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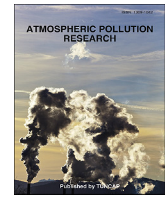

Original article

Characteristics of aerosols over Beijing and Kanpur derived from the AERONET dataset

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ABSTRACT

Beijing and Kanpur are two cities identified as high aerosol optical thickness (AOT) and complex composition of aerosols in Asian monsoon regions. Detail knowledge of key aerosol types in these two countries would be helpful for clarifying the mechanisms of aerosol radiative forcing and improving the accuracy of satellite remote sensing in these two countries. This study examines the characteristics of aerosol types over Beijing and Kanpur derived from a 12-year dataset from Aerosol Robotic Network (AERONET) stations and compares them via cluster analysis of optical and microphysical properties. Aerosols in Beijing are more complex than in Kanpur. Four fine-size dominated aerosol types (including two types of moderately absorbing aerosols, one highly absorbing aerosol type and one non-absorbing aerosol type) and one coarse-size dominated aerosol type are identified over Beijing. In Kanpur, two fine-sized dominated aerosol types (one high absorbing aerosol type and one non-absorbing aerosol type) and one coarse-sized dominated aerosol type are obtained. Compared to Beijing, the average SSAs of non-absorbing and high-absorbing aerosols are lower for the four wavelengths (440 nm, 676 nm, 869 nm, 1020 nm) in Kanpur. High absorbing aerosols usually occur in the months December to February (DJF) for both sites. The proportion in Kanpur (14%) is about twice that in Beijing (7%). Non-absorbing aerosols are usually observed in the months June to August (JJA) for both sites. Their proportion in Kanpur (31%) is ~3 times larger than that in Beijing (11%). Coarse aerosols are frequently observed in the months March to May (MAM) for both sites. Their proportion in Kanpur (54%) is two times larger than in Beijing (21%).

1. Introduction

Atmospheric aerosols are an essential component of the climate system. Due to the variety of aerosol types, mixing processes in the atmosphere and large spatial and temporal variations, aerosols are recognized as the primary uncertainty in estimating the current anthropogenic radiative forcing on Earth (IPCC, 2013). Beijing, China and Kanpur, India are two sources of polluted aerosols in the world (Dey and Tripathi, 2007; Zhao et al., 2011) and are located in Asian monsoon regions with aerosols mixtures composed of coarse particles from dust storms (radius > 1 μm) and fine particles from fossil fuel combustion (radius < 1 μm). These two countries have been identified as hot spots with aerosol optical thickness (AOT) observed from space (Prasad and Singh, 2007; van Donkelaar et al., 2008; Kharol et al., 2011).

Over the last decade, many studies have investigated aerosols over Beijing and Kanpur due to their high aerosol loadings and complex aerosol composition (Singh et al., 2004; Tripathi et al., 2005; Chin et al., 2009; Goloub, 2009; Wang et al., 2011; Kaskaoutis et al., 2012; Li et al., 2015). These studies have generally focused on the optical, microphysical and chemical properties of aerosols, as well as climate model simulation and satellite validation. According to these studies, aerosols observed in Beijing mainly have an anthropogenic origin with dust intrusions during the spring (Eck et al., 2005; Xin et al., 2007; Logan et al., 2010, 2013). The Kanpur aerosols also mainly have an anthropogenic origin; fine mode urban/industrial aerosols contribute more than 75% to the observed AOT during the post-monsoon period and winter, whereas natural dust contributes approximately ~60% to

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the AOT during the pre-monsoon and monsoon periods (Dey et al., 2005; Prasad et al., 2006).

Detailed knowledge of the optical properties of key aerosol types is needed to clarify the mechanisms of aerosol radiative forcing and improve the accuracy of satellite remote sensing (Dubovik et al., 2002). Although much work has focused on the complexity of aerosol optical and chemical properties in Beijing and Kanpur, information concerning the properties of and the spatial and temporal variations in different aerosol types is still limited. To reduce the uncertainty involved in estimating aerosol climate effects and improve satellite retrieval accuracy over the Beijing and Kanpur regions, a systematic study of the optical properties of different aerosol types is required.

Ground-based aerosol observations provide wide angle and spectral measurements of solar and sky radiation. They are best suited to continuously investigate aerosol types and estimate their effects on radiative forcing in key locations (Dubovik et al., 2002). The Aerosol Robotic Network (AERONET) is a useful tool for ground-based aerosol observations (Holben et al., 1998). It catalogs an extensive set of physical and optical aerosol properties, including particle size distribution, complex refractive index, single scattering albedo and particle shape information. The present study aims to investigate the characteristics of different aerosol types over Beijing and Kanpur via cluster analysis of optical and microphysical properties obtained from the AERONET sun-sky radiometer data archive (http://aeronet.gsfc.nasa.gov). Based on the resulting aerosol classification, the aerosol optical and seasonal properties over Beijing and Kanpur are analyzed.

In Section 2, the data and classification method are described. The microphysical and optical properties of aerosol types over Beijing and Kanpur are analyzed and compared in section 3. The seasonal variation in different aerosol types over Beijing and Kanpur are investigated in section 4.

2. Measurements and methodology

2.1. AERONET data

The Aerosol Robotic Network (AERONET) (Holben et al., 1998, 2001) is a network of ground-based sun photometers that provides high quality aerosol measurements. The solar measurements can be used to compute Aerosol Optical Thickness (AOT) at eight wavelengths (0.34, 0.38, 0.44, 0.5, 0.67, 0.87, 0.94 and 1.02 μm). Measurements at 940 nm are used to estimate total precipitable water content. The sky radiance almucantar measurements are used in conjunction with sun measurements to retrieve aerosol optical properties (e.g., complex refractive index, single scattering albedo, sphericity, phase function and absorption properties) and aerosol size distributions (Holben et al., 1998).

The latest retrieval scheme (Dubovik et al., 2006) assumes that aerosols include a mixture of spherical and nonspherical aerosol components and estimates the nonspherical fraction. Accounting for the effects of nonsphericity and aspect ratios in light scattering properties, the mean "%sphericity" is calculated from the AERONET data and fixed spheroid mixture distribution. According to our previous research (Chen et al., 2015), adding the sphericity parameter during the clustering process contributes to the extraction of strongly absorbing aerosols.

The estimated uncertainty for AOT varies spectrally ± 0.01 to ± 0.02 with the highest error in the ultraviolet wavelengths (Eck et al., 1999), and calibrated sky radiance measurements typically have an uncertainty of less than 5% (Holben et al., 1998). Three levels of data are included in the AERONET database: Level 1.0, Level 1.5 and Level 2.0. Level 2.0 data are cloud-screening and quality control results. In this paper, "Level 2 Inversion All Points" measurements are used.

2.2. Site description

The descriptions of Beijing and Kanpur AERONET sites selected for analysis are shown in Table 1. Data collected from the Beijing AERONET site cover the period from 2002 to 2014, while data from the Kanpur AERONET site cover 2001 to 2013. The numbers of effective observation records during all months are shown in Fig. 1. Both sites have a long-term trend and a sufficiently large number of records per month suitable for cluster analysis.

Beijing is the capital city of China and a major commercial and political center with a population of approximately 22 million. It is located on the northwestern border of the Great North China Plain, with the Taihang Mountains to the west and the Yanshan Mountains to the north, and has a complicated landscape. Beijing's is classified as "continental monsoon", and the seasons in Beijing are: spring (MAM), summer (JJA), autumn (SON) and winter (DJF). Beijing is affected by long-range transported dust in the spring, coal burning in the winter and strong local emissions from heavy traffic and industrial factories during the entire year (He et al., 2001; Sun et al., 2004). In summer, Beijing is characterized by relatively hot and humid weather and accounts for about 74% of annual precipitation (Yu et al., 2009). Aerosol optical thickness observed in summer is highest and almost two, three, and four times that in autumn, winter, and spring season respectively (Xia et al., 2006). Autumn in Beijing is generally a good season with a relatively clear and clean sky.

Kanpur is an important industrial city with 3.2 million population located in the central part of the Indo-Gangetic plain (IGP). Aerosol types over Kanpur are similar to those over Beijing. Seasons in the IGP are: winter (DJF), pre-monsoon (MAM), monsoon (JJA), and post-monsoon (SON). During the winter, the entire IGP experiences frequent foggy and hazy conditions (Das et al., 2008). In the late pre-monsoon and early monsoon periods, the area is strongly affected by dust storms originating from the Thar Desert and/or the Arabian Peninsula and the Middle East (Guleria et al., 2011). In the post-monsoon season, crop residue burning leads to dense smoky conditions over the IGP (Sharma et al., 2010). According to Kaskaoutis et al. (2012), the ground-based observed AOT in Kanpur reveal an increase trend in the winter and post-monsoon seasons, while a neutral to weak declining trend during late pre-monsoon and monsoon seasons.

2.3. Methodology

Cluster analysis is a statistical tool used to group large datasets into categories. This method has been used by Omar et al. (2005), Levy et al. (2007), Qin and Mitchell (2009) and Lee et al. (2010). In this study, a hierarchical clustering method using an agglomerative complete-link clustering algorithm was applied (Kotsiantis and Pintelas, 2004; Grira et al., 2005). This method seeks to build a hierarchy of clusters: each observation starts in its own cluster, and pairs of clusters are merged as one moves up the hierarchy. Hierarchical clustering has the distinct advantage that any valid measure of distance can be used.

The following parameters retrieved from the AERONET network are used to classify aerosol types in Beijing and Kanpur. They represent optical and physical properties of aerosols:

(1) Complex refractive index at 0.44, 0.676, 0.869 and 1.02 μm;
(2) Aerosol size distribution: fine and coarse mean radius; fine and coarse standard deviation; and fine and coarse mode total volume;