, such as those produced by forest fires, represent an important source of gas, particle and heat releases into the atmosphere. However, these fires vary widely in three aspects: the pollutants that are emitted, the proportions of the pollutants and the energy with which they are released. The direct or immediate consequences of forest fire emissions are a major issue for air pollution (Miranda, 2004; Goldammer, 2009), climate (Liousse et al., 1996; Wu et al., 2007) and human health (Miranda et al., 2012). For almost three decades the estimation of trace gases and particulate emissions from vegetation fires has been based on the "fuel-map" based method proposed by Seiler and Crutzen (1980). This approach is based on the information on the

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burnt area extent, the amount and type of biomass burnt (fuel types, fuel loads), and the conditions under which fires take place (combustion efficiencies); finally emission factors are used to estimate the amount of emissions of each species (gases and particles). All these variables are affected by high uncertainties, often reaching more than 50% in the final emission estimates at the global scale (Liousse et al., 2004; Ottmar et al., 2008). Currently, the use of detailed space borne data to help reduce such uncertainties is growing, as shown by a comparison exercise at global scale (Stroppiana et al., 2003; Jain, 2007). In order to reduce these uncertainties, and because real-time information is now increasingly needed for operational use in rapid fire damage assessment, an operational fire emission system has been recently developed at regional/European scale and included in the European Forest Fire Information System (EFFIS) (San Miguel et al., 2012). The EFFIS fire emission estimation model is one of the finest resolution fuel-map based operational systems using detailed fuel maps and sequential mapping of the fire evolution on the basis of satellite imagery for all Europe (Liousse et al., 2011).

The objectives of our work are to present the first operational application of the fully-developed EFFIS forest fire emission model for a case study occurring in Portugal, analyze its results in terms of emissions and air quality, and compare its results with anthropogenic emissions. The methodology and the forest fire emission model are detailed in Section 2. The selection and description of the study case are included in Section 3. Analysis of results, including comparisons between forest fires and anthropogenic emissions and their impacts on air quality data are then discussed in Section 4 and the conclusions are highlighted in Section 5.

2. The EFFIS forest fire emission model

EFFIS is a comprehensive system set up to monitor forest fires throughout the whole fire cycle. It was developed to provide comprehensive and harmonized information on forest fires at the European level. It started its operation in 2000 with the fire danger forecasting modules and it has been improved since then with the addition of new modules (see San-Miguel-Ayanz et al., 2013, 2012). The system is organized in modules that provide information on the pre-fire phase, supporting forest fire prevention and preparedness; the active fire phase; and the post-fire phase, mainly dealing with the assessment of forest fire impact, in terms of land cover damage, emissions to the atmosphere and soil degradation and erosion. In addition to these modules, the so-called European Forest Fire Database stores information provided by the members of the EFFIS network, currently 37 countries in Europe, North Africa and the Middle East.

The forest fire emissions module in EFFIS is based on the traditional method that makes use of information on the fire extent, the type of fuels burnt, the burning conditions (to differentiate flaming and smoldering phases) and the duration of the fire to estimate the amount of gases and particles that are emitted to the atmosphere. The key factors influencing the forest fire emissions are fuel types, meteorological conditions, topography, and the fire intensity as related to flaming or smoldering combustion phases (Scott and Reinhardt, 2001). In the EFFIS emissions model system, these key factors are taken into account in the following steps:

(1) Retrieval of information on fire location and extent of the burnt surface. This is obtained from the processing of the Moderate Resolution Imaging Spectroradiometer (MODIS) imagery (Justice et al., 2002) on board of the AQUA and TERRA satellites at 250 m ground resolution. Burned areas are detected on the basis of thresholding algorithms that exploit the information on the red and mid-infrared bands of the spectrum in the MODIS data and using additional information from the EFFIS hot spots (active fire detection) and the EFFIS fire news (see San-Miguel-Ayanz et al., 2009, 2012). As with any other optical sensor, the presence of clouds prevents the observation of burned areas from MODIS.

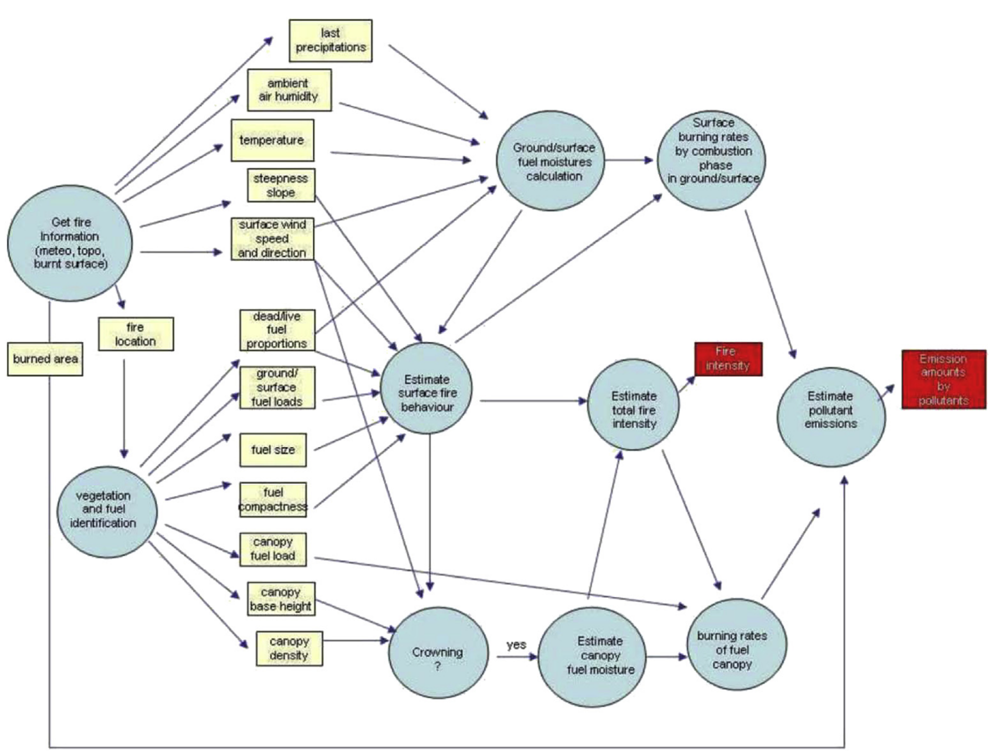

Fig. 1. Schematic representation of the EFFIS forest fire emission model.

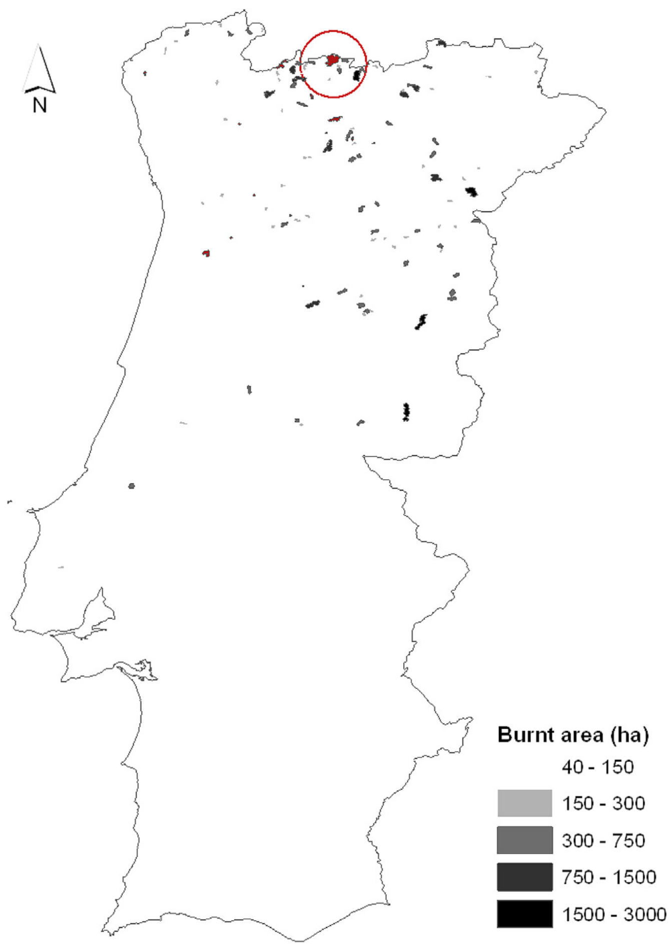

Fig. 2. Spatial distribution of the burnt areas (>40 ha) registered in Portugal during 2011 year.

However, since most of the impact caused by forest fires in Europe occurs during the summer season (San-Miguel-Ayanz and Camia, 2010), cloud coverage does not pose a major problem for the performance of EFFIS in mapping burned areas that can have a significant contribution to fire emissions.

(2) Identification of topography, meteorological fields and fuel composition (surface and canopy fuels) at that site. Topography is obtained from the Shuttle Radar Topography Mission (SRTM) (Rodriguez et al., 2005) model at 100 m resolution, while meteorological fields are obtained from the Deutscher Wetterdienst (DWD) model at 7 km ground spatial resolution, from which the Fire Weather Index (FWI) and its sub-indices are computed in EFFIS.

(3) Evaluation of two key variables: fuel moisture content for ground/surface/canopy and fire line intensity (kW m^{-1}). Fuel moisture for dead fuels is obtained from the FWI sub-indices, while live fuel moisture is obtained from vegetation indices derived from MODIS data herbaceous vegetation (Yebra et al., 2008), from the Drought Code (FWI sub-index) for shrubs, and from empirical data (Dimitrakopoulos et al., 2003; Mitsopoulos, 2010) for fuel canopies.

(4) Assessment of burning efficiency and fuel consumption during the different combustion phases (smoldering/flaming). Information on burning efficiency and fuel consumption is obtained from the coupling of the FOFEM5 and the CONSUME3 models, for non-woody and woody fuels, respectively. FOFEM5 (First Order Fire Effects Model) is used for predicting tree mortality, fuel consumption, smoke production, and soil heating caused by prescribed fire or wildfire (Reinhardt, 2003), while CONSUME3 uses fuel characteristics and fuel conditions to determine fuel consumption and emissions in the combustion phase (Ottmar et al., 2006).

(5) Assessment of emissions from burnt fuel loadings. Fuel loadings are taken from the fuel map derived by Sebastian et al. (2002), while emission coefficients are obtained from the most recent literature on this topic (e.g. Andreae and Merlet, 2001; Miranda et al., 2005) as described in the next paragraphs of this section.

The integration of the emission chain included in the EFFIS modeling system is represented in Fig. 1.

In summary, the main improvements from previous methods are thus:

(1) a more precise estimation of the burning efficiency, considering fuel properties, meteorological factors and for the fire intensity itself, using time-variable meteorology to improve the constant emissivity of the fire, at the finest spatial and

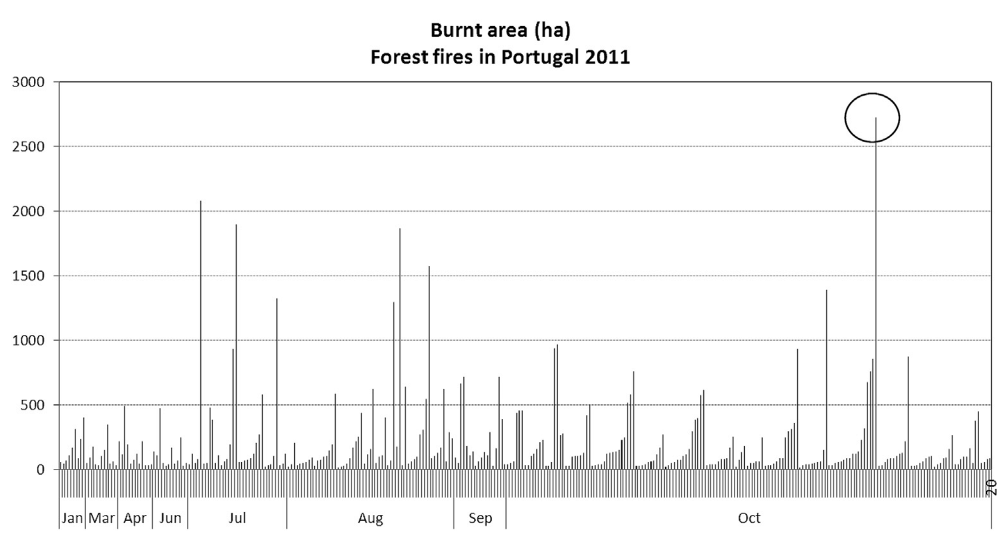

Fig. 3. Forest fire events with burnt area >40 ha registered in Portugal during 2011 year.

Table 1
Summary of the input data used for the emission model application.

Input data	Source	Resolution and format
Burnt area	Daily burnt areas from 250 m resolution MODIS	Shapefile, daily (EFFIS system)
Fuel types	EFFIS fuel map using the US-NFDRS fuel types nomenclature	Raster 250 m (fixed)
Dead fuel moisture contents	EFFIS datasets based on the DWD model	Raster 7 × 7 km^2, daily
Meteorological data	German model DWD model (relative humidity and temperature at ground, wind speed at ground and precipitation amounts)	Raster daily (every 3 h) and by 7 × 7 km^2 spatial resolution.
Emission factors	Up to date bibliography	Based on Miranda et al. (2005) differentiated by flaming and smoldering phases, with corrections (Liousse et al., 2004) and other authors, as described in the text.
Live fuel moisture content - Live grass/shrub fuel moisture	EFFIS fire danger components from the DWD model and MODIS data. Shrubs from Drought Code sub-index of the FWI Live grass/shrub fuel moisture: FMC derived from vegetation indexes from MODIS data.	Shrubs – 7 km × 7 km Herbaceous vegetation – 250 m
Canopy fuel moisture content.	From empirical data	Raster 250 m (GeoTiff)
FWI	EFFIS datasets based on the DWD model	Raster 7 km × 7 km spatial resolution.
Fire intensity	NEXUS based on Rothermel's model	Provided for each fuel at 250 m as kW m^{-1}

associated temporal resolution; estimating surface fire intensity in order to assess the crown fire potential; estimating live fuel moisture using EO (Earth Observation)-based data. It should be noticed that in this model fire intensity is expressed as fire line intensity. There is a correlation between both, although one is linear and the other one is area, described by the Byram's fire intensity equation (Rothermel and Deeming, 1980): $I = Hwr$ where: I is Fire Intensity (kW m^{-1}); H is fuel low heat of combustion (kJ kg^{-1}); w is the weight of fuel consumed per unit area (kg m^{-2}) and r the rate of spread (m s^{-1}).

(2) an update of the emission factors from the most recent literature. Emission factors were first taken from Miranda et al. (2005) for grassland, shrubland and canopy, and then complemented for fine dead fuels with values from Battye and Battye (2002) and Leenhouts (1998) and for medium/large dead fuels with data from Leenhouts (1998). Missing emission factors for some species (SO_2, NH_3, BaP, levoglucosan) were adapted from Andreae and Merlet (2001).

(3) the use of the near-real time burnt area information (twice daily updates of burnt areas and perimeters from MODIS satellite imagery processed in EFFIS), using the fire perimeter evolution rather than a fire perimeter estimated after the fire episode. Estimates of the daily net amount of area burnt were derived from cumulative burnt area mapping since the start of the fire. Additionally, information on fuels is also available in EFFIS, with fuel types identified at a 100 m resolution (Sebastian et al., 2002).

The above improvements make EFFIS a unique system, with no equivalent in spatial and temporal resolution, to retrieve precise fire information in near-real time, both at local scale (for each fire) and at continental scale, covering all of Europe.

Since the EFFIS fire emission model is intended to provide high temporal assessment of emissions, it requires the estimation of fuel moisture and fire intensity, as the key elements in the assessment of burning efficiency. Fire intensity is obtained using Rothermel's model (Rothermel, 1972) within the NEXUS (Scott and Reinhardt, 2001) model. In summary, the estimation of fire emissions in EFFIS is achieved through the coupling of three models: the NEXUS fire behavior model; and the FOFEM5 (Reinhardt, 2003) and CONSUME3 fire effects models. NEXUS is used to model fire behavior, fire intensity and to assess fire crowning potential, while FOFEM5 and CONSUME3 determine the combustion efficiency of woody and non-woody fuels, respectively. The assessment of crown fire potential provided by NEXUS is essential for the estimation fuel consumption and therefore for the estimation of fire emissions. Additional information required in the overall assessment of smoke emissions includes the estimation of fuel moisture of live fuels, which is computed from MODIS derived imagery 8-day composites, and the assessment of dead fine fuel moisture content, which is obtained from the Fine Fuel Moisture Content sub-index of the Fire Weather Index (Van Wagner and Picket, 1987) in the Fire Danger Assessment module of EFFIS (for a detailed description of the EFFIS fire emissions module, see Guillaume et al., 2013).

3. The case study

The location of the burnt areas, superior to 40 ha, registered over the entire 2011 season in mainland Portugal are shown in Fig. 2.

The burnt areas are mainly located in the inner northern and central regions of Portugal, comprising approximately 65 000 ha. This fire-affected region was previously studied by Scotto et al. (2012), who studied fires occurred during the 1980–2010 period. The sequential growth of the area affected by the fires as registered from MODIS imagery in EFFIS over January–October 2011 year is shown in Fig. 3.

All forest fire events registered from January to October were considered in our analysis. The most critical period in terms of burnt area was that for the months of July and August, when several large forest fires events burnt areas larger than 1000 ha. Nevertheless, the highest peak of burnt area in a single day was registered on October 14th (fall season), with more than 2500 ha affected by fires (pointed out with a bullet in Fig. 3).

This largest fire of the 2011 season was selected as a case study to assess the performance of EFFIS fire emissions model. This fire occurred in the North of Portugal, close to the border with Spain, as highlighted in red (in the web version) in the map of Fig. 2. The fire started on October 14th, when it reached its maximum intensity, and was completely extinguished on October 16th. Our analysis will focus on the October 14th, where the highest daily burnt area was reached.

4. Results

4.1. Forest fire emissions estimation

The input data collected for the selected case study are summarized in Table 1, according to the required input variables identified in Section 2.

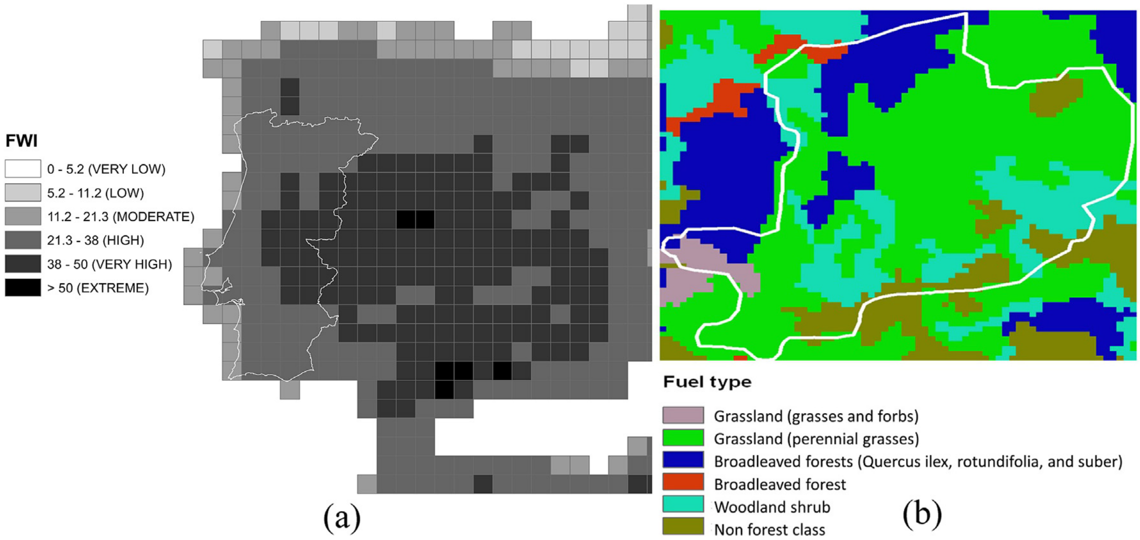

Fig. 4. Examples of input data used for this case study: (a) FWI for the 14th October over whole Portugal and (b) Fuel type for the selected burnt area event.

In Fig. 4 two examples of the input data for the selected case study are presented, namely: (a) Fire Weather Index (FWI) values and (b) fuel type maps.

In EFFIS, the FWI forecast is computed on the basis of meteorological forecast data including precipitation, temperature, relative humidity and wind speed using the original equations in the Canadian system of Van Wagner and Picket (1987). The analysis of the FWI data shows that a “high” fire danger was forecasted over the selected burnt area for the day of the fire event. Regarding the fuel type, the burnt area was composed mainly by grassland (perennial grasses), broadleaved forests, and shrubland.

The EFFIS forest fire emission model was applied for the selected case study and emissions were estimated for the main pollutants (gas and particulate) emitted by fires, namely CO_2, CO, CH_4, PM2.5, PM10, NMHC, VOC, NO_x, BC, OC, SO_2, NH_4, BaP and levoglucosan.

The output dataset (shapefile format) from the emission calculation contains, for each fire, the fire line intensity time evolution

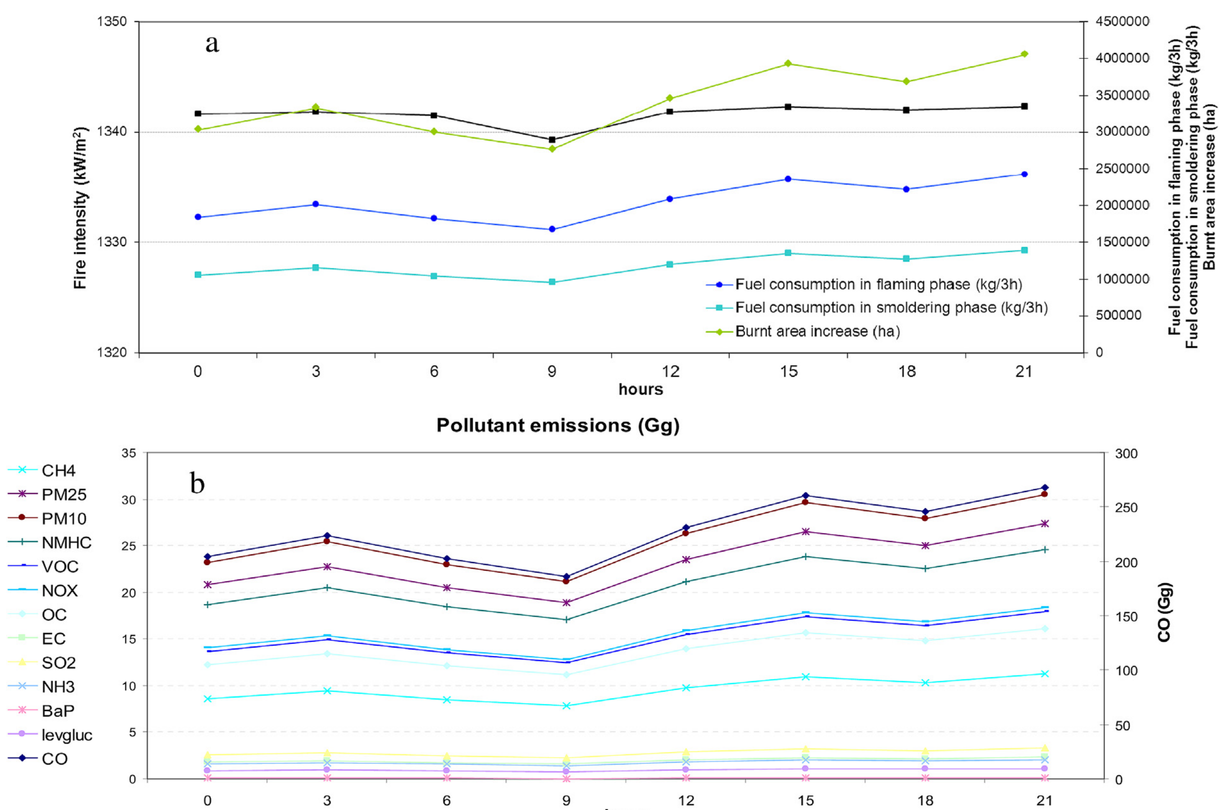

Fig. 5. (a) Fire intensity; fuel consumption and increase of burnt area for the selected case study episode (October 14, 2011); (b) Pollutants emissions (Gg/3 h) calculated by the EFFIS forest fire emission model during the case study (October 14, 2011).

Table 2
Anthropogenic emissions (annually) estimated for the study area and the corresponding burnt area emissions calculated by the EFFIS emission model to the study fire event (October 14, 2011). Emissions are per area (km^2).

Emissions (ton km^{-2})	CO	VOC	NH_3	NO_x	PM10	PM2.5	SO_2
Anthropogenic (annual basis)	0.83	0.36	0.38	0.47	0.11	0.08	0.02
Forest fires (EFFIS model)	523	340	45	340	614	527	57
% Anthropogenic/ total	**0.02**	**0.1**	**0.8**	**0.14**	**0.02**	**0.02**	**0.03**

(every 3 h); burnt area increase and the respective fuel consumption and detailed emitted amounts of each pollutant.

Fig. 5a presents the results obtained with the application of the emission model, as regards to the daily evolution of the fire line intensity (black line), fuel consumption (flaming and smoldering phases) and increase of burnt area.

The fuel consumption in both – flaming and smoldering – phases follows the burnt area increase. Fire line intensity decreases at about 9:00 a.m. being constant over the rest of the day period. These variables – fire intensity, fuel consumption and burnt area increase – determine the daily evolution of the atmospheric pollutants emitted by the forest fires. In Fig. 5b the daily evolution (each 3 h) of the emissions of each type of compound/pollutant are represented.

The temporal variation, similar to all pollutants (gas and particulate), is proportional to the burnt area increase and fuel consumption (shown in Fig. 5b).

The ratio PM2.5/PM10 around 0.9 indicates that mainly fine particles (aerodynamic diameter < 2.5 μm) are emitted by the fire event. This finest fraction of particulate matter has harmful effects on human health (Rohr and Wyzga, 2012).

In order to evaluate the relevance/importance of these forest fire emissions, they were compared with the anthropogenic emissions estimated for a typical week day over that area (Table 2). The anthropogenic emissions include all activity sectors namely: industrial and residential combustion; production processes; solvents use; transport; waste treatment and agriculture. They were compiled using the national emission report developed on an annual basis by the Portuguese Agency for Environment (URL1; Monteiro et al., 2007).

The quantity of pollutants emitted per area by the forest fire event occurred during October 14, 2011, corresponds to more than 95% of the total annual emissions over the study region. In the majority of pollutants, the magnitude of the forest fire emissions is three orders larger than the total annual emitted by all the anthropogenic activities. These extremely relative high values of the forest fire emissions are, in part, explained by the rural characteristics of the municipality under study. In these particular regions, the forest fire emissions can be the most important and relevant source of air pollution.

4.2. Impact of the fire emissions on air quality

To evaluate the potential impact of the forest fire emissions on the ambient air quality over the study region, pollutant concentration values measured at the closest monitoring site (a rural background station named "Douro Litoral"; see location at Fig. 6) were used. First, forward and backward trajectories were simulated to analyze the origin and transport of the air masses during that specific day. These air mass trajectories were obtained with the version Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT v4.8) developed by the National Oceanic and Atmospheric Administration (NOAA)'s Air Resources Laboratory (ARL) (Draxler and Hess, 2004). Reanalysis NCEP/NCAR data were chosen as meteorological input files to calculate the HYSPLIT trajectories. The resulting forward trajectories from the fire location and the backward trajectories that reach the Douro Litoral monitoring site are depicted in Fig. 6a and b, respectively, for October 14, 2011.

The results pointed out that the air masses that reached this air quality monitoring station came from the North-East direction, passing through the forest fire event. Fig. 7 presents the concentrations of the several pollutants (gas and particulates) measured,

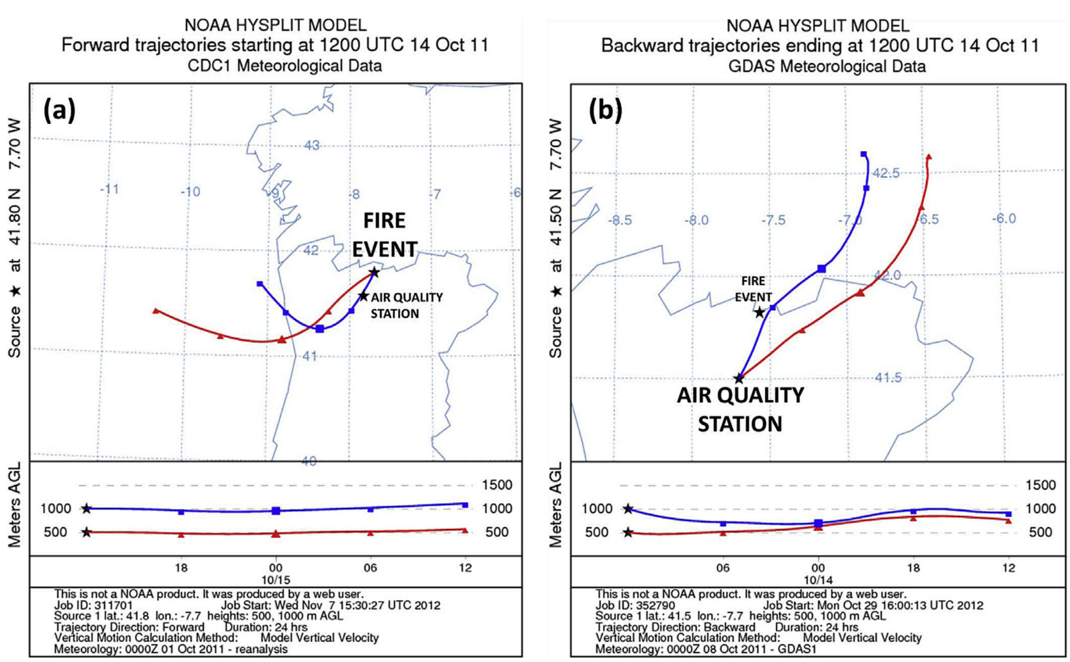

Fig. 6. Forward (a) and Backward (b) trajectories obtained with the HYSPLIT model from the burnt area (forward) and the air quality station located southern to the forest fire episode (backward).

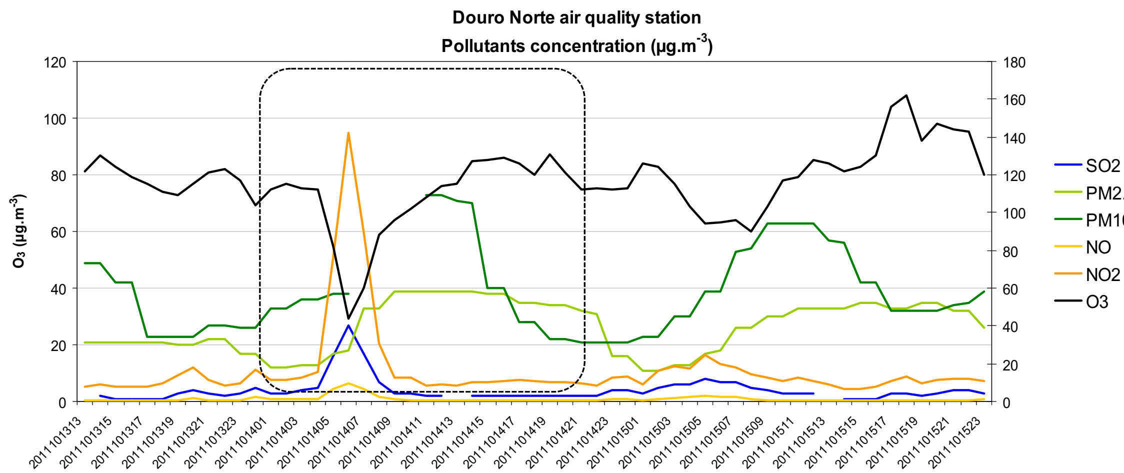

Fig. 7. Pollutants concentration measured in Douro Norte air quality station (located 50 km south the occurrence of the forest fire episode) during October 13–15, 2011.

along the previous and following days of the fire event, at Douro Litoral station (URL2).

The peaks of NO/NO_2, SO_2 and PM are coincident with the forest fire event occurred at north. The delay observed in the PM peaks can be justified by the higher density of this particulate matter, as compared to the amounts of gas species (NO_2 and SO_2). The decrease of ozone that follows these peaks is related to the photochemistry cycle, and more specifically to the consumption/titration of O_3 that take place when high concentrations of NO exist (Seinfeld and Pandis, 1998).

The peaks of NO_2 and SO_2, developed in 2 h, registering an increment of 900% (about 90 µg m^{-3}) in the case of NO_2 and 540% (~20 µg m^{-3}) for SO_2, compared to the previous hours. The increase of PM concentration had an order of magnitude of 50 µg m^{-3} (167%). Despite the large increments, the levels of pollutants didn't exceed the legislation limit values established for short term human health protection: daily mean of 50 µg m^{-3} for PM10 and 125 µg m^{-3} for SO_2 and hourly maximum of 200 µg m^{-3} for NO_2. These results can be explained by the low level of background values that exist in this particular monitoring site, characterized by rural influence and background environment. Other major pollutants emitted by forest fires were CO and VOC, but no measured concentration data was available at this monitoring site.

5. Conclusions

The EFFIS forest fire emission model was developed within a regional and European framework, with new improvements on the classical "fuel-map" based approaches, especially on revisiting the burning efficiency estimations and the choice of emission factors, and on the use of the near-real time fire information. This emission model was applied and tested for a large forest fire event occurred in Portugal, in October 14, 2011.

The input data needed for the emission model application comprehended a series of data, namely the burnt area location; the fuel type and forest properties; meteorological data and fuel moisture. The emissions calculated are, as expected, directly proportional to the increase of burnt area and fuel consumption. The forest fire emissions estimated correspond to more than 90% of the total annual quantity of pollutants emitted (anthropogenic and forest fires) over that study area, mainly in what concerns CO, VOC, PM and SO_2.

The impact of these forest fire emissions was also analyzed in terms of air quality, using observational data from the nearest air quality monitoring station ("Douro Litoral" site). Peaks of NO_2 and SO_2 were registered simultaneously during the period 06–09 a.m. and a later peak of PM from 07 a.m. to 03 p.m. Taking into account the analysis of the air masses background trajectories (obtained through the HYSPLIT model), it can be concluded that the forest fire emissions were transported southerly and were responsible for these peaks. The delay of PM transport was determined by the higher density and dry deposition phenomena. The reduction of O_3 observed at the same time to the NO/NO_2 peaks can be explained by their photochemistry properties (titration of O_3 by high concentration of NO).

Besides this validation in terms of air quality data, it was not possible to compare the emission model results against observation values due to the lack of monitoring or measured field campaigns emission data. In this sense, additional validations are necessary to fully evaluate the forest fire model performance (e.g. its strengths/weaknesses).

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