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Photometric measurements of spring aerosol optical properties in dust and non-dust periods in China

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ABSTRACT

Aerosol observational data spanning three years (2005–2007) from the Chinese Sun Hazemeter Network (CSHN) were analyzed to characterize the optical properties of spring aerosol particles in dust and non-dust weather conditions. The measurements were segregated and the dates of dust period were chosen by ground-based observations and the National Sand-dust Weather Almanac. Observational data obtained under suitable weather conditions and averaged over 15 sites in the CSHN. The data indicated that the mean spring aerosol optical depth (AOD) increased by 33% in dust weather than in non-dust weather over the three years under study. Further, the angstrom exponent (α) decreased by 24% in dust weather compared to in non-dust weather. At dust-source sites, AOD increased by 31% and α decrease by 20%. The atmosphere of dust-source sites is relatively clean, and is generally only contaminated with small quantities of dust particles. Atmospheric aerosols of this region were primarily in the form of coarse mode. Aside from being influenced by dust storms, the atmosphere of both near-source and distant sites displayed a large proportion of man-made aerosols, resulting in a large increase in the AOD and α values. Due to the contribution of sand-dust, the AOD of near-source and distant sites increased by 53% and 23%, respectively, while the value of α was reduced by 22% and 25%, respectively. Due to the content differences of man-made aerosols, and the fact that some observational data cannot be obtained under heavy dust storm weather conditions, the mean AOD and α were highest at distant sites (0.69 and 0.91), intermediate at near-source sites (0.51 and 0.86), and lowest at the dust-source sites (0.36 and 0.48). In addition, if we take into account the impact of strong dust storms in which AOD can't be observed by sunphotometer, the AOD probably become greater the farther form the dust-source region in non-dust periods, and while it is opposite in dust periods. Data were also obtained for both urban and ecology background sites. AOD and α values were both significantly higher at urban sites than at neighboring natural ecology background sites during both dust and non-dust periods, but the occurrence of dust process made the multiplier slightly larger.

1. Introduction

Currently, there is a high degree of uncertainty in applying techniques to estimate and simulate the effects of aerosols on regional climates and environment, and as such, improving these techniques has become a primary focus within the atmospheric sciences (IPCC, 1996, 2001,

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2007; Satheesh and Moorthy, 2005; Lee, 1972; Anderson et al., 2003). The Chinese mainland is a major global aerosol source, and dust storm transportation can bring about large quantities of dust particles (Zhang, 1984; Zhang et al., 2003a,b). During the past few decades, China has become one of the crucial contributors to the uncertainty of aerosol climate and radiation effects (Committee of China's National Assessment Report on Climate Change, 2007). Wind-blown dust, especially from dust storms, has a remarkable impact on the exchange of aerosol optical properties (Xin et al., 2007; Zakey et al., 2006; Li et al., 2003; Zhang et al., 2002a,b). Atmospheric mineral dust, often lifted from arid and semiarid regions in northern China and Mongolia during the spring, influences radiation budgets over local and down-wind regions through the absorption and scattering of solar and infrared radiation (Shao et al., 2007; Kim et al., 2006; Seinfeld et al., 2004; Won et al., 2004). Northern China is the second largest source region for atmospheric dust aerosols in the world (Chen et al., 2006; Zhang et al., 1996), and annual dust and sand emissions in the area amount to over 25 million tons, with the spring emission accounting for more than half of the annual total amount (Xuan et al., 2000). To this end, it is necessary to understand the properties, spatial variations, and temporal variations of the dust aerosols over China.

Research has indicated that high AOD emerges during the spring in many parts of China, and dust or soil is the dominant aerosol mode (Xin et al., 2007; Gao et al., 2004; Han et al., 2005). In Northern China, dusty weather occurs frequently and it includes dust storms, blow dust as well as floating dust. This is due in large part to the arid land surface and great wind speeds that predominate during the spring season. These dust particles account for a large proportion of the total atmospheric aerosols (Zhang et al., 2003a,b; Wang et al., 2007a,b; Li et al., 2005; Zhou et al., 2002). Zeng has shown that the spring dust storms and dust weather account for 66% and 61% of the annual total frequency, respectively, based on data from 681 monitor stations from 2000 to 2004 (Zeng et al., 2006). Further, in recent years, some scientists have begun to investigate and research the optical properties, radiative characteristics, and size distributions of dust aerosols in Asia, especially in the semiarid region and deserts of Northern China (Xia et al., 2004; Zhang et al., 2001; Ogunjobi et al., 2004; Kim et al., 2007; Chen et al., 2006; Xin et al., 2005). There have been several research experiments and conclusions established to study aerosol characteristics in dust weather. Kim and co-workers analyzed the multi-year records of aerosol robotic network (AERONET) sun/sky radiometer measurements, micro-pulse lidar (MPL), and Moderate Resolution Imaging Spectroradiometer (MODIS), and showed that seasonal and spatial distributions of AOD were related to the dust and anthropogenic emission patterns. The maximum AOD values occurred during the spring, and were related to the frequency of dust storms and elevated aerosol loads in the middle troposphere (Kim et al., 2007). Xin has conducted field experiments in the Tengger Desert in Northern China, and found that the AOD was significantly higher, while α values were significantly lower under floating dust and dust storm weather conditions relative to the typical background condition (Xin et al., 2005). Xia has measured the aerosol optical properties by ground-based solar radiometer measurements at Dunhuang, China, and determined that the maximum monthly average AOD takes place in April. Further, a rapid increase in AOD coupled with a decrease in α was measured during dust outbreak episodes (Xia et al., 2004). But, at the present time, there have been few extensive systematic studies of large-scale spring aerosol optical properties in dust and non-dust weather in China. To this end, it is important to monitor aerosol optical properties in varying regions across China in order to compare and quantify the variation of AOD and α in dust and non-dust periods.

2. Principle and method

2.1. Aerosol observation network and data description

Ground-based sunphotometric measurements are among the most effective ways to determine columnar optical properties (Holben et al., 2001, 1998, 1996; Kim et al., 2004). The Chinese Sun Hazemeter Network (CSHN) was developed by the Institute of Atmospheric Physics, Chinese Academy of Sciences (IAP, CAS) and the University of Maryland in July 2004. As China's first and largest set of ground-based aerosol observation platforms, the observation sites of the CSHN have regional and geographical representation, has a more extensive coverage area and universal application, and can provide important observational data for researching aerosol optical properties and their subsequent climatic effects (Xin et al., 2006, 2007).

The observation sites uniformly use LED (Light-emitting Diode) hazemeters, which have been widely employed in the GLOBE (Global Learning and Observations to Benefit the Environment) program and are generally recognized by international scientists (Brooks and Mims, 2001; Hao et al., 2005; Acharya, 2005). The measurement period for this technique generally lasts from 10 am to 2 pm (local time), with measurement frequencies of three times every half an hour. Weather conditions and cloud cover are synchronously recorded during the measurement period. The instrument uses four wavelength channels (880 nm, 650 nm, 500 nm, and 405 nm) for the sunphotometer, while only the 500 nm channel is used for typical AOD measurements, as reported in this paper. For these studies, a calibration centre was located at the Xianghe site, where hand-held hazemeters were uniformly and annually calibrated with CE318 sunphotometers (produced by CIMEL Company, France). A new calibration centre is now located at the Lhasa site, where Langley plot calibrations are made in August or September of each year (Xin et al., 2006). Due to the occurrence and obvious influence of dust weather, primarily in Central and Northern China, we selected 15 sites in the network, including: Beijing city, Beijing forest, Xianghe, Shenyang, Lanzhou city, Eerduosi, Shapotou, Ansai, Fukang, Shanghai city, Lake Tai, Jiaozhou Bay, Fengqiu, Taoyuan, and Yanting (Fig. 1; Table 1).

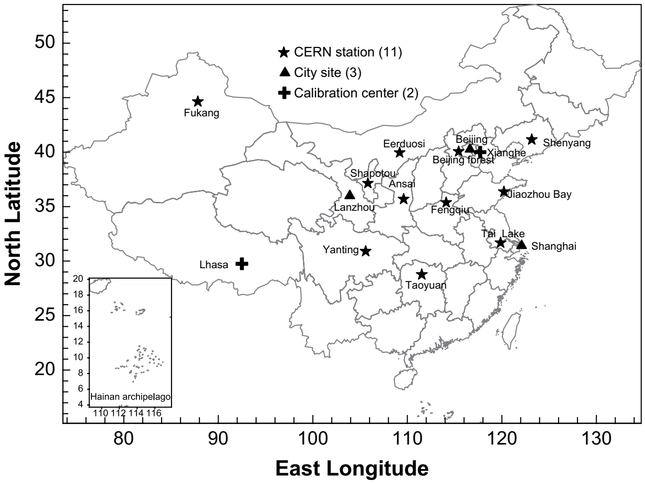

Fig. 1. Distribution of observation sites in the Chinese Sun Hazemeter Network (CSHN). The sites include CERN (Chinese Ecosystem Research Network) sites, city sites and calibration centres.

2.2. Selection and sorting of dust periods and observation sites

For our studies, we combined ground-based observation and the Sand-dust Weather Almanac to select the requisite dust dates. For comparison and further validation, we also employed a simulation of dust AOD changes, as modeled by the latest dust module in Regional Climate Model (RegCM3). The activity of the spectrophotometric observations is adversely affected by sun radiation and cloud cover when dust storms occur over the measurement sites, which are often accompanied by cold wind. As such, it was often difficult to obtain reliable spectrophotometric measurements during these times. The present work analyzes only regional aerosol optical characteristics within suitable weather conditions, during which AOD and α can be observed by the spectrophotometer. These conditions include sunny days and periods immediately before or after dust storms days. Based on the distance of the observation sites from the dust source area, the influence degree of dust storms, and the properties of regional aerosol particles and angstrom exponents, the 15 sites were divided into three categories (Tables 2 and 3), including dust-source sites, near-source sites, and distant sites.

Table 1
The latitude, longitude and elevation of observation sites and calibration sites

Sites	Longitude (°E)	Latitude (°N)	Elevation (m)
Beijing city	116.37	39.97	44
Beijing forest	115.43	39.97	1130
Xianghe	116.96	39.75	20
Shenyang	123.63	41.52	31
Lanzhou city	103.82	36.07	1520
Eerduosi	110.18	39.48	1300
Shapotou	104.90	37.45	1357
Ansai	109.31	36.85	1208
Fukang	87.92	44.28	470
Shanghai city	121.75	31.12	5
Lake Tai	120.22	31.40	6
Jiaozhou Bay	120.18	35.90	6
Fengqiu	114.40	35.00	68
Taoyuan	111.45	28.92	78
Yanting	105.45	31.27	420
Lhasa	91.33	29.67	3688

3. Properties of AOD and α in dust and non-dust periods

We divided the ground-based observational data obtained between 2005 and 2007 into two categories according to the above method, and obtained annual mean AOD and α values during dust and non-dust periods in the spring season. Based on Figs. 2 and 3, the value of AOD during dust periods is higher than during non-dust periods, while the value of α is lower. The mean AOD and α values across the 15 study sites are 0.68 and 0.62, respectively, during dust weather, and 0.51 and 0.82, respectively, during non-dust weather. Atmospheric aerosols concentration has an obvious rise, especially the dust particles content mounts up a lot during dust weather, and which made the AOD increase and α decrease directly. From the changing of AOD and α in two kinds of weather conditions, we can deem that dust weather process has a certain degree of impact on the aerosol optical properties of the 15 observation sites.

3.1. Regional aerosol optical properties

On average, AOD and α are lowest at dust-source sites (Figs. 2 and 3; Table 3), which reflects the atmosphere is quite clean in most northwest regions of China. Further, it indicates that the master mode of aerosol is large-sized dust particles. The three-year spring average AOD and α values were 0.36 and 0.48, average AOD and α values were 0.44 and 0.40 in dust weather, and 0.34 and 0.51 in non-dust weather, respectively (Table 3). The frequency of dust storms is highest in northwest China, and the atmosphere contains abundant dust particles even during non-dust weather. Due to the limitations of weather conditions and cloud cover, the sunphotometer is unable to monitor aerosol optical properties in the situation of serious dust

Table 2
Selected dust dates, and AOD and α ratios in dust and non-dust periods

Sites		2005			2006			2007			AOD_{dust}/$AOD_{non-dust}$	α_{dust}/$\alpha_{non-dust}$
		March	April	May	March	April	May	March	April	May		
Near-source sites	Beijing city	9,19	6,18,27,30	7	20,22,30,31	2,3,5,14,28	11,16,17	12,26		14	1.77	0.74
	Beijing forest	9,19	6,17,18,30	2,3,7,30,31	20,22		17,18,30	12		14	1.58	0.56
	Xianghe		7,16	2,7,28	30	2,30	17	No data	No data	No data	1.77	0.87
	Shenyang		5,18	5,28	16	9,10	3,22,24,26	10		27,28	1.44	0.85
	Lanzhou city	9,10	2,6,12,19,20,21,22	13,14,30,31	9,30	4,6,7,9,17,18,19	17,21,23,25,30	10,25,26,27,29,30,31	1,5,11	2,7,8,16,20,25	1.17	0.81
Dust-source sites	Eerduosi	9,10,15,18	16,29	2,10,12,25,27,29,30	27,28,30	2,7,27	10,23	8	5	14,24	1.38	0.68
	Shapotou	6,9	21	13,14,15	16	4,7,24,25,27,30	5,15,18,31	10,12,19,27,29,31	12,15,17	24	1.12	0.82
	Ansai	No data	No data	No data	18,30,31	7,9,28	1,16,19,23,25,30	19,25,29	9	16	1.40	0.78
	Fukang	8,10,16,17	19	3	12,13,14,27	19,29		9,31	1,23,24	11,16	1.32	0.81
Distant sites	Shanghai city		20,21,22,27			17,25,29	19,20	28,29,30		3,17	1.23	0.74
	Lake Tai		23,27	6,8			20	28			1.15	0.50
	Jiaozhou Bay		2,5,17,28	7,11,26	20,31	11,15,26,29	1,13,17,20,21	13		15,25	1.47	0.83
	Fengqiu	7	7,12,19,20,21,28	6,11	22,27	2,29	16,19	10,27,28,29		9,14,15,27	1.26	0.81
	Taoyuan	3,4	2,19,20	6,7	14	19	22	28	15	26,27	1.11	0.80
	Yanting	2,10,16,22	8,20,24	1,5,6	27	1,18,22,25	21,25	24,25,28	12,15,20	12,24,25,26,27	1.14	0.75

Selection was based on ground-based observations and the Sand-dust Weather Almanac. The spectrophotometer cannot be used in heavy dust storms or during cloudy days, so the selected dust dates are in the extension of ground-based observational recording dates.

Table 3
Spring average AOD and α at three category sites (2005–2007)

Sites	AOD			α		
	Mean	Dust periods	Non-dust periods	Mean	Dust periods	Non-dust periods
Dust-source sites	0.36	0.44	0.34	0.48	0.40	0.51
Near-source sites	0.51	0.71	0.46	0.86	0.70	0.90
Distant sites	0.69	0.81	0.66	0.91	0.71	0.95

storm and cloudy weather, so it lowers the final mean AOD value of dust weather. Overall, during dust weather, AOD increases by 31% and α decreases by 21% according to obtainable observational data.

The increase in AOD during dust weather at near-source sites is evident. The three-year spring average AOD and α values are 0.51 and 0.86, respectively. Mean AOD and α values are 0.71 and 0.70 during dust weather, and 0.46 and 0.90 during non-dust weather (Table 3). As such, AOD increases by 53% and α decreases by 23% in dust weather relative to non-dust weather. The aerosol optical properties have enormous differences and contrasts when dust storm happens compared to usual days, and the impact and contribution of dust particles to the total atmospheric aerosol content is notable during dust periods.

Averaged over the three-years of observational data, AOD and α are maximal at distant sites, with spring AOD and α values at 0.69 and 0.91, respectively. In dust weather, mean AOD and α values are 0.81 and 0.71, while the values are 0.66 and 0.95 in non-dust weather, respectively (Table 3). As such, AOD increases by 23% and α decreases by 25% during dust weather. These sites are far from the dust source, and the impact by dust storms is weaker. However, their aerosol concentrations are the highest among the three category sites. Atmospheric aerosols are primarily generated from anthropogenic emissions in China's south, central and eastern regions, and man-made aerosols dominate regional aerosol composition.

From Table 3, it is evident that the AOD and α values are higher at distant and near-source sites than at dust-source sites. The atmosphere of distant and near-source sites is heavily polluted by human activity and contains high levels of man-made aerosols, while the atmosphere of dust-source sites is relatively clean, with sand and dust being the main aerosols composition.

3.2. Aerosol optical properties at urban sites and neighboring natural ecological background sites

Aerosol concentrations, compositions, and optical properties are affected by anthropogenic emissions in urban areas. As such, there must exist differences in aerosol properties between urban sites and neighboring natural ecology background sites. For the present study, we selected three groups of typical urban and ecology sites, including Beijing city and Beijing forest, Lanzhou city and Shapotou, and Shanghai city and Lake Tai (Table 4).

In dust weather at the Beijing city site and Beijing forest site, the mean AOD values are 0.85 and 0.43, and α values are 1.07 and 0.32, respectively. In non-dust weather, the

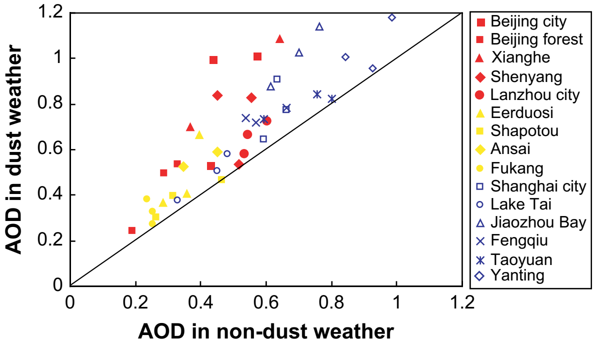

Fig. 2. Comparison of AOD in dust weather and in non-dust weather ($\lambda = 500$ nm). Red symbols represent near-source sites, yellow symbols represent dust-source sites, and blue symbols represent distant sites.

mean AOD values are 0.48 and 0.27, and α values are 1.44 and 0.58, respectively (Table 4). The AOD at the Beijing city site is 1.99 times that of the Beijing forest site, and the value of α at Beijing city is 3.3 times that of Beijing forest site during dust weather, while these values are 1.78 and 2.48 in non-dust weather. The aerosol properties also have obvious differences at Lanzhou city site and the neighboring Shapotou site, as well as in Shanghai city site and the neighboring Lake Tai site (Table 4). The urban atmosphere contains a large amount of man-made fine-sized aerosols and its aerosols concentration is greatly higher than that of neighboring background sites, which made the values of AOD and α at urban sites are much higher than at neighboring background sites (the average AOD and α are 1.61 and 1.36 times at Lanzhou city site than at Shapotou site, and the values are 1.50 and 1.13 times at Shanghai city site than at Lake Tai site). In addition, the increase degree of AOD and α between urban and neighboring background sites in north is more obvious than in south of China. The occurrence of sand-dust process, brings a number of large-sized dust particles, and makes the AOD and α have a certain increase and decrease, respectively. However, due to special land surface characteristics, building structures and complicated aerosols composition, the dust particles are difficult to diffuse and is easy to suspend and accumulate in urban atmosphere, which making its AOD and α increase relatively more than that of ecological background sites (Table 4).

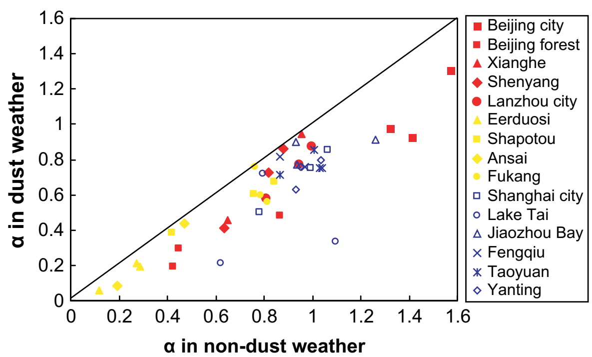

Fig. 3. The comparison of Angstrom exponent (α) in dust weather and in non-dust weather. Red symbols represent near-source sites, yellow symbols represent dust-source sites, and blue symbols represent distant sites.

Table 4
Spring average AOD and α at three groups of typical urban and ecological sites (2005–2007)

Sites	AOD			α		
	Mean	Dust periods	Non-dust periods	Mean	Dust periods	Non-dust periods
Beijing city site	0.55	0.85	0.48	1.36	1.07	1.44
Beijing forest site	0.30	0.43	0.27	0.54	0.32	0.58
Lanzhou city site	0.59	0.66	0.56	0.86	0.74	0.92
Shapotou site	0.36	0.39	0.35	0.65	0.55	0.67
Shanghai city site	0.65	0.78	0.63	0.91	0.70	0.94
Lake Tai site	0.43	0.49	0.42	0.79	0.42	0.84

Based on our results, we concluded that the values of AOD and α at urban sites are all significantly higher than at neighboring natural ecology background sites in both dust and non-dust weather. Further, the multiplier in dust weather slightly larger than in non-dust weather.

3.3. Other sites

Other sites in the CSHN, including Changbai Mountain, Sanjiang, and Hailun in northeastern China, and Lhasa, Haibei, Xishuangbanna, Dinghu Mountain, and Sanya in southwest and south China, are not affected notably by strong dust storms, and atmospheric aerosols of these sites are primarily dominated by large-sized natural emission sources, therefore, are not discussed in the present report.

3.4. Further discussion

The strong dust storms often affect the photometric observation, particularly in dust-source and near-source regions. Based on the statistics of observational data, and the consideration of outbreak and termination date of dust storms, we get that there are about 51.4% and 50.9% dust weather, mainly for the strong sandstorms, can't be observed by sunphotometer in dust-source sites and near-source sites, respectively. According to some other observational methods, including the use of satellite remote sensing, laser radar and other methods, and related research results for representative regions, the average AODs of dust-source sites and near-source sites are about 2.37 and 2.00 in strong dust storm periods (Li et al., 2005; Qian et al., 2006; Shen et al., 2003; Zhang et al., 2002a,b; Niu and Sun, 2001; Qiu and Sun, 1994). We can roughly estimate that in all, including the impact of strong dust storms, the average AOD in dust weather is 1.43 at dust-source sites and 1.40 at near-source sites in light of observation results and the proportion of observational dust storm dates in this paper. Assuming the above description is accurate and combining with the observational AOD of three categories sites in non-dust periods, we can superficially get that the spring dust weather makes the AODs increase from 0.34, 0.46 and 0.66 to 1.43, 1.40 and 0.81 at dust-source sites, near-source sites and distant sites, and the multiples are 4.2, 3.0 and 1.2, respectively.

According to the above analysis and taking into account the impact of strong dust storms in which AOD can't be observed by sunphotometer, we can conclude that the AOD become greater the farther form the dust-source region in non-dust periods, and while it is opposite in dust periods. It will have certain significance for dust modelers and the researchers who engaged in Asian dust storms. In addition, it demonstrates that the observation networks need to be further improved to adapt to the aerosol observation, especially for the dust aerosol optical properties.

4. Conclusions

Due to the high degree of emission and transmission of large dust aerosol, dust storms will inevitably cause a certain extent changes in atmospheric aerosol composition and properties across China. Exceptions include the remote northeast region, the Qinghai-Tibet Plateau, and southwestern and southeastern coastal areas, the mean AOD increases by approximately 35% and α decreases by approximately 25% during dust weather over China. The quantitative changes provide important data toward understanding the climate and environmental effects of dust storms. However, the observations of ground-based spectrophotometers are not valid during strong dust storms, heavy cloud cover, and during the night. The accurate quantification of the climatic and environmental effects of dust aerosol require further improvements in ground-based networks, model simulations, and integrated observation and research of satellite remote sensing. With the establishment of more and more ground-based observation sites and the development and use of latest observation equipments, we will have an accurate understanding of aerosol optical properties in China's different regions and weather conditions. As well as Chinese Government is attaching great importance to global climate change and environment protection, the observation and research of aerosol optical properties will certainly receive more attention in China.

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