Environmental Pollution 221 (2017) 75–84

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Impacts of regional transport on black carbon in Huairou, Beijing, China

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ARTICLE INFO

Article history:
Received 24 June 2016
Received in revised form
9 October 2016
Accepted 2 November 2016
Available online 23 November 2016

Keywords:
RTA
CFA
BC
APEC
Huairou
Control and non-control periods

ABSTRACT

The 22nd Asia-Pacific Economic Cooperation (APEC) Conference was held near Yanqi Lake, Huairou, in Beijing, China during November 10-11, 2014. To guarantee haze-free days during the APEC Conference, the Beijing government and the governments of the surrounding provinces implemented a series of controls. Three months of Aethalometer 880 nm black carbon (BC) measurements were examined to understand the hourly fluctuations in BC concentrations that resulted from emission controls and meteorology changes. Measurements were collected at the University of Chinese Academy of Sciences near the APEC Conference site and in Central Beijing at the Institute of Remote Sensing and Digital Earth of the Chinese Academy of Sciences. Synoptic conditions are successfully represented through analysis of backward trajectories in six cluster groups. The clusters are identified based on air mass transport from various areas such as Inner Mongolia, Russia, three northeastern provinces, and Hebei industrial areas, to the measurement sites. Air pollution control measures during the APEC Conference significantly reduced BC at the conference site (Huairou) and in Central Beijing, with greater reductions in BC concentrations at the conference site than in Central Beijing. The highest BC concentrations in Huairou were associated with air masses originating from Central Beijing rather than from the Hebei industrial region. The success of the control measures implemented in Beijing and the surrounding regions demonstrates that BC concentrations can be effectively reduced to protect human health and mitigate regional climate forcing. This study also demonstrates the need for regional strategies to reduce BC concentrations, since urban areas like Beijing are sources as well as downwind receptors of emissions.

1. Introduction

Black carbon (BC) is a term used to describe particles that are categorized by a particular optical measurement; it is found in the atmosphere in both urban and remote regions and has a graphitic-like structure (Castro et al., 1999). BC is an important component of particulate matter (PM), and it is mainly emitted as a primary pollutant from incomplete combustion of fossil and biomass carbonaceous fuels (Cooke and Wilson, 1996; Hildemann et al., 1991; Koelmans et al., 2006; Penner et al., 1993; Schauer et al., 1996). In general, BC is assumed to be inert and non-volatile (Ogren and Charlson, 1983), hence the light-absorbing aerosol component obtained through optical measurement is usually a good marker for combustion (Allen et al., 1999; Hansen et al., 1988), as well as dust and brown carbon (Bahadur et al., 2012; Devi et al., 2016; Kirchstetter et al., 2004; Wang et al., 2013). Furthermore, BC seems to have significant impacts on both climate change (Menon et al., 2002) and human health (Baumgartner et al., 2014a). Global

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http://dx.doi.org/10.1016/j.envpol.2016.11.006
0269-7491/

and regional climate and meteorological conditions are affected by BC, since it strongly absorbs solar energy, degrades visibility, alters atmospheric stability, influences large-scale circulations, and affects cloud albedo via modification of the hygroscopicity of cloud condensation nuclei (CCN) (Baumgartner et al., 2012; Jacobson, 2001; Liousse et al., 1996; Penner et al., 1993; Watson and Chow, 2002). Additionally, BC contributes to adverse health outcomes (Badarinath et al., 2007; Mauderly and Chow, 2008; Pope and Dockery, 2006), such as negative blood pressure effects (1 μg m^{-3} increase in BC was associated with 4.3-mmHg higher systolic blood pressure) (Baumgartner et al., 2014a, 2014b); harms terrestrial and aquatic ecosystems (Forbes et al., 2006); contaminates building materials (Ghedini et al., 2000); and decreases crop yields (Chameides et al., 1999).

Since China is the world's greatest emitter of BC (Cooke et al., 1999; Penner et al., 2001), studies about BC emissions are important in both its megacities (Cheng et al., 2006; Gao et al., 2015; He et al., 2001; Ye et al., 2003) and in rural areas (e.g., Huairou, Beijing). The 22nd Asia-Pacific Economic Cooperation (APEC) Conference was held near Yanqi Lake, Huairou, in Beijing, China during November 10-11, 2014. The local government implemented a series of measures to guarantee haze-free days in Beijing and in the surrounding provinces during the APEC Conference. Many studies have been published regarding air quality improvement and air pollution mitigation in Beijing in the context of the control measures implemented during the APEC Conference (Chen et al., 2015a, 2015b; Liang et al., 2015; Sun et al., 2016; Tang et al., 2015; Yang et al., 2016). Most of them explore source apportionment of fine particles ($PM_{2.5}$), variation in PM composition, and optical characteristics of $PM_{2.5}$. However, few of these air quality studies explore the BC levels during and after the APEC Conference, the factors that affect changes in BC loadings, or even the impacts of meteorology on rural and urban areas. As a result, this study looks to access the impacts of large-scale control measures that reduce BC concentrations and, consequently, decrease haze, regional climate forcing, and adverse impacts on human health. The study evaluates the relative impacts of controls on BC concentrations in Central Beijing and Huairou, a suburban location outside Beijing; it also assesses the role of regional transport of BC on BC concentrations at the urban and rural sites. Backward air mass trajectories are used to examine the sources and relative impacts of APEC controls on local and regional sources in urban and rural locations around Beijing.

2. Data and methods

2.1. Sampling and BC measurements

From November 1st, 2014 to January 28th, 2015, black carbon was measured continuously as 5-min averages by quartz-fiber filter tape (Olson et al., 2015) transmission at an 880 nm wavelength with an Aethalometer (Magee Scientific Company, USA), which was factory calibrated to ± 2% accuracy (Allen et al., 1999; Hansen et al., 1984). A model AE-31 Aethalometer® was positioned atop the Teaching One Building (40°25′N, 116°41′E) of the University of Chinese Academy of Sciences (UCAS) in northeastern Beijing, and a model AE-51 hand-held Aethalometer was placed atop the roof of the Institute of Remote Sensing and Digital Earth (RADI, 40°00′N, 116°23′E, Central Beijing) of UCAS (Fig. 1). The particles were deposited on a quartz-fiber filter tape and the change of light transmission through the filter tape measured by light source and detector was used to calculate 5-min average BC concentrations; the filter tape is automatically advanced when its optical density attains 0.75. The reported BC in this study is equivalent to the BC (Lack et al., 2014; Petzold et al., 2013) using the Magee Scientific's recommended mass absorption coefficient (MAC) at an 880 nm wavelength. The attenuation was converted to a BC mass concentration (in μg m^{-3}) using a δ_{abs} of 14,625/λ (m^2/g). When λ = 880 nm, δ_{abs} is 16.6 m^2/g (Cao et al., 2009; Park et al., 2006, 2010). Previous studies show that BC structures significantly affect BC optical properties (e.g., He et al., 2015). Different BC particles could have different extinction/absorption depending on structures. However, these particles, after emission, generally undergo aging processes by condensation and coagulation, as well as cloud/fog processing; and gradually become internally mixed (coated) with other chemical compounds (Cheng et al., 2012 and references therein). In general, the Aethalometer in this study cannot separate the particles as clearly as He et al. (2015). Hence, it is difficult to estimate the uncertainty of BC measurements. For a better comparison between the two sampling sites, only 880 nm BC data were used. This measurement may reflect additional interferences in addition to the actual BC mass, including particle scattering and filter loading artifacts. A number of MAC have been applied in the literature (Bond and Bergstrom, 2006; Bond et al., 2013; Knox et al., 2009; Petzold et al., 1997). In an attempt to more accurately quantify the “true” BC in the atmosphere, this study focuses on the relative changes of BC measured using the same MAC for varied but similar particle compositions. The range in MAC can vary greatly based on the measurement and correction technique; for example, Knox et al. (2009) reported an Aethalometer average MAC_{880} of 19.3–19.7 m^2/g and a photoacoustic-determined average MAC_{760} of 9.3–9.9 m^2/g for aged and unaged ambient $PM_{2.5}$, similar to those reported by Lack et al. (Knox et al., 2009; Lack et al., 2014). However, Knox et al. (2009) noted that there was not a statistical difference between MAC for aged, semi-aged and fresh $PM_{2.5}$ when measured by the same instrument. Essentially, this study does not attempt to develop a specific MAC to relate the observed light attenuation to ambient elemental carbon concentrations.

2.2. Backward trajectory analysis

Meteorological simulations were performed for the Beijing-Tianjin region with the Weather Research and Forecast model (WRF) (Skamarock et al., 2005) and were initialized using the FNL (Final) Operational Global Analysis data from the United States National Centers for Environmental Prediction. In this study, the model was run on three nested domains with 27, 9 and 3 km resolution and 40 vertical levels using version 3.6.1 (Wang et al., 2016). The detailed numerical simulations procedures were described in de Foy et al. (de Foy et al., 2015; de Foy et al., 2012a; de Foy et al., 2012b). Particle backward trajectories are calculated with FLEXPART (Stohl et al., 2005) using FLEXPART-WRF (Brioude et al., 2013) for a duration of two days starting every hour of the source contributions at BC sources. Every hour, 1000 particles are released for the layer between 0 and 100 m above the ground and are allowed to disperse in the domain using the WRF mixing heights and surface friction velocity. The hourly particle positions are projected onto a rectangular grid to provide a residence time analysis (RTA) (Ashbaugh et al., 1985). A clustering algorithm was used to identify different flow patterns for every hour of the field campaign. K-means clustering was applied to polar grids of the residence time analysis. Six clusters were found to represent the dominant flow patterns to the measurement site. A concentration field analysis (CFA) (Seibert et al., 1994) was obtained by multiplying daily RTA grids with daily BC levels and normalizing the sum over the entire measurement period. CFA serves to identify potential source regions using time series of pollutant concentration measurements by yielding an image of the dominant wind patterns associated with high pollution levels at the site (de Foy et al., 2009). When the air masses arriving at the site are fairly uniform, CFA highlights the