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Near-source grid-based measurement of CO and PM2.5 concentration during a full-scale fire experiment in southern European shrubland

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HIGHLIGHTS

- Dynamics of wildland firefighters' exposure to smoke still scarcely understood.
- Grid of portable sensors allows detailed monitoring of near-source smoke levels.
- Individual exposure largely impacted by extreme spatial concentration gradients.
- Critical risk of acute exposure during smouldering.
- Visual estimate of fire safety conditions potentially misleading.

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ABSTRACT

There is limited research on the exposure of wildland firefighters to smoke because of the operational obstacles when monitoring air pollutants in the field. In this work, a grid of portable sensors was used to measure PM2.5 and CO concentrations in the near-source region during the burn of two shrubland research blocks in Central Portugal. Strong spatial variability of smoke levels was observed in the analysis of the ratios between mean concentrations of neighbouring sensors, with values as high as 4.4 for PM2.5 and 7.4 for CO. These large gradients were registered at a distance of only 5 m suggesting that considerable differences on individual exposure can occur depending on the location of that individual in relation to the smoke plume trajectory. Also, peak events of 2–3 times the mean were observed in periods exceeding 6 min. In the two experiments, the average concentrations of both PM2.5 and CO were higher during smouldering, which represents a risk of acute exposure due to the closer proximity of firefighters to the emission source during mop-up, stressing the importance of wearing portable gas detectors for managing critical exposure. The collected data constitutes a step forward in the effort to understand the mechanisms controlling the exposure during firefighting operations, by providing a source of information on near-ground concentration fluctuations within a biomass-burning smoke plume at a fine spatial-temporal resolution.

1. Introduction

Forest fires are a large source of air pollutants that may lead to environmental and human impacts. At the operational level, firefighters are often confronted with a smoky and toxic atmosphere with reduced visibility. In this context, the constituents of smoke can potentially have significant effects on the safety and health of personnel (e.g., Reinhardt and Ottmar, 2004; Miranda et al., 2010, 2012). The complex mixture of smoke constituents may induce adverse health effects such as acute and instantaneous eye and

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respiratory irritation and shortness of breath. These health effects can lead to headaches, dizziness and nausea, and mild impairment of lung function that may last for hours or days (Reinhardt et al., 2000). Long-term effects are characterised by impaired respiratory function, increased risk of cancer, and cardiovascular disease (Rothman et al., 1991). The exposure to respirable particles and potentially toxic compounds adsorbed by the particles, such as polycyclic aromatic hydrocarbons (PAHs) and semivolatile organic compounds, are of increased concern since some may be carcinogenic (LeMasters et al., 2006; Youakim, 2006; IARC, 2010a), which led the International Agency for Research on Cancer (IARC) to classify the occupational exposure of a firefighter as possibly carcinogenic (IARC, 2010b).

There are a number of factors that affect the impacts of smoke on firefighter's health, including the concentration of specific air pollutants within the breathing zone, the exposure duration, the exertion levels, and the individual susceptibility (e.g., pre-existing lung or heart diseases) (Reisen and Brown, 2009). The composition of smoke itself depends on several other factors, such as the characteristics of the vegetation consumed, the efficiency of combustion, the fuel moisture content, fire temperature, and the weather conditions (e.g., Crutzen and Andreae, 1990; Levine, 1999; Ottmar et al., 2009). Despite the smoke exposure research studies carried out in the United States of America (Reinhardt et al., 2000; Reinhardt and Ottmar, 2000, 2004), Australia (McMahon and Bush, 1992; Materna et al., 1993; De Vos et al., 2009; Reisen and Brown, 2009; Reisen et al., 2011), Canada (Austin, 2008) and Portugal (Miranda et al., 2005, 2010, 2012), the current state of knowledge in this field is still limited. The inherent difficulty of monitoring smoke and personal exposure levels during a fire has contributed to this scientific gap.

To establish cause/effect relationships between fire activity, exposure to smoke and the effect on firefighter's health, a better understanding of the smoke plume dynamics in the near-source region is needed. In this context, the main goal of this work is to evaluate the spatial and temporal variation of the concentration of particles smaller than 2.5 μm in aerodynamic diameter (PM2.5) and carbon monoxide (CO) in the vicinity of the emission source during experimental bushfires, and how this translates into human safety issues during firefighting operations. This paper provides a source of information on near-ground concentration fluctuations within a smoke plume at a fine spatial-temporal resolution.

2. Site description and methods

The fire experiments were performed on May 6, 2010, on two research blocks in the mountain range of Lousã, Central Portugal (40° 15′N, 8° 10′W), at an elevation of approximately 1000 m. This area, known as ‘Gestosa’, has been an important field laboratory for over 20 years on the study of fire and its impacts, including smoke emissions, air quality and human exposure (Miranda et al., 2005, 2010, 2012; Viegas et al., 2002, 2006). Average physical characteristics of the burn blocks and vegetation are given in Table 1.

Meteorological observations were collected with an automated weather station and a 3 m high measurement mast positioned at approximately 150 m from the research blocks.

The fire ignition procedure was not meant to replicate a realistic fire scenario, but to create a consistent smoke plume that could be tracked by the ground sensors, while guaranteeing the safety of personnel and equipment during the experiments. In both research blocks the ignition pattern consisted of a line of fire along the top borders of the blocks, followed by a downhill linear ignition along the lateral borders. In block 2 there was an additional ignition at the lower corner that substantially increased the propagation. No fire suppression (direct or indirect attack) was used during the experiments. Table 2 summarizes the chronological sequence of the most significant events.

The technical characteristics of the portable monitoring equipment used for measuring the spatiotemporal dynamics of PM2.5 and CO concentration are detailed in Table 3. All the equipment was previously calibrated at the laboratory. In the case of SidePack AM510 sensors, the default calibration factor (standard ISO 12,103, A1 Test Dust) was applied for the determination of concentration. This test dust has a wide size distribution that averages the effect of particle size dependence on the measured signal and, therefore, is considered to be representative of a wide variety of ambient aerosols (TSI, 2012). Notwithstanding, similar instruments using real-time photometric technology have been shown to over-report PM levels in different wood smoke environments in comparison to gravimetric or filter-based methods (McNamara et al., 2011), and thus measurements should be interpreted with caution.

The position of the sensors in each research block is shown in Fig. 1. The grid layout was defined according to the prevailing wind during the burn to facilitate the capture of the smoke plume close to the fire and at ground level. The purpose of defining fixed positions for the sensors is to provide a better understanding of the spatial gradients of smoke levels in the near-source region of a fire, and not to measure the exposure of individuals in activity, as in previous papers by the authors (Miranda et al., 2010, 2012). The sensors were distributed around the higher section of the blocks at intervals of approximately 5 m. The first line of sensors distanced 5 m from the block border, and each line was roughly 5 m apart.

Each sensor was fixed to a mast at approximately 1.7 m above ground, as shown in Fig. 2, representing the average breathing zone of a firefighter.

3. Results and discussion

In the following sub-sections the data monitored in the two blocks is analysed in terms of: (3.1) meteorology, (3.2) fire behaviour, (3.3) smoke plume behaviour, and (3.4) air pollutant levels.

Table 2
Chronological description of the fire experiments (t is the local time and Δt is the elapsed time after ignition). Flaming and smouldering were differentiated by the analysis of infrared (IR) camera footage taken from an opposite hill.

Event	Block 1		Block 2	
	t (hh:mm)	Δ*t* (min)	*t* (hh:mm)	Δ*t* (min)
Fire ignition	09:56	0	11:25	0
End of flaming stage	10:30	34	11:31	6
End of smouldering stage	10:50	54	12:00	35

Table 1
Physical characteristics of the burn blocks. Fuel moisture was sampled 40 min before the first fire ignition.

Research block	Area (m^2)	Avg. slope (°)	Fuel cover (%)	Avg. fuel height (m)	Avg. fuel load ($t\ ha^{-1}$)	Avg. fuel moisture (%)	Fuel species
1	1853	16	67	0.31	32.50	Live: 46.6	*Erica umbellata, Erica australis, Ulex minor, Chamaespartium tridentatum*
2	1743	18	105	0.68	35.50	Dead: 9.0	