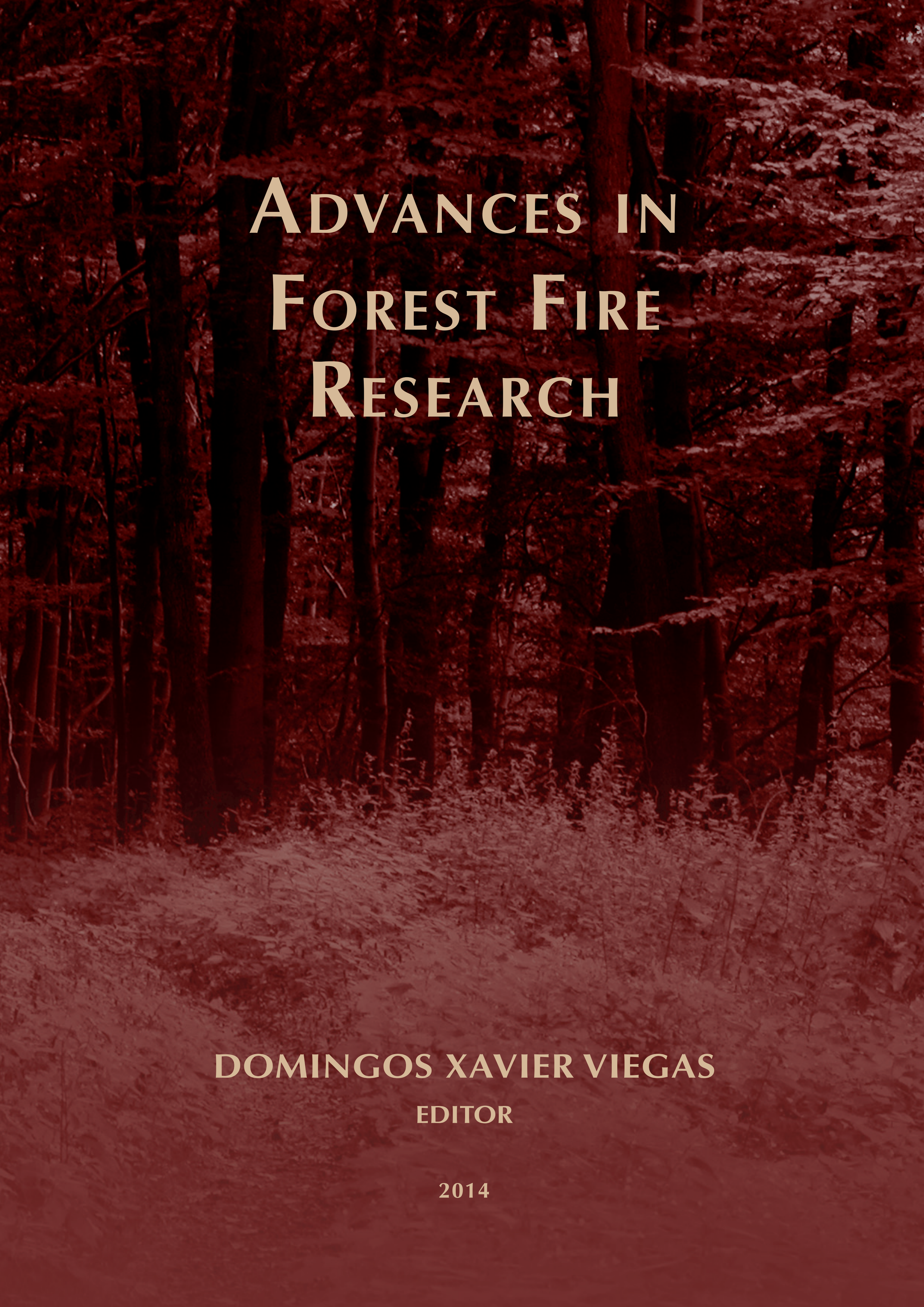

Advances in Forest Fire Research

DOMINGOS XAVIER VIEGAS
EDITOR

2014

Forest fires effects on the atmosphere: 20 years of research in Portugal

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Abstract

Forest fires are one of the most impressive forces of nature. Large amounts of gases and particles are emitted to the atmosphere, with significant impacts on operational safety, air quality, human health and climate change. In the European context, Portugal, together with other south European countries, has a dark record concerning forest fires, with alarming statistics, concerning occurrences, burnt areas, economic and ecological losses and human casualties.

Due to the frequency, magnitude and effects on the environment, health, economy and security, forest fires have increasingly become a major subject of concern for decision-makers, firefighters, scientists and citizens in general.

The GEMAC (Group of Emissions, Modelling and Climate Change) research team, at the University of Aveiro in Portugal, completed 20 years of experience in dealing with the effects of forest fires on the atmosphere, working on the monitoring and modelling of the impacts on the environment and human health, together with national and international teams, through the participation in numerous national and international projects. This research team has been involved in several experimental fires performed since 1998 in the GESTOSA experiments, at Serra da Lousã, Central Portugal. GEMAC has collected a large quantity of experimental data, used to support the development of new methods and models, aiming to estimate the effects of forest fires on the atmosphere. The work presented summarizes GEMAC's most relevant research in what respects the integrated and multi-scale analysis of the interrelations between forest fires and air quality, human safety and health, suppression and climate change.

Keywords*: fire emissions, air quality, smoke, health effects, visibility impairment, climate change, measurement and modelling*

1. Introduction

Forest fires are one of the most impressive forces of nature. A forest fire is a large-scale natural combustion process consuming various types of botanical specimen growing outdoors. Among their consequences, is the emission of various gases and solid particulate matter to the atmosphere with significant impacts on operational safety, air quality, human health and climate change.

In the European context, Portugal, together with other south European countries, has a dark record concerning forest fires, with alarming statistics, concerning occurrences, burnt areas, economic and ecological losses and human casualties.

The GEMAC (Group of Emissions, Modelling and Climate Change) research team, at the University of Aveiro in Portugal, completed 20 years of experience in dealing with the effects of forest fires on the atmosphere, working on the monitoring and modelling of the impacts on the environment and human health, together with national and international teams, through the participation in numerous national and international projects. The work here presented summarizes its most relevant research in what respects forest fires atmospheric emissions and its impact on air quality, human exposure and climate change.

2. Emissions

Smoke from forest fires includes important amounts of carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), nitrogen oxides (NOx), ammonia, particulate matter (PM), non-methane hydrocarbon (NMHC) and other chemical compounds. These air pollutants can cause serious consequences to local and regional air quality. Therefore it is essential to understand and establish the relationship between emissions and air quality. The characterization of forest fire emissions is based on two different, but complimentary approaches: direct measurements and estimation of emissions based on emission factors. Miranda *et al.* (2005) measured, among other gases and particulate matter, volatile organic compounds (VOC) emissions in the flaming and smouldering phase of an experimental fire, verifying that despite the small size of the burning plots when compared to wildfires, the measured levels of pollutants were considerable, indicating the effect of these experiments on the local air quality and stressing the serious levels of air pollution that can be expected during wildfires. Moreover, emission measurements have been done in laboratory and during experimental field fires aiming to evaluate the impact of the use of fire retardants, concluding that in that specific case, though the production of smoke is increased by the application of retardants, the extension of the fire (both in area burned and in duration) is reduced, thus contributing to a decrease of the total smoke emissions (Amorim *et al*., 2010).
Although there is an extensive body of literature on emission factors from forest fires, there are not many works that reflect the specificity of Southern European countries. Miranda (2004) performed and presented a selection of emission factors for South-European forest. This review and summarizing work was further updated and expanded, taking into account more recent works and additional pollutants (Miranda *et al*., 2009). The GEMAC team has an extensive work on the estimation of pollutants emissions using emission factors (see e.g. Martins *et al*. 2012, Figure 1).

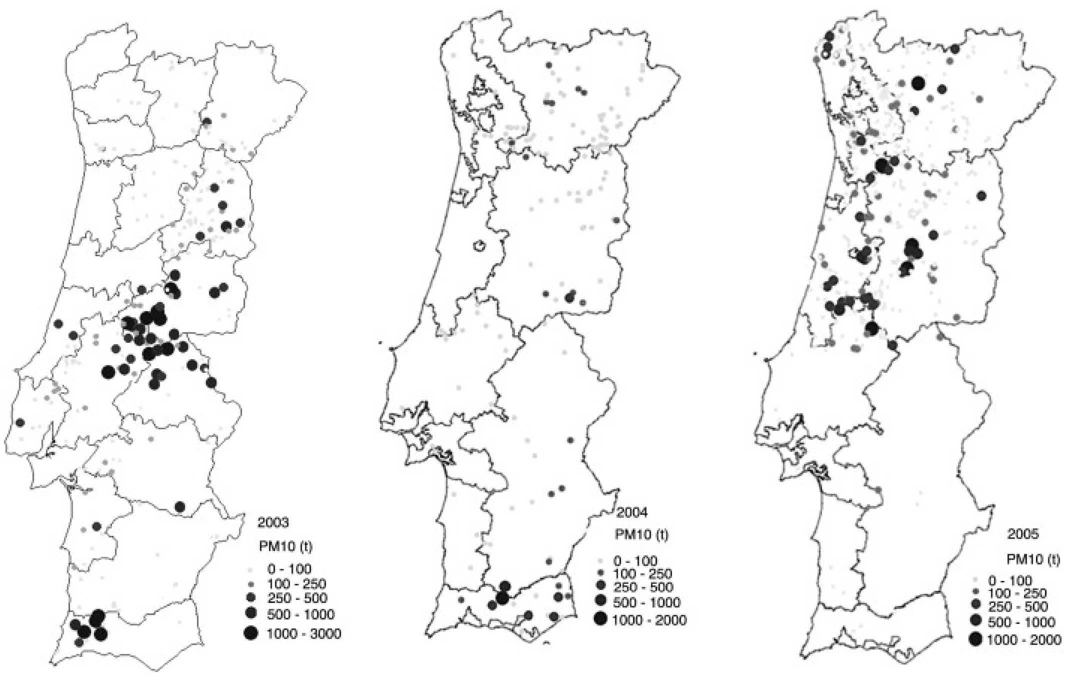

Figure 1. PM10 forest fire emissions spatial distribution for 2003 - 2005 fire seasons in Portugal (only large forest fires were considered (Martins et al., 2012).

Figure 1 shows the spatial distribution of forest fire PM10 emissions for 2003, 2004 and 2005 estimated for air quality modelling purposes. A comparison between the estimated forest fire emission values and values reported by other available inventories is shown in Table 1, which presents the total forest fire emissions for Portugal (2003–2005) for CO_2, CO, CH_4, NMHC, PM2.5, PM10, total particulate matter (TPM) and NOx, based on three different inventories: the aforementioned Portuguese inventory, the Global Fire Emissions Database (GFED) inventory (Van Der Werf *et al*., 2010), and the European Forest Fire Information System (EFFIS) inventory (San-Miguel-Ayanz, J. Steinbrecher, 2009).

Table 1- Total forest fire emissions (t) in Portugal for 2003, 2004 and 2005 fire seasons based on different methodologies (Martins et al., 2012.).

Source	Forest fire emissions (t)							
Year	CO_2	CO	CH_4	NMHC	PM2.5	PM10	TPM	NO_x
2003								
Portuguese inventory	6,842,000	456,000	26,000	32,000	26,000	53,000	-	21,000
GFED	8,000,000	500,000	70,000	30,000	20,000	-	140,000	14,000
EFFIS	10,510,119	411,945	21,475	17,834	41,406	48,913	68,749	28,745
2004								
Portuguese inventory	2,096,000	137,000	8000	10,000	14,000	16,000	-	7000
GFED	3,000,000	200,000	20,000	10,000	10,000	-	50,000	5000
EFFIS	3,312,543	129,112	6735	5599	13,001	15,361	21,597	9013
2005								
Portuguese inventory	3,470,000	230,000	13,000	16,000	24,000	27,000	-	11,000
GFED	14,000,000	800,000	120,000	50,000	40,000	-	250,000	25,000
EFFIS	7,866,267	325,628	16,843	13,833	32,206	38,034	53,180	22,719

- Not available.

In general, the emission data presents the same order of magnitude, but in some cases it is possible to verify a larger difference, namely: for CH_4 in 2004 and 2005 in the GFED inventory; for NMHC in EFFIS inventory in 2004; for TPM for both GFED and EFFIS inventories. The differences were in some way expected because different methodologies were applied.

The GEMAC team is exploring new methodologies for the estimation of forest fire emissions, based on space borne data and on the fuelbed concept. Currently, large use is made of detailed space borne data to help reduce emissions estimation uncertainties, as shown by a recent comparison exercise at global scale (Jain, 2007; Stroppiana, Grégoire, & Pereira, 2003). 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 model has been recently developed at regional/European scale in the European Forest Fire Information System (EFFIS) (San-Miguel-Ayanz, Schulte, Schmuck, & Camia, 2013). This system was applied and tested for a forest fire case study occurred in Portugal on 14th October 2011 (with a total of 4400 ha of burnt area), using detailed fuel maps and sequential mapping of the fire evolution on the basis of satellite imagery (Monteiro *et al*., 2014). 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 Selected Nomenclature for Air Pollution (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 the 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) (Monteiro et al., 2014).

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 from Table 2, the quantity of pollutants emitted by the forest fire event, corresponds to more than 90% of the total annual emissions over the study region. In the case of CO and PM10, forest fire emissions are three orders of magnitude larger than the total annual emissions by all anthropogenic

activities. These high values of forest fires emissions are, in part, explained by the rural characteristics of the study municipality. In this type of rural areas forest fire emissions can be the most important and relevant source of air pollution.
Although air pollutants released from forest fires depend on a number of factors (area burned, fuel loading, fuel consumption, and pollutant-specific emission factors), two factors alone – fuel loading and fuel consumption – account for up to 80% of the error on smoke emissions estimation (Ottmar, Miranda, & Sandberg, 2008). GEMAC is contributing to a higher accuracy of smoke emission estimates for Mediterranean Climate Areas (MCA) by using the Fuel Characteristic Classification System (FCCS) (Ottmar, Sandberg, Riccardi, & Prichard, 2007), to build fuelbeds for Portugal. The FCCS fuelbeds capture the structural complexity, geographic diversity and potential flammability of a fuelbed, encompassing all fuelbed components that have the potential to burn including trees, shrubs, grasses, woody material, litter, and duff. The FCCS evaluates fuelbed hazard by calculating fire potentials, reaction intensity, flame length, and rate of spread. Typical Portuguese fuelbeds were identified and built using the National Forest Inventory, other fuels datasets, published scientific literature, and fuel photo series. The mapping of the defined fuelbeds using vegetation classification and quantitative vegetation data is under development.

3. Air Quality Monitoring and Modelling

The gases and particles emitted during a forest fire undergo chemical transformations in the atmosphere as they are being dispersed, and its impacts can be found at long distances from the source. Despite current evidence, the connection between forest fires and air quality is still an ongoing topic, that only during the last decade started to be more frequently addressed. For the fire community, the main concern consisted in its direct effects, such as human fatalities and material damage. On the other hand, the air quality community was mainly focused on anthropogenic sources of pollutants, particularly in traditional sectors of industry and road traffic.
To evaluate the effects of forest fires on air quality both measurements and numerical models can be used. The research team has been involved in several experimental fires performed since 1998 in Serra da Lousã, Central Portugal, the GESTOSA experiments, collecting a large quantity of experimental data (e.g. Miranda 2004, Miranda *et al.* 2005; Valente *et al.* 2007), used to support the development of new methods and models. Figure 2 shows some of the equipment used to measure air pollutant concentrations during GESTOSA experimental fires.

Figure 2- Photo of van nr. 2 and its air quality equipment. Photo of passive samplers.

The GEMAC team has developed numerical models, AIRFIRE (Miranda, 2004) and DISPERFIRESTATION (Valente *et al*., 2007), that are able to simulate the effects of fire emissions on air quality, at different scales. DISPERFIRESTATION is a fire behavior system, developed to estimate fire progression, smoke dispersion and visibility impairment, at local scale, while AIRFIRE is a numerical system, developed to estimate the effects of forest fires on air quality, at the mesoscale, integrating several components, namely the meteorological model MEMO, the photochemical model MARS and the Rothermel fire spread model. These modelling tools have been applied to various case studies in Portugal, showing that concentrations of pollutants attain levels of concern (e.g. Miranda, 2004; and Valente *et al*., 2007). Figure 3 depicts an output of the DISPERFIRESTATION system, a PM10 concentration field resulting from a burning plot in a GESTOSA experiment, and an AIRFIRE output, showing a vertical profile of wind and CO concentrations.

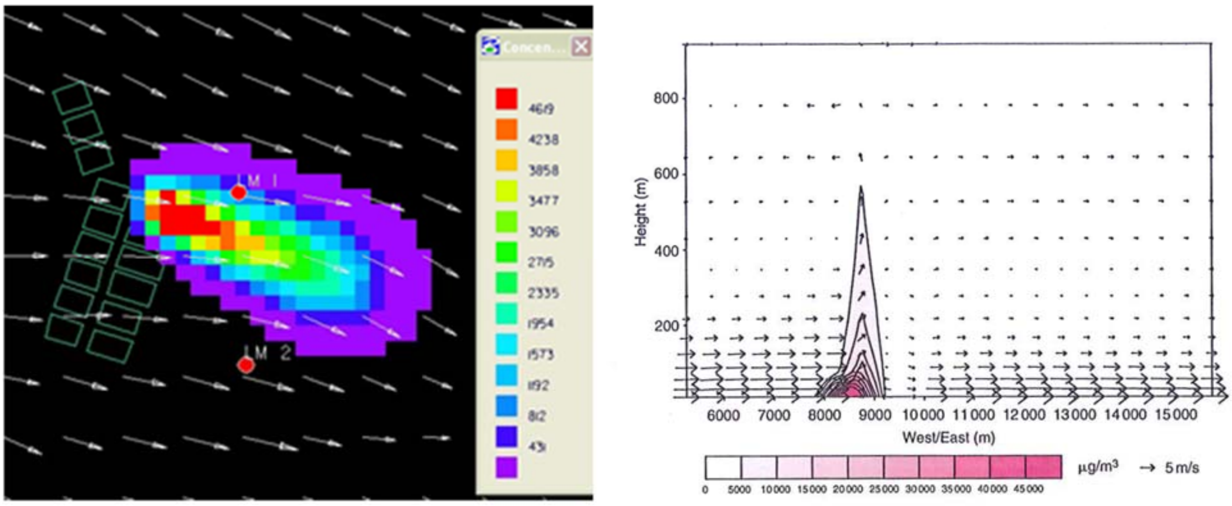

Figure 3. (left) PM10 concentration fields ($\mu g.m^{-3}$), at ground level, after the burn of three plots (400m x 330m) at GESTOSA 2004 experiments (Valente et al., 2007). (right) Vertical profile of wind and CO concentration in a forest fire in Arrábida (Portugal)(Miranda, 2004) .

At the local scale the effect of fire as a heat source is not considered in DISPERFIRESTATION, but AIRFIRE includes this effect in the simulations.
The GEMAC team also worked on the modelling of wildland urban interface fires. Miranda, Marchi, *et al.* (2009) simulated the temporal evolution of the hourly averaged PM10 concentration fields during September 13, 2003. Figure 4 shows the surface hourly averaged PM10 concentration patterns for 22.00 LST as estimated by AIRFIRE. There is an obvious contribution by forest fires to the particularly high levels of PM10 measured in the urban area of Lisbon at night.

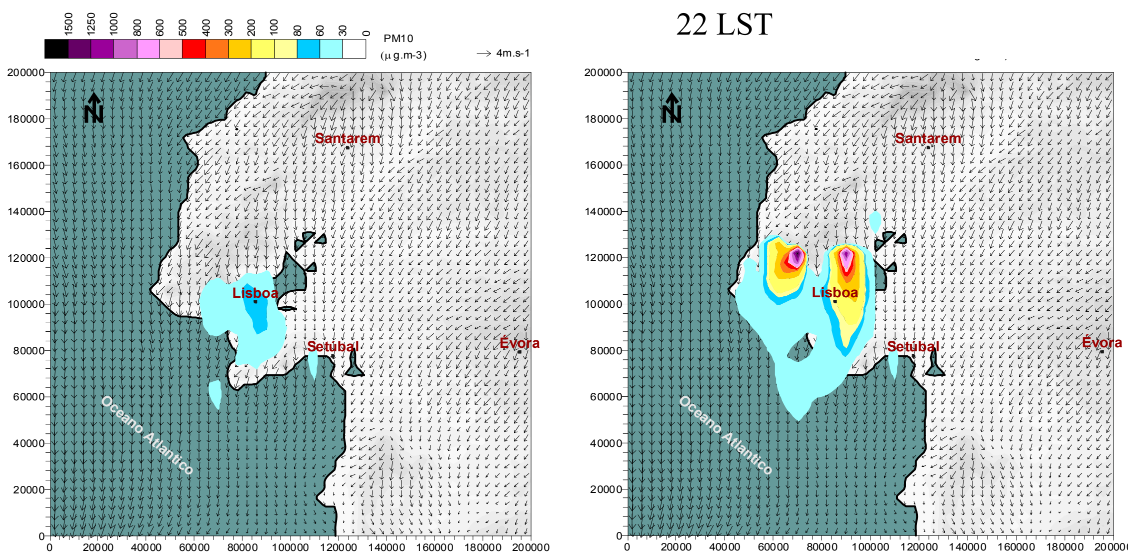

Figure 4. Hourly-averaged surface PM10 concentration ($\mu g\ m^{-3}$) and wind values at 22.00 LST, excluding forest fire emissions(left) and including forest fire emissions (right).

At a larger scale the contribution of 2006 western Russia wildfires, during spring, to the air quality impairment over Europe was evaluated too (Miranda, Sá, Martins, Borrego, & Sofiev, 2010). Figure 5 presents simulation and measurement results of the PM10 hourly midday spatial distribution for one of the simulation days.

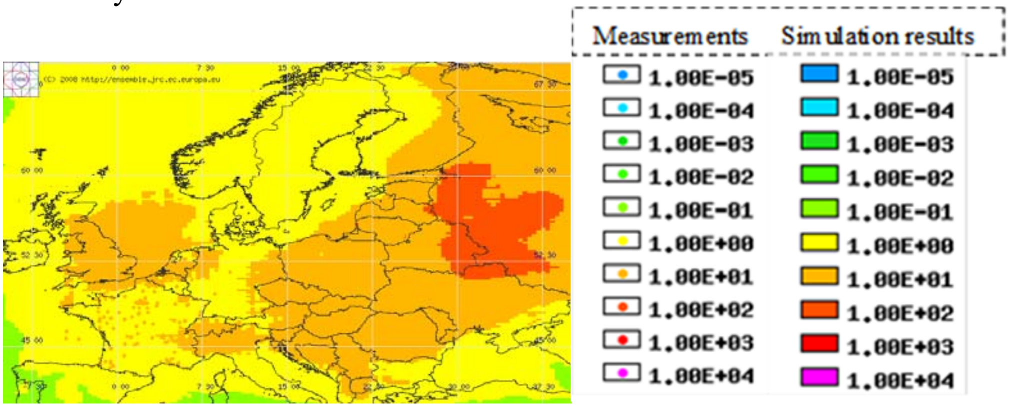

Figure 5. Spatial distribution of PM10 hourly midday concentration values (µg.m^{-3}) May 4 (Miranda et al., 2010).

This simulation of the 2006 spring fires over Europe allowed confirming the transboundary characteristics of wildland fires, clearly showing the impact of fires spreading over Russia in several European countries. The evaluation of the impact of wildfires on the air quality should be included in air quality assessment procedures at the European level, and air quality modelling systems can be important tools to achieve this goal.

4. Safety

Wildland firefighting implies many hazards to firefighters, including burns, heat stress, tripping and falling hazards, and inhalation exposure to smoke. Personal monitoring is a reliable way of estimating the exposure of an individual to a specific air pollutant. It assesses an individuals' inhalation exposure based on the measurement of a pollutant concentration within a person's breathing zone for a defined time.

Recently, exposure studies were conducted in Portugal to determine firefighter's individual exposure to smoke, using for that purpose personnel sampling devices to monitor CO, VOC, and nitrogen dioxide (NO_2) and a GPS instrument to track their position on site (Miranda *et al.*, 2010; Miranda *et al.*, 2012). The measurement of firefighters individual exposure to smoke was conducted in 2008 and 2009: (i) in Gestosa fire experiments, in Central Portugal, at the end of the spring season; and (ii) during the fire season (May to October) in Central Portugal. Data on individual exposure to CO, PM2.5 and NO_2 were measured for a group of ten firefighters equipped with portable measuring devices.

The selection of monitoring equipment was based on toughness, weight, possibility of continuous data acquisition, and ease of operation. Table 3 presents the main characteristics of the equipment used in the exposure monitoring.

Table 3- Characteristics of the equipment.

Pollutant	Type of data	Equipment	Characteristics	
			Range	Resolution
NO_2	Continuous measurement: 5 seconds interval	GasAlertMicro 5 PID from BW Technologies	0-99.9 ppm	0.1 ppm
CO	Continuous measurement: 5 seconds interval	GasAlertMicroClip from BW Technologies	0-500 ppm	0.1 ppm
		GasAlertextreme from BW Technologies	0-1,000 ppm	1 ppm
PM2.5	Continuous measurement: 1 minute interval	Personal Aerosol Monitor SidePack AM510 from TSI	0-20 $mg.m^{-3}$	0.001 $mg.m^{-3}$

Exposure results were compared to the occupational exposure standards (OES) defined for different air pollutants. According to the American Conference of Governmental Industrial Hygienists (ACGHI), OES are presented as the:

- threshold limit value (TLV) of the time-weighted average (TWA);
- TLV of the short-term exposure limit (STEL); and
- peak limit.

The TWA is calculated over a normal 8-hours working day and a five days working week. The TLV-STEL corresponds to a 15-minutes time-weighted average exposure that should not be exceeded at any time during a workday, even if the 8-hours TWA is under the TLV. The TLV-STEL is the highest concentration to which it is believed that workers can be exposed continuously for a short period of time without suffering effects. Table 4 presents the OES values for the different air pollutants analysed under this study.

Table 4. OES limit values for different air pollutants contained in biomass burning smoke. For some VOC these values are not available (n.a.) in National or International regulations.

Air pollutant	TLV-TWA	Reference	TLV-STEL	Reference	Peak Limit	Reference
CO	25 ppm	NP 1796:2007	200 ppm	Australian legislation	400 ppm	Australian legislation
NO_2	3 ppm		5 ppm	NP 1796:2007	20 ppm	NIOSH
Respirable particles without other classification	3 $mg.m^{-3}$	NP 1796:2007	n.a.	n.a.	n.a.	n.a.

Most firefighters use a bandana for respiratory protection, nevertheless, according to (Reh, Letts, & Deitchman, 1994) the pore size of this type of bandanas is approximately 200 µm x 200 µm, roughly 500 to 2000 times larger than the smaller smoke particles (0.100-0.400 µm), and consequently, gases and fine particulate matter can pass through the fabric.

Several exceedances to the OES values for CO were observed (maximum registered was 1000 ppm which is the equipment upper detection limit), meaning that firefighters are exposed to levels higher than the allowed limits of current legislation. NO_2 values are within the OES, except for some peak values exceedances (maximum registered was 33 ppm). Measured PM2.5 is within the OES, however, it should be noted that the OES is much higher than the standard defined by the World Health Organization for air quality.

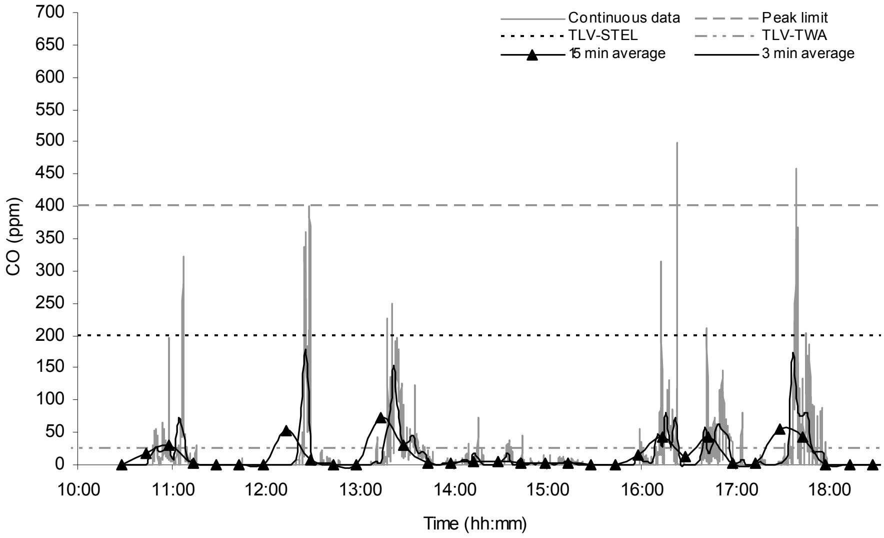

Figure 6. CO concentrations (ppm) measured for one of the firefighters during an experimental fire in GESTOSA.

This data (Table 6) shows the magnitude of the exposure peaks that occurred during regular firefighting operations, indicating that the firefighters are exposed to CO concentrations that pose their health and safety at risk and diminish their capability of taking decisions in emergency situations.

Medical tests conducted on the firefighters also indicate a considerable effect on measured medical parameters, with a large increase of CO and a decrease of NO in the exhaled air of majority of the firefighters (Miranda *et al*., 2012).

Visibility reduction and air quality degradation are a common consequence of biomass burning and a recurring problem in almost every parts of the world. It may lead to a pronounced diminishing of safety conditions during firefighting operations and terrestrial and aerial traffic, even in small scale experimental fires. Valente *et al.* (2007) developed and integrated in a smoke dispersion model, a specific module to calculate the visibility impairment caused by forest fire pollutants emissions, based on its concentrations in the atmosphere.

5. Suppression

GEMAC's work on fire suppression has been focused on both aerial and ground-based operations. These two lines of research share the objective of optimizing the efficiency of operations while guaranteeing the safety of personnel and civilians in the affected fire zones.

The efficiency of the aerial drop of firefighting agents (water and retardants) using airplanes or helicopters is highly conditioned by local atmospheric conditions (e.g., wind intensity, wind gusts, air turbulence, fire intensity, visibility), together with flight parameters (e.g., altitude, speed, route) and pilot perception. Despite these, and contrarily to commercial aviation, on-board systems for computer-assisted drops have not yet been used operationally. Aiming to provide an enhanced understanding of the behaviour of aerially delivered firefighting liquids and the factors that influence the overall suppression effectiveness, Amorim (2011a, 2011b) developed the Aerial Drop Model ADM, for water and chemical retardant applications, that can potentially be used in training activities with firefighters; or in testing the effectiveness of new firefighting chemicals or delivery systems, complementing the data obtained from real scale drop tests. This numerical tool allows a near real-time simulation of aerial drops with fixed-wing aircraft, while covering the fundamental stages of the process. It copes with a wide range of product viscosities, from water to highly thickened long-term retardants. Figure 7 presents a result of a retardant cloud drop as simulated by ADM.

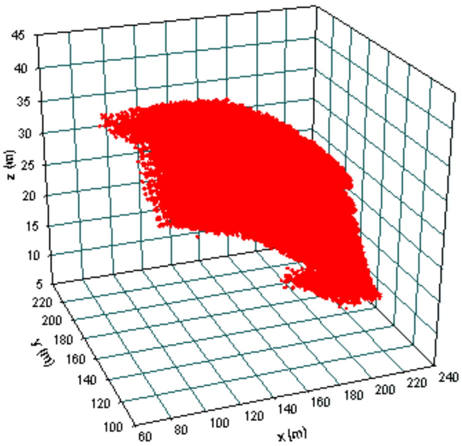

Figure 7. ADM simulation of a 3D retardant cloud, 3s after release initiation.

ADM was validated against experimental data acquired in a large number of real-scale drop tests carried out in Europe and in the United States of America. In general, the model produced a good representation of the spatial distribution of the agent in the ground for various coverage levels and its accuracy was, in fact, within the statistical uncertainty of the experimental sampling method.

On an operational basis too, GEMAC team is currently working on the development of a firefighting Decision Support System, that will combine the monitoring and forecast of smoke exposure, to help decision making in an operational scenario. The goal of this research is to develop an emergency response support system for firefighting ground-based operations during forest fire events. The target of the under-development computational tool is to provide knowledge-based aid to firefighters at critical decision-making situations, helping with the safe and successful management of fire. This DSS will support the following features:

- capture of 'live' sensor data from a set of wearable monitoring equipment that will be based on a previously developed certified medical wearable technology named "VitalJacket®";
- capture of meteorological observations from a mast placed in one of the vehicles;
- enable projections of fire progression, smoke levels and critical exposure in a predefined time-step (up to 30 minutes);
- interpretation of results in an easy and intuitive form to be used by fire managers or firefighters involved in operations.

To achieve this goal hardware technology (e.g. wearable, mobile, communications) was combined with processing/simulation software algorithms and user interactive interfaces. A data assimilation technique will allow near real-time observations from wearable monitoring equipment to be integrated into the exposure forecast modelling system, increasing the accuracy of the estimates.

A first prototype of the DSS, running in off-line mode, will be tested in the terrain during the fire season of 2014. An improved online version of the prototype will be tested in the following autumn in a series of prescribed burns.

In conclusion, this work proposes the development and testing (under real conditions) of a DSS intended to provide optimized firefighting efficiency, enhanced hazard awareness, and knowledge-based response to forest fire events. Advances in the computational modelling of fire and smoke behaviour, in conjunction with personal monitoring data, provide near real-time simulation of local fire conditions and short-term smoke exposure forecasts, with the needed advance in time to permit the safe and efficient positioning of crews in the terrain.

6. Climate change

Greenhouse gases emissions by forest fires can have an important contribution in climate change Miranda, Coutinho & Borrego, 1994). Forest fire activity and air quality under a changing climate are considered one of the main threats to sustainable development. Carvalho *et al.* (2008a, 2010) investigated the impact of future climate change on fire activity across Portugal, assessing the fire weather and subsequent fire activity under a 2 × CO_2 scenario and studying the relationship between the weather, the Fire Weather Index (FWI) System components, and both the area burned and fire occurrence across Portugal. Temperature was predicted to increase and precipitation to decrease, resulting in an increased FWI in all areas studied along with more severe and longer fire seasons. Future fire activity will increase dramatically across the entire country, with area burned and fire occurrence both rising substantially.

Air quality modelling results for Portugal (Carvalho *et al*., 2011) pointed out that future forest fire activity will increase the ozone concentration levels by almost 23 $\mu g\ m^{-3}$ by 2100 but a decrease of approximately 6 $\mu g\ m^{-3}$ is expected close to the main forest fire locations. Future forest fire emissions will also impact the PM10 concentrations over Portugal with increases reaching 20 $\mu g\ m^{-3}$ along the Northern coastal region in July. The highest increases are estimated over the north and centre of Portugal where the area burned projections in future climate are higher.

7. Final Remarks

Due to the frequency of occurrence and the magnitude of forest fires, and also to their effects on the environment, health, economy and security, they have increasingly become a major subject of concern for decision-makers, firefighters, scientists and citizens in general, in many regions of the world, including the southern European countries.

Experimental field fires represent a valuable tool for understanding wildfires in all its extension: behaviour, impacts on environment, security conditions and health, suppression techniques efficiency, among others.

The application of numerical emissions and air quality modelling systems is also an added value when evaluating and assessing air quality levels in areas affected by forest fires. Environmental policies, in particular the south-European ones must integrate both the traditional air pollution-oriented and the forested-land management issues into a unique system. Better forested-land management can help to reduce both the number of air pollution episodes and the risk of unwanted fires.

Wildland firefighting implies many hazards to the population in general, but also for firefighters, including burns, heat stress, tripping and falling hazards, and inhalation exposure to smoke. The development of monitoring solutions and solid science based DSS is of paramount importance both for fire management, but also for the personal safety of operational personnel.

These predicted increases in fire activity in a changing climate will have environmental, social, and economic impacts and would dramatically impact the organizational structures that deal with wildland fire and also society in general.

8. Acknowledgements

This work was supported by European Funds through COMPETE and by National Funds through the Portuguese Science Foundation (FCT) within projects PEst-C/MAR/LA0017/2013 and VitalResponder2 (PTDC/EEI-ELC/2760/2012), and the Post-Doc grants of J.H. Amorim (SFRH/BPD/48121/2008), J. Valente (SFRH/BPD/78933/2011), A. Monteiro (SFRH/BPD/63796/2009) and J. Ferreira (SFRH/BPD/40620/2007).

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