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Monumental heritage exposure to urban black carbon pollution

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HIGHLIGHTS

- BC monitoring in and near monument is essential for preventive conservation strategy.
- Unexpected high levels of BC were found inside and around the Alhambra monument.
- Road traffic emissions from the nearby urban area were the main source of BC.
- Contribution of biomass burning from the nearby rural areas was found.
- Stagnant weather conditions have a large impact on BC at the Alhambra.

GRAPHICAL ABSTRACT

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ABSTRACT

In this study, aerosol light-absorption measurements obtained at three sites during a winter campaign were used to analyse and identify the major sources of Black Carbon (BC) particles in and around the Alhambra monument, a UNESCO World Heritage Site that receives over 2 million visitors per year. The Conditional Bivariate Probability Function and the Aethalometer model were employed to identify the main sources of BC particles and to estimate the contributions of biomass burning and fossil fuel emissions to the total Equivalent Black Carbon (EBC) concentrations over the monumental complex. Unexpected high levels of EBC were found at the Alhambra, comparable to those measured in relatively polluted European urban areas during winter. EBC concentrations above 3.0 μg/m^3, which are associated with unacceptable levels of soiling and negative public reactions, were observed at Alhambra monument on 13 days from 12 October 2015 to 29 February 2016, which can pose a risk to its long-term conservation and may cause negative social and economic impacts. It was found that road traffic emissions from the nearby urban area and access road to the Alhambra were the main sources of BC particles over the monument. However, biomass burning emissions were found to have very small impact on EBC concentrations at the Alhambra. The highest EBC concentrations were observed during an extended stagnant episode associated with persistent high-pressure systems, reflecting the large impact that can have these synoptic conditions on BC over the Alhambra.

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1. Introduction

Urban air pollution is a matter of great concern due to its adverse effects on human health and the environment. Although a number of European Directives and measures aimed at improving the air quality have been elaborated and implemented in recent years, concentrations of certain atmospheric pollutants continue exceeding legal limits and a large part of the European population are still exposed to high levels of these substances (EEA, 2016). In addition to the health and environmental adverse effects of air pollution, clear evidence exists on its negative impact on the historical heritage as well (e.g. Bonazza et al., 2007; Graue et al., 2013). In this context, the interest in better understanding the impacts of urban air pollution on cultural heritage has increased considerably (e.g. Nava et al., 2010; Ghedini et al., 2011; Krupińska et al., 2013). A large part of the historic-artistic heritage objects in cities are located in the open air, where different atmospheric processes and pollutants emitted mainly by road traffic, industry and domestic heating cause aesthetic and material damage (e.g. Horemans et al., 2011; Kontozova-Deutsch et al., 2011). These harmful effects may produce an irreversible deterioration of monuments and artworks over time and may also have significant economic and social impacts (e.g. Grossi and Brimblecombe, 2004; Fort, 2007; Urosevic et al., 2012). Therefore, the characterization and source identification of air pollutants in the vicinity of cultural heritage objects is necessary in order to provide sound scientific data and technical guidance that can help policy makers to develop more efficient preventive conservation measures and sustainable management (Ghedini et al., 2011; De la Fuente et al., 2013).

Ambient levels of sulphur dioxide (SO_2) in Europe have been drastically reduced over recent decades (Vestreng et al., 2007; Guerreiro et al., 2014) and consequently the adverse effects on historical heritage caused by this gaseous pollutant (e.g. corrosion and discoloration processes) have become less important (Ivaskova et al., 2015). However, concentrations of particulate matter (PM) have continued exceeding European air quality standards in urban and suburban areas (EEA, 2016). In the last years, several studies have focused on the relationship between this air pollutant and the gradual decay of historic monuments, paying special attention to the relevant role of carbonaceous particles, such as black carbon (BC), in black crust formation and other undesirable aesthetic effects (e.g. Rodriguez-Navarro and Sebastian, 1996; Sabbioni et al., 2003; Bonazza et al., 2005, 2007). In fact, BC is the principal agent in blackening the outdoor surfaces of heritage materials and Equivalent Black Carbon (EBC) concentrations above 2–3 $\mu g/m^3$ were found to be associated with unacceptable levels of soiling and negative public reactions (Brimblecombe and Grossi, 2005).

BC is the most strongly light-absorbing constituent of particulate matter in the atmosphere (Bond and Bergstrom, 2006; Moosmüller et al., 2009) with clear implications on the air quality (Querol et al., 2013). These particles are emitted directly from diesel engines (mainly from the traffic sector), open biomass burning and residential heating as a result of the incomplete combustion of carbonaceous fuels (e.g. Hamilton and Mansfield, 1991; Bond et al., 2004). Their mean atmospheric lifetime varies from a few days to weeks and they can be removed from the atmosphere via precipitation and dry deposition (Bond et al., 2013). BC is the dominant light-absorbing aerosol species in many European cities and represents a good primary tracer to assess the impact of vehicle traffic emissions on the environment (Reche et al., 2011).

The monumental complex of the Alhambra and Generalife (Granada, Spain) was a palatial citadel constructed from the 11th to the 15th century and represents a unique example of Islamic architecture in the Western world. One of the masterpieces of Nasrid art is the Patio de los Leones (Courtyard of the Lions), a rectangular courtyard surrounded by a low gallery supported on marble columns, which is located inside the palace complex. The famous Fountain of the Lions is situated at the middle of this courtyard and has recently been under restoration in an effort to preserve its integrity. The Alhambra was listed as UNESCO World Heritage Site in 1984 and is currently under intense pressure from tourism and urban development (over 2 million visitors in 2015 according to the Patronato de la Alhambra y Generalife). However, the influence of ambient air pollution, especially BC particles, on this artistic-historical monumental group has not been extensively studied (Horemans et al., 2011). The study of Horemans et al. (2011) focused on the analysis of indoor and outdoor atmospheric aerosol chemical composition (PM_1 and PM_{10-1}) and pollutant gases (O_3, NO_2, SO_2 and NH_3) measured at Alhambra and its surrounding during short summer (from 15th of June until 5th of July 2009) and winter campaigns (from 1st until 10th of February 2010). Although this last study pointed out to the traffic as one of the sources of particle matter and BC particles over Alhambra, detailed investigation of the sources of BC particles and their contributions to the total BC concentrations over the monumental complex was not previously done. Thus, the identification of the major sources of BC particles and the estimation of their contributions to the total EBC concentrations in and around the Alhambra monument can help us to provide information and operational guidance for a sustainable management by the competent authorities.

The intensity and duration of urban air pollution episodes not only depend on the amount of anthropogenic emissions but also on specific meteorological situations such as persistent high pressure system, low wind and, especially surface thermal inversion, which constrain horizontal and vertical dispersion of air pollutants (e.g. Charron and Harrison, 2003; Tiwari et al., 2013; Whiteman et al., 2014). In the urban area of Granada, located in a natural valley surrounded by high mountains (between 1 000 and 3 500 m a.s.l.), stagnant wintertime weather conditions associated with surface thermal inversions are relatively frequent and this contributes to a significant accumulation of fine anthropogenic particulate pollution near ground level (Lyamani et al., 2012). However, the influence of these stagnation episodes on BC concentrations at the Alhambra, located on the highest hill of the city, is unknown. Global climate change is expected to be accompanied by an increase in the frequency, duration and intensity of stagnation conditions, especially in Europe and North America (IPCC, 2013; Horton et al., 2014). Therefore, the analysis of BC particles during stagnation events will permit better understanding of the possible adverse effects of BC particles on monuments during future events.

Hence, the main aim of this study is the evaluation of the EBC concentrations and the identification of the major sources of BC particles as well as the estimation of their contributions to the total EBC concentrations in and around the Alhambra monument during winter. We also aim to investigate the impact of stagnant wintertime weather conditions on EBC concentrations in this monumental complex.

2. Methodology

2.1. Measurement sites

Equivalent black carbon measurements were performed at three different sites located in Granada city (37.16° N, 3.61° W, 680 m a.s.l.). Granada, situated in the south-eastern Iberian Peninsula, is a non-industrialized mid-size city with a population of 234 758 inhabitants, which increases up to 530 000 when including the metropolitan area (www.ine.es). The climate is typically Mediterranean-continental, with cool winters, dry and hot summers and large diurnal temperature variability. Due to its