THE EFFIS FOREST FIRE EMISSION MODEL: APPLICATION TO A MAJOR FIRE EVENT IN PORTUGAL

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Abstract:
Forest fires are a major contributor of gaseous and particulate compounds to the atmosphere, which can impair air quality and affect 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 forest fire emission model was built on classical methodologies of fuel-map based emission estimation with improvements, especially on the burning efficiency and fuel consumption estimation (using a fuel map and fuel moisture estimates) and emission factors (literature updated). This new emission model makes the best use of near-real time and detailed information on forest fires in EFFIS, mainly concerning products with a high temporal resolution, which is needed to simulate smoke dispersion and chemical transformations in the atmosphere.
A study case of a forest fire episode 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-hr resolution meteorological fields; (2) daily evolution of cumulative fire perimeter from the EFFIS rapid damage assessment system, and (3) a fine spatial resolution of fuel map, a forest type map and topography. The daily evolution (each 3h) of pollutant emissions were calculated for all gas and particulate species following 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, SO_2 were registered simultaneously during the period 06-09 a.m. and a later peak of PM from 07 a.m.-15p.m.

Key words: *Burnt area; forest fires; emissions; gas and particulate pollutants; air quality.*

INTRODUCTION

Biomass burning events, such as those produced by forest fires, represent an important source of gases, particles 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 fires emissions are a major issue for air pollution (Miranda et al., 2004; Goldhammer, 2009), climate and human health (Wu et al., 2007). For almost three decades the estimation of trace gases 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 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).

Currently, large use is made of detailed space borne data to help reduce such uncertainties, as shown by a recent comparison exercise at global scale (Jain, 2007; Stroppiana et al., 2010). 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 in EFFIS (San Miguel et al., 2011). This European Forest Fire Information System (EFFIS) provides one of the finest resolution fuel-map based operational system, allowing to retrieve the required spaceborne information for estimating forest fire emissions over Europe (Liousse et al., 2011).

The main improvements from previous methods are thus: (1) a more precise estimation of the burning efficiency, accounting not only for fuel properties, but also for 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 associated temporal resolution; estimating surface fire intensity in order to assess the potential of fire propagation to canopy; estimating fuel moisture using preferably EO-based data (possible for live grass/shrub) or, if not, EO-based data obtained through empirical modeling in EFFIS; (2) an update of the emission factors from the most recent literature. Emission factors were first taken from Miranda et al. (2005) for grasslands, shrublands 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) and (3) the use of the most recent fire information (daily updates of burnt areas and perimeters from MODIS imagery processed in EFFIS), using the fire perimeter evolution rather than a fire perimeter estimated after the fire episode (or a combination of both); estimating a daily net amount of area burnt from a cumulative burnt area (cumulated from the beginning of the fire). Additionally, information on fuels is also available, with fuel types identified at 100 m resolution (Sebastian-Lopez et al, 2002). The above improvements make EFFIS a unique system, with no equivalent in spatial and temporal resolution, to retrieve in near-real time precise fire information, both at local scale (for each fire) and at continental scale, covering the entire Europe.

The objective of this work is to present a first operational application of the full-developed EFFIS forest fire emission model for a study case occurred in Portugal, to compare the results with the anthropogenic emissions in the area and to assess its impact on the air quality.

THE FOREST FIRE EMISSION MODEL (THE EFFIS SYSTEM)

EFFIS is a comprehensive system set up to monitor forest fires throughout the whole fire cycle. 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 damage to the land cover, emissions into the atmosphere and soil degradation and erosion.
As shortly described above, 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 that 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 (Guillaume et al., 2012).

The key factors influencing the forest fire emissions are fuel types, meteorological conditions, topography, and the fire itself (fire intensity evolving during the combustion phases). In the EFFIS model system, these key factors are taken into account in the following steps:
(1) retrieval of information on fire location and burnt surface;
(2) identification of topography, meteorological fields and fuel composition (ground, surface, canopy fuels) at that site;
(3) evaluation of two key variables: fuel moisture (% of relative humidity in fuel) for ground/surface/canopy and fire intensity ($kW.m^{-2}$);
(4) assessment of burning efficiencies and amounts of fuel burnt (or fuel consumptions) during the different combustion phases (smoldering/flaming); and finally
(5) evaluation of emissions from burnt fuel loadings.

THE STUDY REGION

The location of the burnt areas, superior to 40 ha, registered over the entire 2011 season in mainland Portugal are shown in Figure 1a. The burnt areas are mainly located in the inner northern and central regions of Portugal. The time distribution of the burnt area registered over 2011 year is shown in Figure 1b.

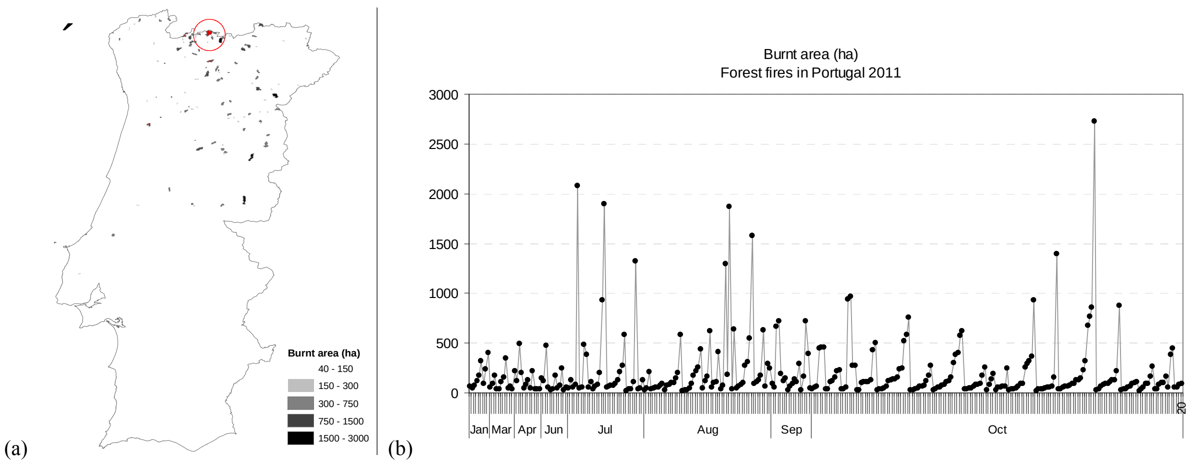

Figure 1. (a) Spatial distribution and (b) temporal evolution of the burnt areas (> 40 ha) registered in Portugal in 2011.

Forest fire episodes were registered from January to October. It is clearly noticeable that the most critical period in terms of burnt area occurred during July/August months, with several forest fire events with burnt areas larger than 1000 ha. Nevertheless, the highest peak of burnt area was registered in October 14 (fall season), with more than 2500 ha. This forest fire episode was located in the North of Portugal (close to the Spanish frontier and pointed out in Figure 1a), starting on October 14 and only completely extinguished in October 17, was selected as a case study to assess the functioning of the EFFIS emission model.

FOREST FIRE EMISSIONS ESTIMATION

The input data collected for the selected study case are summarize in Table 1, according to the required input variables described previously.

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

Input data	Source	Format, Resolution, Frequency
Burnt area	MODIS	Shapefile, daily; 1km resolution
Fuel type	US-NFDRS fuel types	Raster 250 m
Forest canopy properties	EFFIS datasets	Raster 250 m (GeoTiff)
Meteorological data	German model COSMO-EU	Grib; daily (every 3h);7km resolution
Topography		DEM ACE2; 3 arcseconds
Emission factors	Bibliography updated based on Miranda et al. (2005) differentiated by flaming and smouldering phases, with corrections (Liousse et al. , 2004)	
Fuel moisture content - Dead fuel moisture -Live grass/shrub fuel moisture	Dead fuel moisture based on FWI; Live grass/shrub fuel moisture deduced from vegetation indexes inferred from MODIS surface corrected reflectances (following Yebra et al., 2009) Raster 40x40km^2, daily	
FWI	EFFIS datasets	Shapefile
Fire intensity	MODIS satellite data	Fire Radiative Power satellite product

The EFFIS forest fire emission model was applied for the selected study case 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, NOx, BC, OC, SO_2, NH_4, BaP and levoglucosan. The output dataset (shapefile format) from the emission calculation contains, for each fire, the time resolution (for each 3 hrs) of the fire intensity; burnt area increase and the respective fuel consumption and the detailed emitted amounts of each pollutant.

ANALYSIS OF RESULTS

Since there were no direct measurements of emission amounts at regional/continental scales, no validation with observation data was possible. Figure 2a presents the results obtained with the application of the emission model, as regards the daily evolution of the fire 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 intensity is constant all over the day period with a significant decrease about 9:00 a.m. These variables – fire intensity, fuel consumption and burnt area increase – determine the daily evolution of the atmospheric pollutants emitted by the forest fires. In Figure 2b is represented the daily evolution (each 3h) of the emissions of each type of compound/pollutant.

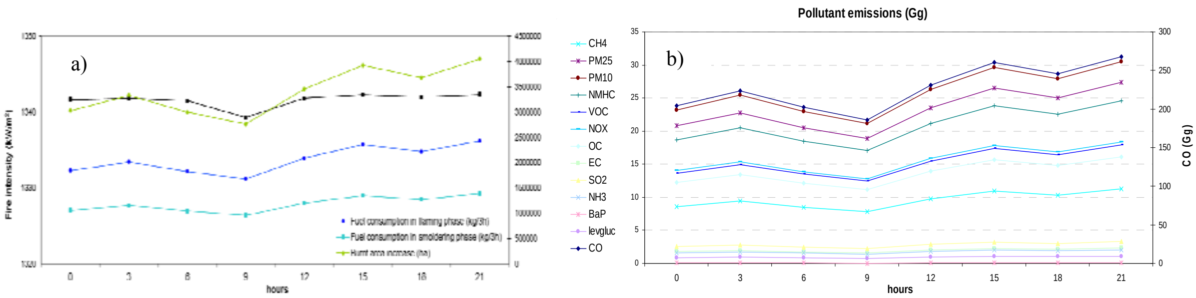

Figure 2. (a) Fire intensity; fuel consumption and increase of burnt area for the selected study case episode; (b) Pollutants emissions (Gg/3h) calculated by the EFFIS forest fire emission model during the study case.

The temporal variation, similar to all pollutants (gas and particulate), is proportional to the burnt area increase and fuel consumption. The ratio PM2.5/PM10 around 0.9 indicates that mainly fine particles (aerodynamic diameter < 2.5 μm) are emitted by the fires. These are the particulate matter with harmful effects over human health. 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 SNAP activities like industrial and residential combustion; production processes; solvents use; transports; waste treatment and agriculture, and were compiled using the national emission report developed on an annual basis by the Portuguese Agency for Environment (Monteiro et al., 2007).

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

Emissions (ton)	CO	VOC	NH_3	NOX	PM10	SO_2
Anthropogenic (annual basis)	660	284	303	373	86	12
Forest fires (EFFIS model)	230000	15000	2000	15000	27000	2500
% anthropogenic/total	0.3	1.9	13.2	2.4	0.3	0.5

As observed, the quantity of pollutants emitted by the forest fire event occurred during October 14, 2011, correspond to more than 90% of the total annual emissions over the study region. In the case of CO and PM10, the magnitudes of the forest fire emissions are three orders of magnitude larger than those of the total annual emissions by all the anthropogenic activities. These extremely relative high values of the forest fires emissions are, in part, justified by the rural characteristics of the study municipality. In these particular regions, the forest fire emissions can be the most important and relevant source of air pollution.

To evaluate the potential impact of these forest fire emissions on the ambient air quality over the study region, pollutants concentration measured at the closest monitoring site ("Douro Litoral" station) was analyzed. 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 (Draxler and Hess 2004). Reanalysis NCEP/NCAR data were chosen as meteorological input files to calculate the HYSPLIT trajectories. The results pointed out that the air masses that reached this air quality monitoring station came from North-East direction, passing through the forest fire event (not shown). Figure 3 presents the several pollutants concentration (gas and particulates) measured along the study period at Douro Litoral station (www.qualar.org).

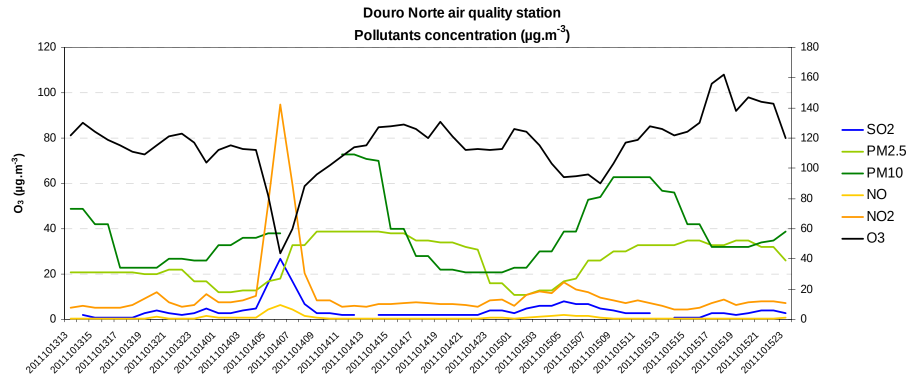

Figure 3. Pollutants concentration measured in Douro Norte air quality station (located 50 km south the occurrence of the forest fire episode) during October 13-15, 2011.

The peaks of NO/NO_2, SO_2 and PM are coincident with the forest fire event occurred at north. The delay observed on 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 O_3 that follows these peaks is related to the photochemistry cycle, and more specifically to the consume/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 hours, registering an increment of 900% (about 90 $\mu g.m^{-3}$) in case of NO_2 and 540% (~ 20 $\mu g.m^{-3}$) for SO_2. The increase of PM concentration had an order of magnitude of 50 $\mu g.m^{-3}$ (167%). Despite the large increments, the levels of pollutants didn't exceed the legislation limit values established for the short term human health protection: daily mean of 50 $\mu g.m^{-3}$ for PM10 and 125 $\mu g.m^{-3}$ for SO_2 and hourly maximum of 200 $\mu g.m^{-3}$ for NO_2. This results can be explained by the low level of background values that exists 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 were available at this monitoring site.

CONCLUSIONS

The EFFIS forest fire emission model was developed for 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 high 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 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 which 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. Peaks of NO_2, SO_2 were registered simultaneously during the period 06-09 a.m. and a later peak of PM from 07 a.m.-15p.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 in the occurrence of these species. 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 the photochemistry properties (titration of O_3 by high concentration of NO).

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