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Religious burning as a potential major source of atmospheric fine aerosols in summertime Lhasa on the Tibetan Plateau

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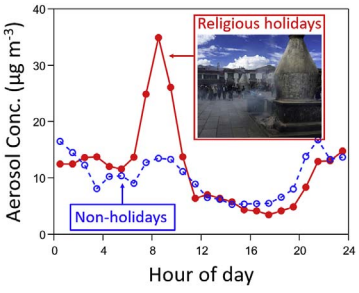
GRAPHICAL ABSTRACT



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ABSTRACT

We carried out field measurements of aerosols in Lhasa, a major city in the Tibetan Plateau that has been experiencing fast urbanization and industrialization. Aerosol number size distribution was continuously measured using an optical particle size spectrometer near the center of Lhasa city during the Asian summer monsoon season in 2016. The mass concentration of fine particles was modulated by boundary layer dynamics, with an average of 11 $\mu g\,m^{-3}$ and the high values exceeding 50 $\mu g\,m^{-3}$ during religious holidays. Daytime high concentration coincided with the religious burning of biomass and incense in the temples during morning hours, which produced heavy smoke. Factor analysis revealed a factor that likely represented religious burning. The factor contributed 34% of the campaign-average fine particle mass and the contribution reached up to 80% during religious holidays. The mass size distribution of aerosols produced from religious burnings peaked at ~500 nm, indicating that these particles could efficiently decrease visibility and promote health risk. Because of its significance, our results suggest that further studies of religious burning, a currently under-studied source, are

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needed in the Tibetan Plateau and in other regions of the world where religious burnings are frequently practiced.

1. Introduction

The Tibetan Plateau (TP), the largest and highest highland in the world, plays a key role in regional climate in Central and East Asia (Kutzbach et al., 1993; Wu et al., 2012). The TP is generally considered as a pristine environment and background region for atmospheric aerosols (Cong et al., 2007; Liu et al., 2017). Concerns have been raised that the rapid increase of anthropogenic emissions in Asia may influence the air quality in the TP region (Cong et al., 2007). Measurements of air pollutants in the TP, however, are scant because of the high altitude and harsh climate.

Lhasa is the capital of the Tibet Autonomous Region of China, as well as the economic and cultural center of the TP. The city has experienced fast urbanization and economic growth during the past decades (Gong et al., 2011). As the hub of Tibetan Buddhism, Lhasa has been attracting thousands of visitors each year, making tourism the pillar of the city's GDP. As a result, the 63 km^2 urban area of Lhasa city hosts ~0.4 million floating population, which doubles the ~0.2 million local residents estimated for year 2012 (Ran et al., 2014). The thriving tourism has boosted the energy consumption, construction projects, and religious burning activities that can deteriorate the city's air quality. In addition, Lhasa city lies in the Lhasa River Valley (Fig. 1). The mountain range surrounding the Lhasa city prevents efficient diffusion of air pollutants. Moreover, incomplete fuel combustion resulting from the low oxygen concentration in the Lhasa (3.6 km above sea level) atmosphere may amplify the extent of air pollution in the city (Bishop et al., 2001; Wang et al., 2010). The high solar radiation can further enhance photochemistry and thus the production of secondary pollution, such as ozone and secondary organic aerosols (Norsang et al., 2009; Ran et al., 2014). Overall, the remoteness, high elevation, increased combustion emissions, and unfavorable topography make Lhasa a unique site for the air quality research.

Aerosol measurements in Lhasa are extremely limited. Most of the studies investigated the elemental composition of aerosols, either through single-particle (Duo et al., 2015; Zhang et al., 2000, 2001a) or bulk sample analysis (Cong et al., 2011; Zhang et al., 2001b). Others focused on particle-bound organochlorine (Li et al., 2008) or polycyclic aromatic hydrocarbons (PAHs; Liu et al., 2013). Huang et al. (2010) separated the fossil and non-fossil fractions of carbon in total suspended particles (TSP) using ^{14}C measurements. They found that non-fossil carbon (likely included biomass burning and biogenic aerosols) contributed ~40% of total carbon to TSP in summer, which is consistent with previous studies implying that biomass burning could be an important source in Lhasa (Duo et al., 2015; Zhang et al., 2001b). However, the source apportionment of total aerosol mass, especially for fine aerosols, have not been conducted to the best of our knowledge.

In this work, we studied the aerosol size distribution in Lhasa city. The size distribution of fine aerosols was continuously measured with a high-sensitivity optical particle counter for a ~three-week period, followed by source identification using factor analysis. Special attention was given to the aerosols generated from religious burnings, which have not been extensively studied in the air quality research community (Lung et al., 2003).

2. Experimental methods

2.1. Instrumentation and model simulation

The ground-based sampling site was located at the China Reference Climatological Station of Lhasa in the downtown area (29.66° N, 91.14° E), which is 3.6 km above sea level. The station occupies approximately 25,000 m^2 open space with a suite of instruments situating on the ground. The ground is covered by lawn. There are no tall buildings surrounding the station. Our instrument was located near the center of the station, with an inlet height of 1.5 m above ground level. Particle number size distribution was continuously measured using a custom-built optical particle sensor, the Printed Optical Particle Spectrometer (POPS) in the period of 2–20 August 2016 during the Asian summer monsoon. The POPS is a single particle counter that records the pulse information produced by each particle passing through a 405 nm laser beam (Gao et al., 2016). The performance of the POPS instrument has been carefully established using standard calibration material and validated via inter-comparison with other accepted instruments (e.g. UHSAS and LAS, Gao et al., 2016). Its scientific usefulness has been demonstrated by recent field studies (Telg et al., 2017; Yu et al., 2017). Particle size is calculated from the calibration curve, which relates the pulse height to the size of the particle. The calibration curve was derived by introducing a series of size-selected particles to the POPS instrument. The size-selected particles were generated by atomizing solution of dioctyl sebacate (DOS) followed by sizing with a differential mobility analyzer. Therefore, the reported particle size in this paper is DOS-equivalent diameter. The size calibration was further checked using commercial polystyrene latex spheres. The mass of each detected particle was calculated using its retrieved size, assuming that the particles are spherical and have a constant density of 1.6 g cm^{-3}. The measured particles were binned logarithmically into 14 size bins across the POPS detection range (140– 3 000 nm) with ΔlogDp of 0.1, except for the last bin with a smaller ΔlogDp of 0.03 because of the upper detection limit of 3 000 nm. The aerosol mass for each size (ΔM) bin was calculated as the sum of all individual particle mass in the size bin. ΔM values were normalized by their respective ΔlogDp to derive the particle mass size distribution, expressed as dM/dlogDp. The ensemble particle mass was calculated as the sum of the mass of all measured particles. The data were averaged to 10-min intervals for in-depth analysis.

The planetary boundary layer (PBL) height was measured using the meteorological operational GTS1 radiosonde (Bian et al., 2011) carried into the atmosphere by weather balloons. Three balloons were launched daily in the morning (7:15), around noon (13:15), and in the evening (19:15) during the sampling period. We note that Tibet Autonomous Region uses Beijing Time, which is ~1.9 h earlier than the apparent solar time in Tibet. Beijing time (local time) is used throughout the text. The PBL height was determined by vertical profile of the virtual potential temperature (θ_v). Under the nocturnal stable

Fig. 1. Topographic map of Lhasa City. The star indicates the sampling site.