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Dust aerosol optical properties over North China

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Abstract

Aerosol optical properties were obtained from ground-based sunphotometer data at nine observatories over North China during two periods of 1996–1998 and 2002–2003. The seasonal changes of aerosol optical depth (AOD) at five wavelengths were observed, with the highest value of AOD in spring, while the lowest in winter. Four patterns of AOD diurnal variation were obtained, of which the high value occurred in the morning, noon, evening and no remarkable change, respectively. Together with meteorological records, the characteristics of AOD during dust weather were analyzed, and the results show that it was more detailed and accurate to use AOD to depict the strength change of dust weather than to use surface visibility. Based on measurements by aerodynamic instrument for particle size distribution, a positive correlation between dust particle number concentration and Ångström turbidity coefficient β, and a negative correlation between aerosol geometric mean diameter (GMD) and wavelength exponent αwere revealed.

1 Introduction

Aerosol radiative forcing remains one of the largest uncertainties in the simulation of climate system and the projection of future climate change (Duce, 1995; IPCC, 2001; Schwartz and Andreae, 1996). On the global scale, three major components: sulfate, dust and carbonaceous particles, appeared to contribute equally to the column-integrated total optical depth (Tegen et al., 1997). Great progresses have been made recently with regard to the dust aerosol radiative forcing due to much attention having been paid to this issue (Hong et al., 2006; Lim and Chun, 2006; Sokolik and Golitsyn, 1993; Tegen and Lacis, 1996; Zhao et al., 2006); however, we need to admit that we are far from the fully understanding of the role dust plays in the climate system. Considerable uncertainties in the estimation of dust radiative forcing were highlighted in the IPCC assessment report (IPCC, 2001). This is partly due to our poor understanding of dust aerosol properties and their spatial and temporal variations. Hence, it is significant to obtain such information via all possible channels.

Northern China is the second largest source region of atmospheric dust aerosols in the world. It was estimated that nearly 800 Tg a^{-1} (with an uncertainty of approximately 40%) of mineral aerosols were emitted into the atmosphere each year, 50% of which might be deposited back to the source and adjacent regions, and the dust is often transported beyond the remote Pacific Ocean (Arimoto et al., 1996; Gong et al., 2006; Lee et al., 2006; Zhang, 2001). The research showed that the recent lasting drought in North China may be associated with the solar absorption of aerosol (Menon et al., 2002). Therefore, it is necessary to understand the properties and spatial and temporal variations of the dust aerosols in Northern China so that we can estimate more accurately the influence of dust aerosols on global and regional climate change. The objective of this study is to characterize the dust aerosol optical properties over North China via ground-based multi-wavelength sunphotometers.

2 Instrument and measurement

The AOD and particulate size distribution (PSD) used in this paper were got from two field experiments. Figure 1 shows the distribution of observatories. During the first experiment, a MS-120 sunphotometer, made by USA, was utilized during April and May from 1996 to 1998 at four observatories: Jilantai (JI) and Alashanyouqi (AL) of Inner-Mongolia, and Yinchuan (YI) and Yanchi (YA) of Ningxia Hui Autonomous Region in China. The MS-120 has three channels (530, 630, 695 nm) to detect direct solar radiation. We also used an APS-3100 to determine aerodynamic geometric mean diameter (GMD) of atmospheric aerosols at the same time. During the second one, the CE-318 sun-photometer was used at five observatories: Yinchuan of Ningxia, and Ejinaqi (EJ), Wulatezhongqi (WU), Dongsheng (DO), Zhurihe (ZH) and Xilinhaote (XI) of North China from 2002 to 2003. The CE-318 sun-photometer, produced by CIMEL, uses the five wavelengths (440, 670, 870, 936, 1020 nm) to detect direct and scattering radiation by the same detector with a 10 nm half bandwidth.

3 Results and discussions

In this section, some characteristics of AOD over North China are presented based on the analyses of the following dust aerosol field observation data and routine meteorological observations.

Firstly, the monthly and diurnal variations of AOD were analyzed using continue measurements with the CE-318 from May 2002 to June 2003 at three sites (Ejinaqi, Dongsheng, Xilinghaote).

Secondly, the diurnal variations of AOD during four dust storms (10–11 November 2002, 8–11, 13–15, 15–17 April 2003) were analyzed using the CE-318 measurements and routine meteorological observations at five observation sites of Inner Mongolia (Ejinaqi, Wulatezhongqi, Dongsheng, Zhurihe, Xilinhaote).

Finally, the relationship between the optical properties of dust aerosols (Ångström turbidity coefficient β, wavelength exponent α) and the particulate parameters (number concentration Cn, aerodynamic GMD) are presented based on measurements with the MS-120 and APS-3100 at three sites (Yinchuan, Jilantai and Alashanyouqi).

In this paper, we focused on the variations of AOD in dust weather. According to the prescription of China Meteorological Administration, dust weather includes four kind of weathers, which are floating dust (visibility$<$10 km), blowing sand (1 km$<$visibility$<$10 km), dust storm (visibility$<$1 km) and strong dust storm (visibility$<$0.5 km).

3.1 Monthly mean AOD variation

We take March, April and May as spring, June, July and August as summer, September, October and November as autumn, December, January and February as winter. The monthly mean AOD variations of Ejinaqi, Dongsheng and Xilinhaote are presented in Fig. 2.

Figure 2a displays the monthly mean AOD variation of Ejinaqi from July 2002 to May 2003. The AOD increased rapidly from March to May and then dramatically dropped to a small value in July. After a slight climbing up in August, it decreased gradually to the minimum of the year in November. Noticeably, although the AOD of winter was in lower value region of the year, a peak value appeared in December. After a primary analysis of routine meteorological records, we considered that it associated with dust weather.

Figure 2b shows the AOD variation of Dongsheng, which is similar to Fig. 2a except for its relatively lower values. The maximum value of AOD was 0.51 at the wavelength of 440 nm in spring, while the minimum 0.14 in winter. Dongsheng locates in the mid-south part of Inner Mongolia, as the extension part of Maowusu sandy land. According to the meteorological records, Dongsheng had more precipitation and less frequency of dusty weather, so it was cleaner than the other two cities.

The AOD of Xilinhaote (Fig. 2c) was equivalent to that of Ejinaqi (Fig. 2a). The maximum value of AOD, 0.78 ,occurred at the wavelength of 440 nm in spring, while the minimum, 0.18, in winter. Xilinhaote is located in the degenerating grassland of Inner Mongolia. Excessive reclamation and grazing make it the severest region of vegetation degradation and grassland desertification in China. The desertificating land and abundant wind power offers adequate sources of sand dust. Although more precipitation here than in Ejinaqi, it contributed little to AOD. According to MacTainsh et al. (1998), the presence of dust aerosols associated mostly with soil humidity and vegetation type, but not precipitation.

Although locations of the three stations are different (Fig. 1), a similar variation trend of AOD was obvious (Fig. 2). The maximum value appeared in spring, and was about 2–6 times that in other seasons, while the minimum occurred in winter. Compared with spring, the AOD of summer was much smaller and reached a valley value in July. We estimated that two reasons may be responsible for this phenomenon. On the one hand, the activities of cold fronts were most frequent in spring in northwest Inner Mongolia, and the gales accompanied with clod fronts provided the primary driving force for blowing sand. On the other hand, bared soils became thawing out when temperature increased in spring. It was easy to blow sand if gales occurred, which increased the concentration of dust particulates in the air, and then the AOD increased. In summer, the much more precipitation enhanced the wet deposition of atmospheric aerosols, and the dense vegetations reduced the chance of deflation. All of these made the air cleaner in summer. As to the AOD peaked in August, it might be associated with intense solar radiation. In August, small solar zenith angle brought high temperature, which made atmospheric stratification unstable and reinforced the upward transport of dust particles from surface sources. With more dust particles into the air, dust weather such as floating dust and blowing sand appeared, and then the AOD increased. In autumn, the synoptic system became more stable. Less gales and dust weather leaded to declining in AOD. In winter, stable atmospheric stratification, low temperature and frozen or snow-covered surface reduced the chances of dust particles escaping from the surface, so it is hard to blow sand even if gales happened. Frequent passages of cold air also diluted aerosol concentration in the air obviously in winter.

Table 1 shows the monthly distribution of dust weather days including dust storm, blowing sand and floating dust. Compared with Fig. 2, it was found that the months with high AOD accorded with those with more dust weather days. The more days of dust weather happened, the higher AOD appeared, and vice versa. This proved further that the dust particulate was the most significant influence factor to AOD in these areas.

3.2 Diurnal variation of AOD

Figure 3 presents the main four types of AOD diurnal variation in the daytime, which were:

1. type A, wherein the AOD was high in the morning and low in the evening or the AOD was high in the morning or forenoon and then decreased gradually in the rest time.

2. type B, wherein the AOD was low in the morning and high in the evening, showing

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an increasing trend in the daytime.

3. type C, wherein the AOD was low both in the morning and evening, but high in the noon.

4. type D, wherein the AOD showed no remarkable change.

Table 2 shows the statistics of AOD diurnal variations in Ejinaqi, Dongsheng and Xilinhaote, respectively. It could be found that the AOD diurnal variation of type B is the most frequent type in all of the three cities, accounting for 36%, 36% and 35% of the total, respectively. Another two statistics were performed in order to find out why this happened. Firstly, we made a statistics for the types of AOD diurnal variations in dust weather because dust particulates contributed most to AOD. Due to lack of enough data, Xilinhaote was not analyzed. The results showed that about 56% and 75% of dust weather days belonged to type B in Ejinaqi and Dongsheng, respectively. This told us information that the period between noon and evening was the most probable time for dust weather, which agreed with the statistical results found by Niu (2004) who found that about 66% of dust storms occurred in the period between noon and evening in the Helan Mountain area in Northwest China. Secondly, as to seasonal distribution, about 64% and 85% of type B happened in autumn in Ejinaqi and Dongsheng, respectively. In autumn, the steady atmosphere slowed down the settlement of floating aerosol particles. The concentration of floating aerosol reached a relatively high level in the afternoon after a whole day's accumulation, and then AOD increased to the highest level of the daytime.

As to Table 2, the ratio of days with no remarkable AOD change (type D) was small in all three stations. According to meteorological records, these days were clear with steady atmosphere and no dust weather. Because the concentration and physical and chemical properties of aerosols were stable, the AOD of these days could be regarded as background value.

As to the type of low AOD in the morning and evening but high in the noon (type C), the unstable atmospheric stratification played an important role in it. Intense solar radi-

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ation heated the ground surface, and then the surface heated the bottom atmosphere, which in turn made the atmosphere unstable. After a period of accumulation, this unstable state induced local turbulences during midday. The dust particulates blown up by winds made the AOD higher. When the local turbulences became stronger, even floating dust and blowing sand could happen.

In Table 2, the type of AOD high in the morning and low in the evening also took a higher ratio (type A). It may be associated with the dissipation process of inversion layer. In the morning, the temperature within the surface layer of the atmosphere formed an inversion layer which suppressed the convection and restrained the upward transport of aerosols. Along with the dissipation of the inversion layer during the midday, vertical convections became stronger and the concentration of aerosols in the bottom layer was diluted gradually. Another probability of type A may be associated with people's activities. In the morning, largely increased emission sources such as vehicles, boilers and cooking ranges aggravated air pollution.

The type of high in the morning and evening but low in the noon appeared rarely in all of the three stations. This was just opposite to the results given by Zhang (2000) in Dangxiong in Tibet, who thought that high temperature during noon reduced relative humidity, and then shrank hygroscopic aerosol particles. It can be inferred that the non-hygroscopic dust particles played the most important role in the AOD composition in all of the three stations.

3.3 AOD variation during dust weather

Characteristics of AOD variations in the two processes of dust weather, 10–11 November 2002 in Wulatezhongqi and 13–15 April 2003 in Xilinhaote, were analyzed in the following (Figs. 4 and 5). According to strengths, AOD in dust weather was obviously higher than these before and after the dust.

In the day before the dust weather in Wulatezhongqi (Fig. 4, 9th), AOD was on the normal level, but a little higher than that in clear day (<0.35), which represented a little increase of particle concentration in the air. Sharply increase of AOD in the afternoon showed the coming signature of dust storm. During the two days of dust weather (10th, 11th), the AOD maintained above 1.0, even 2.0 during the dust storm on 10 November. Along with the weakening of the dust storm, the AOD declined quickly from the afternoon of 11th and returned to the normal level on 12th. Because a part of small particles blown up by the gale still floated in the air, the AOD on 12th was a little higher than those in clear days.

The process of dust weather in Xilinhaote in April 2003 (Fig. 5) was similar to that in Wulatezhongqi in November 2002 (Fig. 4) except for the intensity. In the day immediately before and after the dust weather, the AOD remained at the normal level, while it hold on a high level during the three days of dust weather (13th–15th). According to Fig. 5, a relatively weaker dust storm in Xilinhaote than that in Wulatezhongqi could be inferred. On 16 April, the day after the dust weather, a sharp drop of AOD could be clearly seen.

According to the above analyses, the temporal variation of AOD was distinct and drastic during dust weather processes. Despite the different intensities of dust weather, the variations of AOD were similar. The AOD might rapidly increase to a rather high level when a dust storm came, and returned to the normal level quickly when the dust storm went away. Due to the sudden change of dust storm during dust weather, it is hard to predict it, so it is urgent to reinforce the earlier stage observations.

Table 3 presents the variations of AOD and horizontal surface visibility during the dust weather in Xilinhaote during 13–16 April 2003. The visibility was 15 km both at 09:00 BST on 13th and 06:00 BST on 14th, but the AOD was 0.75 and 1.25, respectively. The AOD still remained to be 1.25 while the visibility decreased to 9 km at 09:00 on 14th. With the weakening of dust weather, the visibility increased to 20 km at 09:00 on 15th, but the AOD increased to 2.25. The discrepancy between AOD and visibility was due to that the visibility was estimated roughly in horizontal direction by observer's eyes, which only implied the status of dust near surface, while the AOD suggested the column content of aerosols in the vertical direction. When most of dust particles were near surface, the AOD and visibility showed a good agreement, but when most of dust particles were in upper air, a great discrepancy between AOD and visibility like the above case would appear again.

3.4 Relationships between turbidity coefficient (β) and wavelength exponent (α)

The inverse correlativity between turbidity coefficient (β) and wavelength exponent (α) had been proved by many scholars, such as Kaufman and Fraser (1983), Mohamed et al. (1992), Prodi et al. (1984) and Tanaka et al. (1989). According to the records in the springs of 1996 and 1997 in three stations (Jilantai, Yinchuan and Alashayouqi), the distributions of β and α are presented in Fig. 6 and the inverse relationship between β and α is also remarkable. The solid lines in Fig. 6 are the fitting results of β and α by the least square method. The expressions of them are as the follows:

$$\text{a:}\beta = -0.1651 \ln \alpha + 0.3305,$$
$$\text{b:}\beta = -0.3455 \ln \alpha + 0.4712,$$
$$\text{c:}\beta = -0.1212 \ln \alpha + 0.2329,$$
$$\text{d:}\beta = -0.0950 \ln \alpha + 0.2365.$$

With the decrease of α, β showed an increasing trend, suggesting that the number of large size particles increased with the concentration of dust particles.

3.5 Relationships between optical characteristic quantities and parameters of particle size distribution

Figure 7a presents the relationship between the number concentration Cn and β of dust aerosols in the near surface layer in the blowing sand weather on 30 April 1996 at Jilantai station. The Cn increased from 17.2 cm^{-3} at 07:08 BST to 80.0 cm^{-3} at 16:10 BST and β from 0.14 to 0.86 in this period. At the same time, the number concentration of dust particles with diameter between 0.5 and 0.7 μm increased from 1.3 cm^{-3} to 8.1 cm^{-3}. According to this, a positive correlativity between Cn and β could be found in Fig. 7a. An inverse correlativity between aerodynamic GMD and α of dust aerosols

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near surface is presented in Fig. 7b, which shows that the effective radius of aerosols could be expressed with the wavelength exponent α.

4 Conclusions

Based on the analysis for a few of dust weather processes in North China, some pieces of conclusions are obtained as follow:

1. AOD, influenced mostly by dust weather in North China, had an apparent seasonal variation: maximum in spring and minimum in winter.

2. There were four patterns of AOD diurnal variations over North China: high value in the morning, in the evening, during the noon, and no remarkable variation.

3. AOD showed a good response to the intensity of dust weather.

4. Compared to surface visibility, AOD had superiority in depicting the intensity of dust weather more detailedly and accurately.

5. According to the measurements of particle size distribution, a positive correlativity between Cn and β, and an inverse correlativity between GMD and α, existed in the near surface layer in blowing dust weather.

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Table 1. The number of dust weather days for each month from June 2002 to May 2003

	2002							2003				
	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Ejinaqi	3	1	5	2	3	1	2	0	2	1	5	5
Dongsheng	0	0	0	1	0	2	0	0	0	0	2	0
Xinlinhaote	3	0	1	0	0	2	2	0	0	0	1	0

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Table 2. Statistics for AOD diurnal variation types. The numbers in parentheses represent the percentage.

station	days	A	B	C	D	other
Ejinaqi	116	29 (25)	42 (36)	28 (24)	13 (11)	4 (3)
Dongsheng	124	36 (29)	45 (36)	26 (21)	17 (14)	0 (0)
Xilinhaote	54	13 (24)	19 (35)	18 (33)	2 (4)	2 (4)

Note: The capital characters (A, B, C, D) represent four patterns of AOD diurnal variations, respectively. A, high in the morning and low in the evening; B, low in the morning and high in the evening; C, low in the morning and evening, but high in the noon; D, no remarkable change; other, other types.

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Table 3. Variations of surface visibility and AOD in Xilinhaote during 13–16 April 2003.

	13th		14th		15th		16th	
	06:00	09:00	06:00	09:00	06:00	09:00	06:00	09:00
Visibility(km)	30	15	15	9	30	20	30	30
AOD	0.2	0.75	1.25	1.25	0.5	2.25	0.5	0.25

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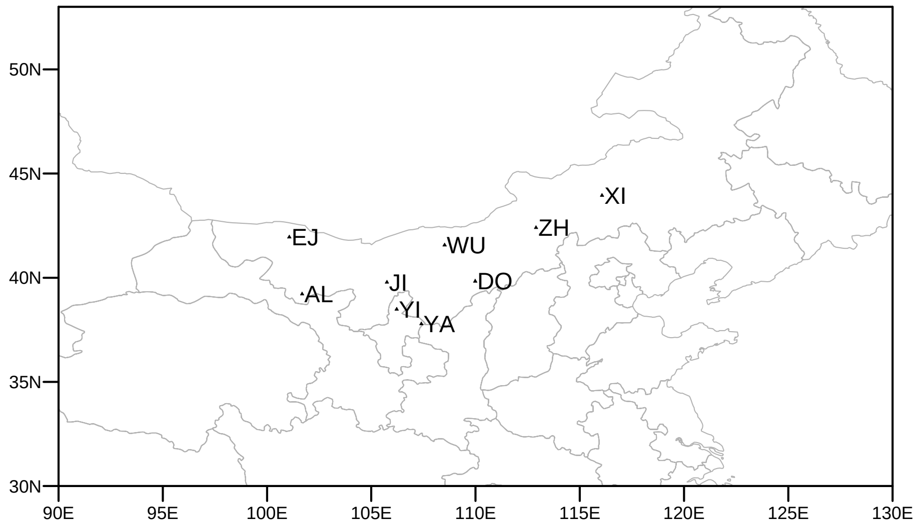

Fig. 1. Locations of nine observatories. JI: Jilantai, AL: Alashanyouqi, YI: Yinchuan, YA: Yanchi, EJ: Ejinaqi, WU: Wulatezhongqi, DO: Dongsheng, ZH: Zhurihe and XI: Xilinhaote.

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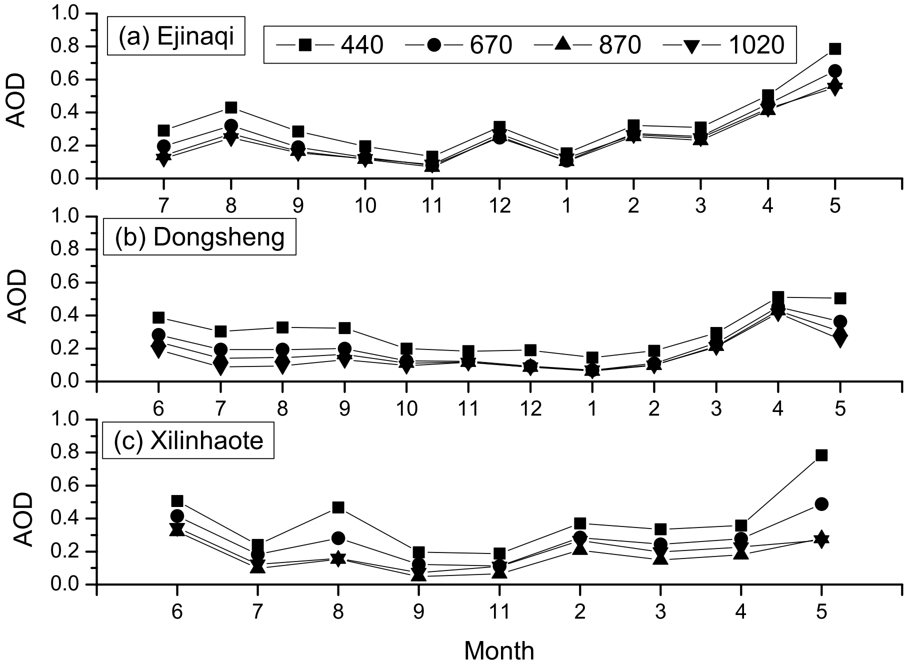

Fig. 2. Monthly average AOD variations of **(a)** Ejinaqi, **(b)** Dongsheng, and **(c)** Xilinhaote. from June 2002 to May 2003.

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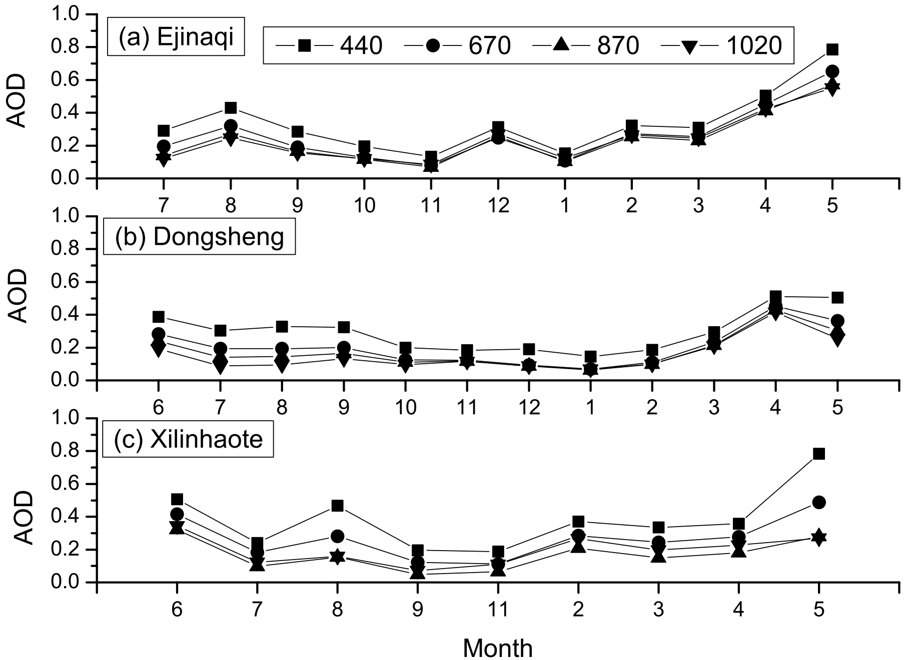

Fig. 3. Four patterns of AOD diurnal variation.

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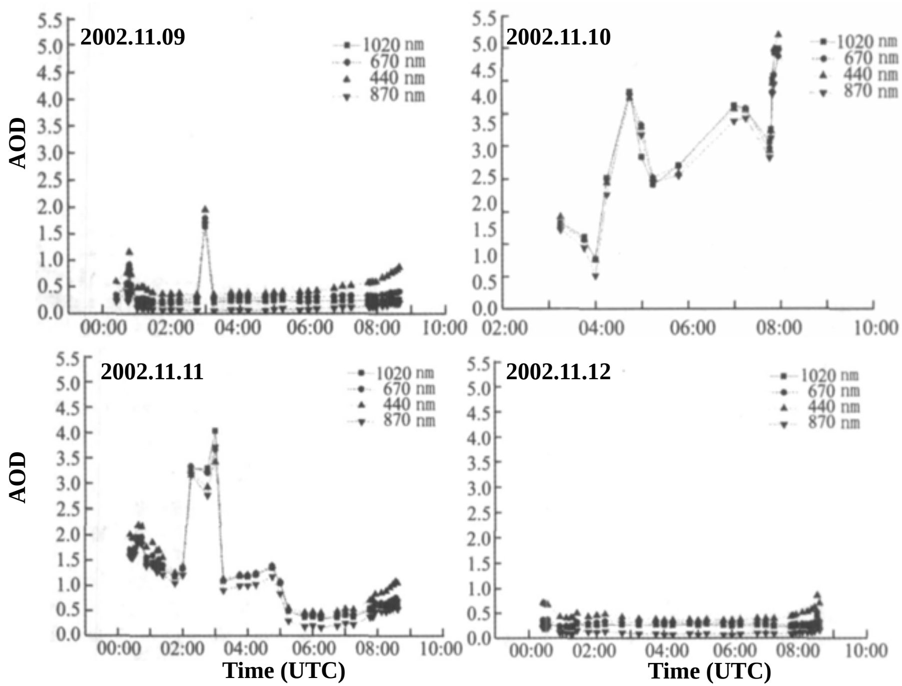

Fig. 4. Diurnal variations of AOD in Wulatezhongqi during a dust weather and in the day immediately before and after the dust weather (9–12 November 2002).

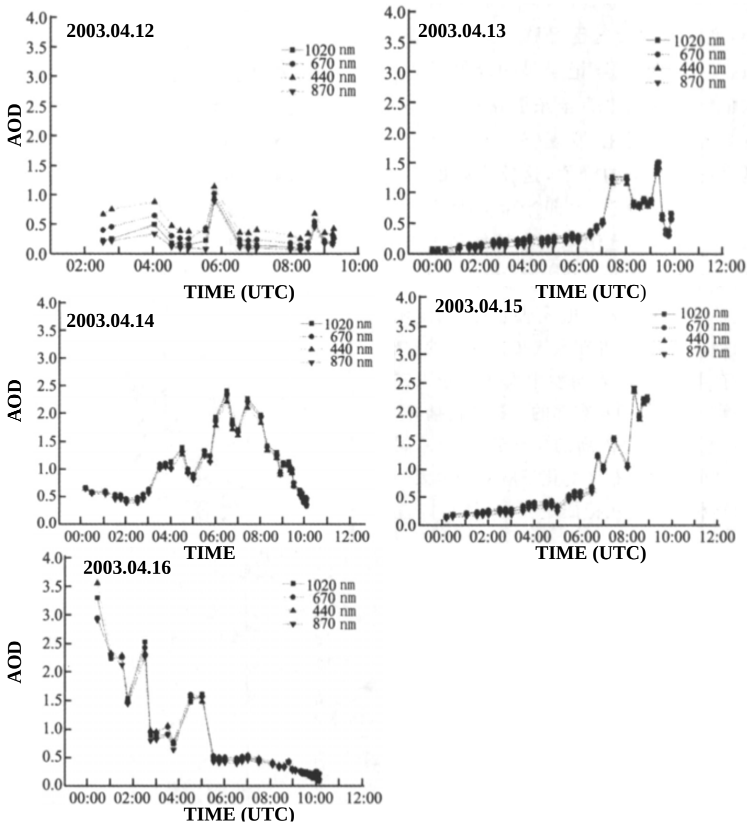

Fig. 5. Diurnal variations of AOD in Xilinhaote during a dust weather and in the day immediately before and after the dust weather (12–16 April 2003).

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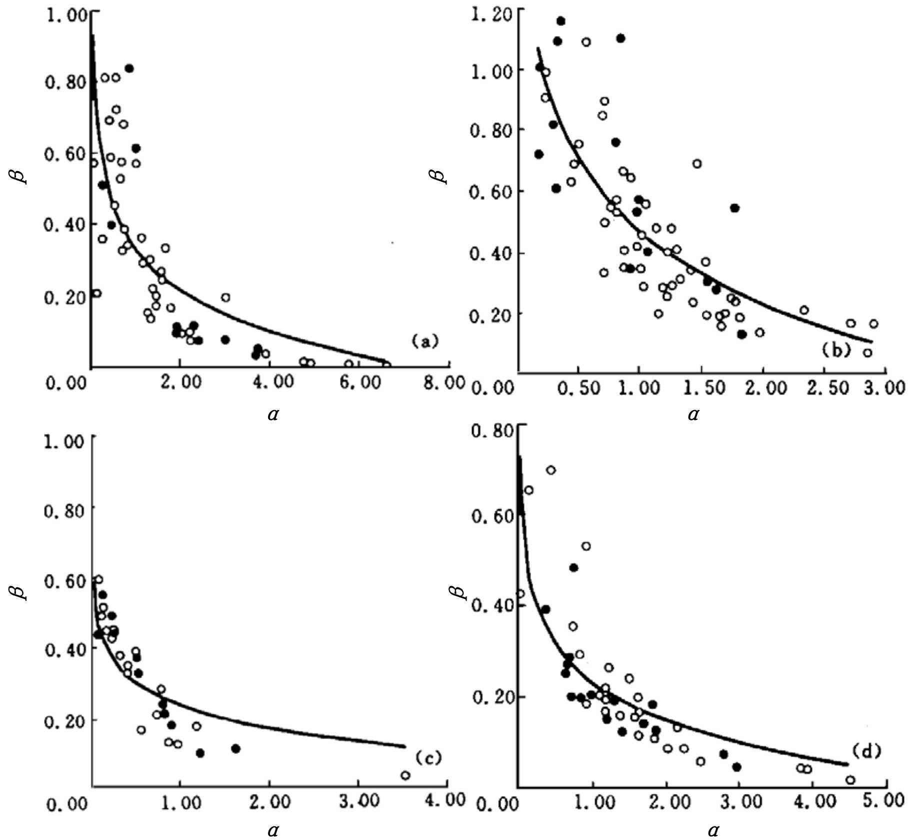

Fig. 6. Distributions of turbidity coefficient (β) and wavelength exponent (α) for Jilantai in **(a)** April, and **(b)** May; **(c)** Yinchuan in April and **(d)** Alashanyouqi in April, respectively. The abscissa and ordinate represent α and β, respectively.

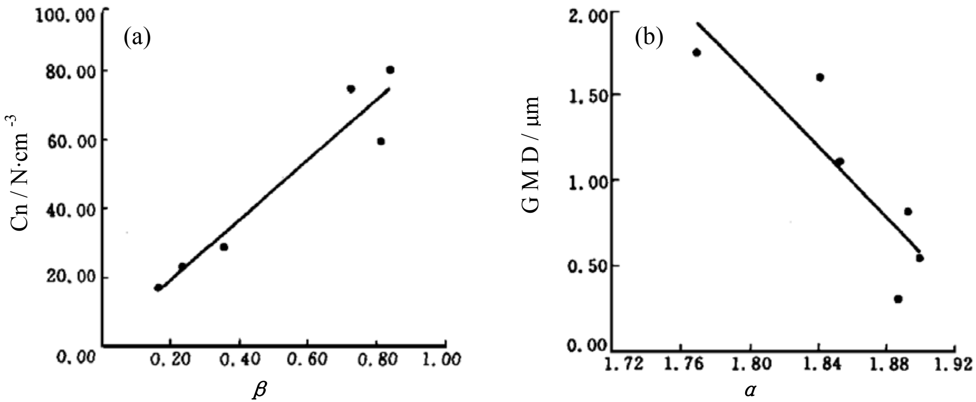

Fig. 7. Relationships **(a)** between aerosol number concentration Cn and β, and **(b)** between the aerodynamic GMD of aerosols and α in the near surface layer on 30 April 1996 in Jilantai.

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