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Climatological aspects of aerosol optical properties in North China Plain based on ground and satellite remote-sensing data

Xiangao Xia [a,*], Hongbin Chen [a], Philippe Goloub [b], Xuemei Zong [a], Wenxing Zhang [a], Pucai Wang [a]

[a] LAGEO, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China
[b] LOA (Laboratoire d'Optique Atmospherique), Universite Lille, Lille, France

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ABSTRACT

Aerosol data from the Aerosol Robotic Network (AERONET), Moderate Resolution Imaging Spectroradiometer (MODIS), and Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP) recorded during the new millennium were used to investigate the spatio-temporal variation of aerosol optical properties in the North China Plain (114–120°E; 34.5–41°N). The external linear mixing of both fine and coarse mode components dominated variations of the refractive index and the single scattering albedo (ω) in spring and winter when the fine mode fraction (FMF) was <0.6–0.7. The effective radius of fine mode component increased rapidly with FMF in every season when FMF exceeded ~0.6–0.7, and thereby when ω increased significantly. With the exception of dust cases, aerosols resembled the mixed category in every season except summer; summer aerosols resembled the industry/urban category. The aerosol layer height was observed to be 2–3 km in summer; however, aerosols were trapped below 1–2 km in fall and winter. Aerosol optical depth (AOD) retrieved by the MODIS was in good agreement with the AERONET AOD ($R>0.80$). The MODIS tended to overestimate AOD in spring and summer. This feature was most prominent at 660 nm; therefore, MODIS Ångström exponents were poorly derived. A strong correlation ($R>0.7$) between the AERONET AODs in Beijing and the MODIS level 2.0 pixel AODs persisted for a large and strongly anisotropic area of ~17,000 km^2 in winter to ~100,000 km^2 in fall, indicating that the aerosol pollution is regional in nature. A decreasing trend was derived for the AERONET and MODIS AOD data, although no trends were significant. Further understanding of the seasonal variations of aerosol optical properties in this polluted region would help to improve satellite aerosol retrieval and to promote regional climate change research.

1. Introduction

The climate is a complex system controlled by the energy budget of Earth. Aerosols interact with the Earth's energy balance through the scattering and absorption of sunlight [1]. Indirectly, aerosols have a substantial effect on cloud properties and the initiation of precipitation [2] (and references therein). Much of the uncertainty in climate modeling and projections of climate change is due to the complexity of aerosols. To identify and quantify the uncertainty in radiative forcing and climate change, observation of the physical and optical properties of aerosols and their radiative and climatic impacts is urgently required, particularly over polluted regions.

The North China Plain (NCP; 114–120°E, 34.5–41°N) is based on the deposits of the Yellow River and is the largest alluvial plain of eastern Asia. The plain is bordered to the north by the Yanshan Mountains and to the west by the Taihang Mountains at the edge of the Loess Plateau. To the south, it merges into the Yangtze Plain. From northeast to southeast, the plain fronts the Bohai Sea, the highlands of

* Corresponding author. Tel.: +86 108 299 5071; fax: +86 108 299 5073.
E-mail address: xxa@mail.iap.ac.cn (X. Xia).

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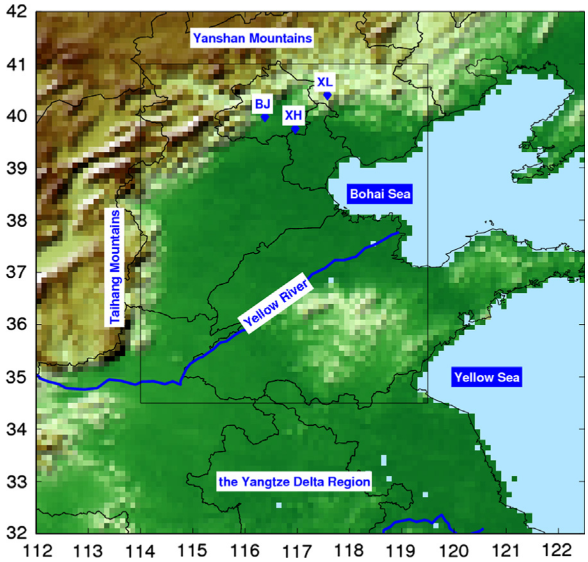

Fig. 1. Topography of North China Plain (NCP) and the three representative AERONET stations including Beijing—urban: 116.92, 39.75; Xianghe—suburban: 116.38, 39.98; and Xinglong—background: 117.58, 40.39.

Shandong Peninsula, and the Yellow Sea (Fig. 1). The NCP is a densely populated region in China and has experienced unprecedented economic and population growth during the past three decades, which has resulted in a general decline in air quality [3–5]. The mixture of coarse dust particles with heavy anthropogenic pollution created by industrial and agricultural activities and urbanization has resulted in a rather complex nature of aerosol physical and optical properties [6,7].

To monitor the long-term changes in atmospheric components at a regional scale, three Aerosol Robotic Network (AERONET) stations were established in urban, suburban, and background areas of the NCP (Fig. 1). These AERONET data were widely used to characterize aerosol optical properties [8], to validate satellite retrievals [9,10], to study aerosol radiative forcing [11,12], and to reveal regional air pollution episodes [13,14]. The Moderate Resolution Imaging Spectroradiometer (MODIS), which was deployed on the Terra and Aqua satellites in early 2000 and mid-2002, respectively, has retrieved aerosol optical depth (AOD) with 20% accuracy over land [15], and its aerosol data has provided regional and global views of the aerosol system. The MODIS aerosol product has been widely used in geophysical applications such as studies of regional and seasonal distributions of major aerosol systems [16,17], intercontinental transportation of pollutants [18], and aerosol–cloud interaction [19]. In addition, its product has been used to determine and quantify aerosol source strength [20]. Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP) is the primary instrument of the Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite launched in mid-2006. CALIOP was designed to provide a global 3-D view of aerosols and clouds and is expected to improve the performance of a variety of atmospheric models ranging from global climate to small-scale cloud resolving models [21] (and references therein).

The objective of this study is to present a 4-D view of aerosol optical properties in the NCP by using AERONET, MODIS, and CALIPSO data. The variability of aerosol optical properties on various spatial and time scales is shown in this paper.

2. Ground and satellite remote sensing aerosol data

2.1. Ground sunphotometer data

In spring of 2001, two Cimel sunphotometers were installed temporarily in Beijing and Xianghe, as part of the Aerosol Characterization Experiment—Asia project (ACE—Asia). Three permanent AERONET sites were established in the NCP. The first two locations were in Beijing and Xianghe in April 2002 and August 2004, respectively. In February 2006, the third AERONET site was established at the top of a mountain (970 m a.s.l.) in Xinglong at a regional background station. A long-term, continuous, and readily accessible public domain database of aerosol optical, microphysical, and radiative properties recorded at these three stations are downloaded from the AERONET website (http://aeronet.gsfc.nasa.gov). The measurement and calibration protocol, processing algorithm, and data quality have been detailed in previous research [22,23]. Table 1 shows the observation period at these 3 AERONET stations.

2.2. MODIS data

MODIS was deployed on Terra and Aqua satellites launched in December 1999 and May 2002, respectively. The MODIS aerosol retrieval algorithm over land has been improved periodically and has been designated by various collections since its initial launch [15]. The MODIS dark-target AOD data have evolved to the Collection 5.1 that is used in this study. Validation at more than 30 sites across China showed that the correlation coefficient between MODIS and ground-based AODs was 0.84. The offset and the slope was 0.047 and 0.98, respectively [9]. We used the Level 2.0 MODIS AOD data, which have a spatial resolution of 10 km at nadir. The Level 2 MODIS aerosol products also contain retrieval quality assurance (QA). Only QA3 (high confidence) data were used in the analysis. The data since March 2000 from Terra and July 2002 from Aqua were downloaded from the GSFC LAADS web (http://ladsweb.nascom.nasa.gov).

2.3. CALIOP data

CALIOP is the primary instrument on the CALIPSO satellite. Its main function is to acquire vertical profiles of elastic backscatter at 532 nm and 1064 nm from a near

Table 1
AERONET data at Beijing, Xianghe and Xinglong.

Station	Observation period	Number of month
BJ	2001/03–2001/05; 2004/04–2012/08	123
XH	2001/04–2001/05; 2005/09–2012/06	94
XL	2006/02–2012/09	57