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Spatial and temporal variations of dust concentrations in the Gobi Desert of Mongolia

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ABSTRACT

Dust mass concentrations of PM_{10} and $PM_{2.5}$ from four monitoring stations in the Gobi Desert region of Mongolia were analyzed for a 16-month period in 2009–2010. Annual averaged PM_{10} concentration ranged from 9 μg m^{-3} to 49 μg m^{-3} at these stations during 2009. Concentrations were high in winter owing to air pollution and in spring owing to dust storms; the monthly mean concentrations of PM_{10} ($PM_{2.5}$) at the three stations except for Sainshand reached yearly maxima in December and January, ranging from 60 (38) μg m^{-3} to 120 (94) μg m^{-3}. Diurnal variations of PM_{10} and $PM_{2.5}$ concentrations at two sites, Dalanzadgad and Zamyn-Uud, included two maxima in the morning and evening and two minima in the afternoon and early morning. However, at Erdene PM_{10} maxima occurred in the afternoon and evening. Both PM_{10} and $PM_{2.5}$ concentrations were enhanced from March to May by dust storms. Dust storms raised huge amounts of fine dust particles in the Gobi of Mongolia. Maximum daily mean PM_{10} ($PM_{2.5}$) concentrations reached 821 (500) μg m^{-3} at Dalanzadgad, 308 (129) μg m^{-3} at Zamyn-Uud, and 1328 μg m^{-3} at Erdene. Hourly maximum PM_{10} ($PM_{2.5}$) concentrations were as high as 6626 (2899) μg m^{-3} at Dalanzadgad during a dust storm.

1. Introduction

Dust storms in the extensive Gobi and desert-steppe zones of Mongolia occur frequently and sometimes cause serious disasters (Shao and Dong, 2006). Dust and sand storms disrupt human life and economic activities and result in soil erosion in Mongolia (Natsagdorj et al., 2003).

Dust storms progress from source regions to downstream regions. Coarse dust particles (31–62 μm) can travel up to 320 km from their source, medium dust particles (16–31 μm) can travel up to 1600 km, and fine dust particles (<16 μm) can be transported globally (Goudie and Middleton, 2006). A sand storm that began in the northern Taklamakan Desert on 22 April 1999 traveled southward to the city of Hotan at the southern edge of the Taklamakan Desert. Surface soil and fallout dust particles sampled in the vicinity of Hotan had average diameters of 130 and 63 μm, respectively, and particles 10 μm and smaller were readily transported as aeolian aerosols (Nishikawa et al., 2000).

The severe dust storm in eastern Mongolia of 26–27 May 2008 caused the deaths of 52 people (including 14 children) and about 242,000 livestock, as well as damage to 110 buildings, 221 houses, 62 electric poles, and 668 telecommunication poles. Total costs for this single event, including losses, disinfection and rehabilitation, were around 640.2 million Tugrig (USD 457,000) (Tsogt and Munkjargal, 2008). The storm went on to affect downstream regions of northeast Asia. The observed PM_{10} concentration in Seoul peaked at 0600 UTC on 30 May 2008 with a maximum hourly average of 900 μg m^{-3}, and maximum PM_{10} concentrations in Jeonju, Gwangju, and Daegu in Korea were 650 to 700 μg m^{-3} during that time period (Kim et al., 2010).

In recent years the role of desert dust has become increasingly important not only in global climate change (Park et al., 2005; Goudie and Middleton, 2006; Park and Jeong, 2008) but also in human health (e.g., Meng and Zhang, 2006; Wei and Meng, 2006; Deng et al., 2007; Lee et al., 2007, Park et al., 2010). Recently, dust storms are usually studied by measuring particulate matter in the atmosphere. Natural particulate matter arises from dust storms, volcanoes, forest and grassland fires, pollen and spores released by plants, and salt particles from breaking waves (Lutgens and Tarbuck, 1998). Anthropogenic sources related to urbanization, industrialization, and exploitation of natural resources also generate aerosols such as smoke, dust, haze,

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Fig. 1. Locations of dust monitoring sites in Mongolia.

and fog and rain droplets. Particulate matter in the air is usually divided into populations with aerodynamic diameters less than 10 μm (PM_{10}), 2.5 μm ($PM_{2.5}$), or 1.0 μm ($PM_{1.0}$) and is measured by instruments near the ground surface and by lidar in the troposphere.

During dust storm periods, PM_{10} concentrations increase substantially in source areas as well as downstream regions. For example, in the Taklamakan Desert, a source area, the highest PM_{10} concentrations during 2004–2006 were observed during spring at stations Tazhong (876 μg m^{-3}) and Hetian (703 μg m^{-3}), located respectively in the center and southern margin of the desert (Wang et al., 2007). In Beijing, a downstream location, the PM_{10} mass concentration during the severe dust storm days of 6 and 25 April 2000 reached 898 and 720 μg m^{-3}, respectively, several times the daily average concentration of 190 μg m^{-3} in Beijing and the National Ambient Air Quality Standard of 150 μg m^{-3} for 24-h PM_{10} concentration in China (Xie et al., 2005). Similar incidents have been documented of Mongolian dust reaching Taiwan in 2004 (Liu et al., 2009) and Korea in 2002 (Lee et al., 2006).

A collaboration between Korea, Japan, China and Mongolia installed and maintained a new monitoring network for dust storms in Mongolia from 2007 to 2010. Quantitative data from this network promise to be an important source of data on dust storms for model development and validation (Shao and Dong, 2006; Park and Jeong, 2008, Park et al., 2010), assessing dust impact on human health, and other purposes.

Because of the lack of quantitative data on dust concentrations in Mongolian dust source regions, most previous studies have mainly analyzed synoptic data on dust storms (Natsagdorj et al., 2003). Recently, Shinoda et al. (2010a) studied dust emission and saltation processes and vegetation conditions at Bayan Unjuul, in the steppe zone of Mongolia, during a dust storm period. Park et al. (2010) analyzed in detail temporal variations of dust concentrations (PM_{10}) during 2009 together with meteorological data from Erdene, in the Gobi Desert of Mongolia.

This study was the first to examine quantitative data on dust storms using dust concentrations (PM_{10} and $PM_{2.5}$) observed at four sites in the Gobi Desert of Mongolia. One of our goals was to find characteristic features of dust storms in these data. We analyzed annual and diurnal variations of PM_{10} and $PM_{2.5}$ concentrations associated with dust storms during 2009–2010, and made a case study of the dust storm of 26–27 May 2008 using mass concentrations of PM_{10} and $PM_{2.5}$ as well as vertical profiles obtained by lidar.

2. Data and method

For the Regional Master Plan for prevention and control of dust and sand storms in Northeast Asia, the governments of Japan, Korea, and China provided support for nine dust monitoring stations in Mongolia from 2007 to 2010 (Fig. 1 and Table 1). These stations were established at existing meteorological stations in dust storm source regions. Five stations were in the Gobi Desert: Zamyn-Uud, Sainshand, and Erdene in Dornogobi province, Dalanzadgad in Umnugobi province, and Altai in Gobi-Altai province (Mongolia

Table 1
Used dust monitoring sites in Mongolia.

No.	Site	Location (lat. long.)	Measurements	Period of data available	Lidar measurements	Supporting countries
1	Dalanzadgad	43.57° N, 104.42° E	PM_{10}, $PM_{2.5}$, visibility, wind	From Dec. 2008		Japan
2	Sainshand	44.87° N, 110.12° E	PM_{10}, $PM_{2.5}$, visibility, wind	From Dec. 2008	From Oct. 2007	Japan
3	Erdene (Ulaan-Uul)	44.27° N, 111.05° E	PM_{10}, soil moisture, surface and soil depth temperatures, soil heat flux, radiation, pressure, precipitation, wind zonal (U) and meridional (V) components, air temperature, wind and humidity at 2, 4, 6, 8, 16 and 20 m levels	From Dec. 2008		South Korea
4	Zamyn-Uud	43.72° N, 111.90° E	PM_{10}, $PM_{2.5}$, visibility, wind	From Dec. 2008	From Oct. 2007	Japan

Table 2
Ratio ($PM_{2.5}/PM_{10}$) between monthly averaged concentrations of PM_{10} and $PM_{2.5}$.

		Dalanzadgad	Zamyn-Uud	Sainshand
2009	Jan	0.83		0.50
	Feb	0.75		0.44
	Mar	0.67	0.53	0.54
	Apr	0.56	0.53	0.77
	May	0.52	0.50	0.68
	Jun	0.50	0.34	0.52
	Jul	0.44		0.57
	Aug	0.36		0.54
	Sep	0.42		0.56
	Oct	0.68		0.41
	Nov	0.78	0.62	0.53
	Dec	0.78	0.63	0.53
2010	Jan	0.84	0.61	0.54
	Feb	0.78	0.64	0.51
	Mar	0.60	0.52	0.53
	Apr	0.72	0.53	0.56

Assessment on Climate Change et al., 2009). Four stations were in the steppe region: Arvaikheer in Uverkhangai province, Undurkhaan in Khentei province, Bayan Unjuul in Tuv province, and Ulaanbaatar (Fig. 1).

Mie scattering lidar units were installed at Zamyn-Uud, Sainshand, and Ulaanbaatar by the Japanese International Cooperation Agency (JICA) and the Japan National Institute for Environmental Studies (NIES). A 20-m monitoring tower was installed at Erdene during 2007–2008 by the Korean Meteorological Administration (KMA) and equipped with meteorological instruments at 2, 4, 6, 8, 16, and 20 m above ground level and a PM_{10} measurement instrument at 3 m above ground level. The China Meteorological Administration established dust/sand storm monitoring stations at Arvaikheer, Underkhaan, and Altai during 2008–2010. A dust monitoring site was built at Bayan Unjuul in 2008 by the joint Japan–Mongolia–USA project DUVEX (Dust-Vegetation Interaction Experiment) (Shinoda et al., 2010a). This site was established for the drought experiment DREX in 2004 (Shinoda et al., 2010b).

In this study, we used data measured at Dalanzadgad, Sainshand, Zamyn-Uud, and Erdene in the Gobi region. We mainly made use of mass concentrations of PM_{10} ($PM_{2.5}$), visibility, wind speed, and relative humidity measured at 2 m above ground level at these four sites during 2009–2010, although we used some data from 2008 for a case study. The hourly measurements of PM_{10} ($PM_{2.5}$) concentrations were analyzed together with the wind speed, visibility, and weather conditions from the daily surface and 500 hPa upper-level charts produced by the Institute of Meteorology and Hydrology, Mongolia, and the KMA. PM_{10} ($PM_{2.5}$) concentrations during dust storms were analyzed along with synoptic observations and passages of atmospheric fronts.

At Dalanzadgad, Sainshand and Zamyn-Uud, concentrations of PM_{10} ($PM_{2.5}$) were measured by a nephelometer, an instrument that measures light scattering by airborne particulates. The atmospheric visibility, also known as the meteorological optical range (MOR), is determined by the amount of light scattered by particles of all types in the air that passes through the optical sample volume. At Erdene, PM_{10} concentration data were obtained with a β gauge (the beta attenuation method). Although meteorological data were available for levels up to 20 m above the ground, we used only the wind speed and relative humidity at the 2 m level.

We used lidar data processed by NIES. A Mie-scattering lidar network established by NIES operates at 23 locations in Japan, Korea, China, Mongolia, and Thailand. The lidar system has a polarization capability and uses observation wavelengths of 532 nm and 1064 nm (Sugimoto et al., 2008). Extinction coefficients, aerosol depolarization ratios, and attenuated backscatter coefficients are available from the lidar measurements for aerosol vertical profiles from ground level to 18 km every 15 min. Detailed information on measurement methods and calibrations have been reported by Nishizawa et al. (2010a, 2010b).

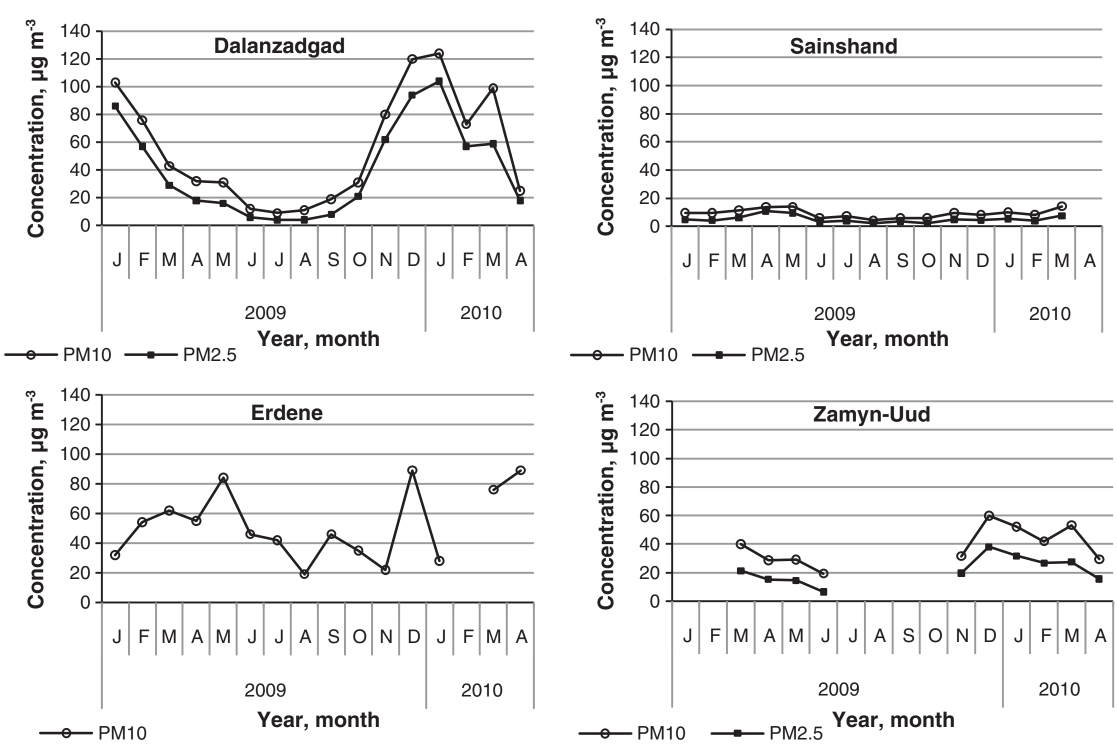

Fig. 2. Monthly mean PM_{10} and $PM_{2.5}$ concentrations at Dalanzadgad, Sainshand, Erdene and Zamyn-Uud from January 2009 to April 2010.

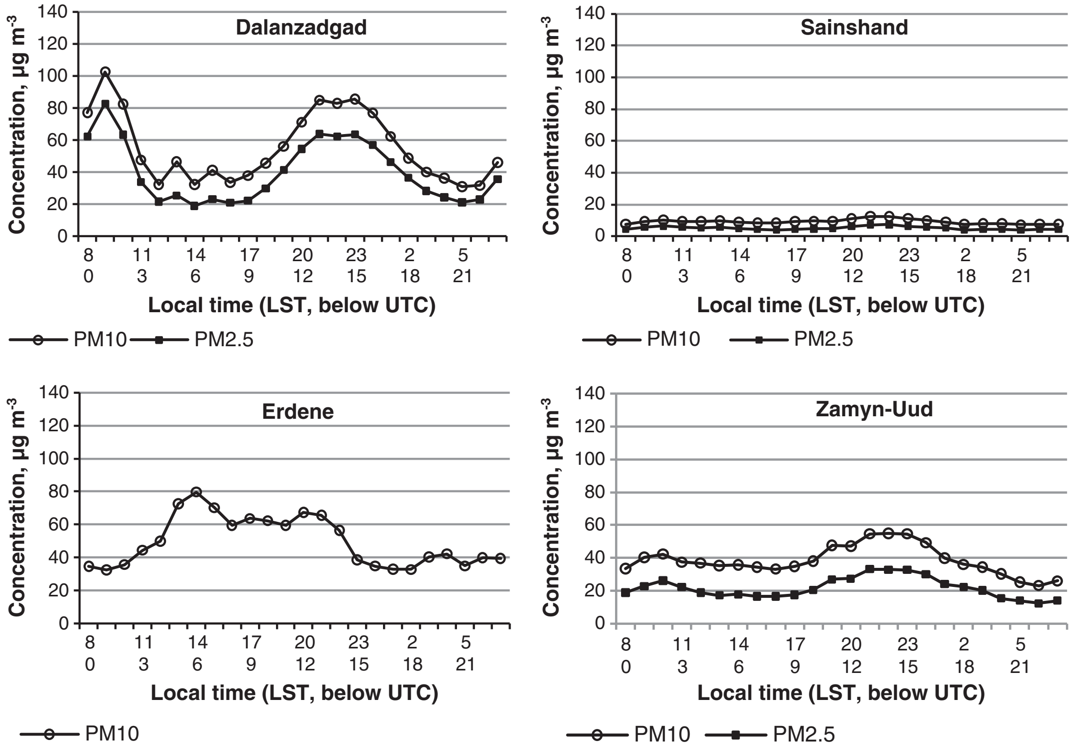

Fig. 3. Diurnal variations of PM_{10} and $PM_{2.5}$ concentrations at Dalanzadgad, Sainshand, Erdene, and Zamyn-Uud in 2009–2010.

3. Results

3.1. Annual and diurnal variations of PM_{10} and $PM_{2.5}$ concentrations

PM_{10} and $PM_{2.5}$ concentration data measured at Dalanzadgad, Sainshand, Erdene, and Zamyn-Uud during 2009–2010 were analyzed. If the ratios between PM_{10} and $PM_{2.5}$ are stable, then the quality of the data can ordinarily be assured (Nishikawa, 2009). The ratios for our data were relatively stable seasonally. For example, the ratios between monthly mean PM_{10} and $PM_{2.5}$ concentrations at Dalanzadgad were 0.70–0.80 in winter and 0.52–0.67 in spring, and at Zamyn-Uud they were 0.52–0.63 in both winter and spring (Table 2).

Our data on PM_{10} and $PM_{2.5}$ concentrations in the Gobi of Mongolia showed annual and diurnal variations. Annual mean concentrations of PM_{10} ($PM_{2.5}$) during 2009 were 47 (34) μg m^{-3} at Dalanzadgad, 9 (5) μg m^{-3} at Sainshand, and 49 μg m^{-3} at Erdene. Measurements at Zamyn-Uud were made for only six months in 2009 because of instrumental failure, and no annual mean could be calculated.

The monthly mean PM_{10} and $PM_{2.5}$ concentrations were high in winter and spring, with maxima in December or January and March to May, and low in summer (Fig. 2). Monthly mean PM_{10} ($PM_{2.5}$) concentrations were highest at Dalanzadgad in December and January, owing to air pollution, and highest at Erdene in March to May, attributable to dust storms (Fig. 2). For example, the maximum monthly mean PM_{10} ($PM_{2.5}$) concentration in December 2009 was 120 (94) μg m^{-3} at Dalanzadgad, about 60 (38) μg m^{-3} at Zamyn-Uud, 8 (4) μg m^{-3} at Sainshand, and 89 μg m^{-3} at Erdene, while in March 2010, it was about 99 (59) μg m^{-3} at Dalanzadgad, about 53 (28) μg m^{-3} at Zamyn-Uud, 14 (8) μg m^{-3} at Sainshand, and 76 μg m^{-3} at Erdene (Fig. 2). PM_{10} and $PM_{2.5}$ concentrations were highest at Dalanzadgad and lowest at Sainshand.

The diurnal variation of PM_{10} and $PM_{2.5}$ concentrations at Dalanzadgad and Zamyn-Uud (Fig. 3) had two maxima, at 0900–0010 local standard time (LST) and 2100–2300 LST, and two minima, at 1400–1600 LST and 0500–0600 LST. In addition, PM_{10} and $PM_{2.5}$ concentrations had some increasing trend in the afternoon from 1300 LST to 1500LST, especially at Dalanzadgad and Erdene (Fig. 3).

3.2. PM_{10} and $PM_{2.5}$ concentrations during dust storms

In this section, we analyzed the daily and hourly means and maxima of wind speeds, PM_{10} ($PM_{2.5}$) concentrations and visibilities at four sites during the period from January 2009 to April 2010. Our criterion for dust storm events was an hourly mean PM_{10} concentration exceeding 100 μg m^{-3} and a daily maximum wind speed exceeding 6.0 m s^{-1}. The criterion for the hourly mean PM_{10} concentration is close to the values of 102 to 105 μg m^{-3} measured during dust storms in the Thar Desert of India and the Great Plains of the United States (Goudie and Middleton, 2006). Park et al. (2010) identified dust events at Erdene as the peak PM_{10} concentration exceeding one standard deviation of the annual mean concentration (150 μg m^{-3}).

Based on the two criteria, from 2009 to 2010, we identified 32, 36, 50, and 9 dust events at Dalanzadgad, Zamyn-Uud, Erdene and Sainshand, respectively. In the winter of 2009–2010, about 6, 5 and 3 events were identified at Dalanzadgad, Zamyn-Uud and Erdene,

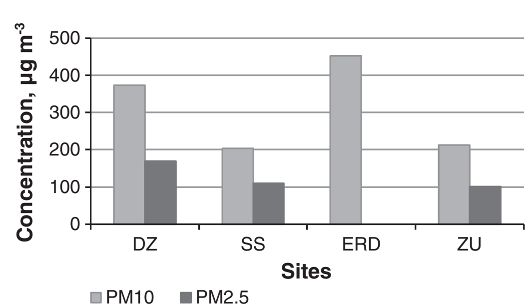

Fig. 4. Averaged PM_{10} and $PM_{2.5}$ concentrations during dust storms at Dalanzadgad (DZ), Sainshand (SS), Erdene (ERD), and Zamyn-Uud (ZU) in 2009–2010.

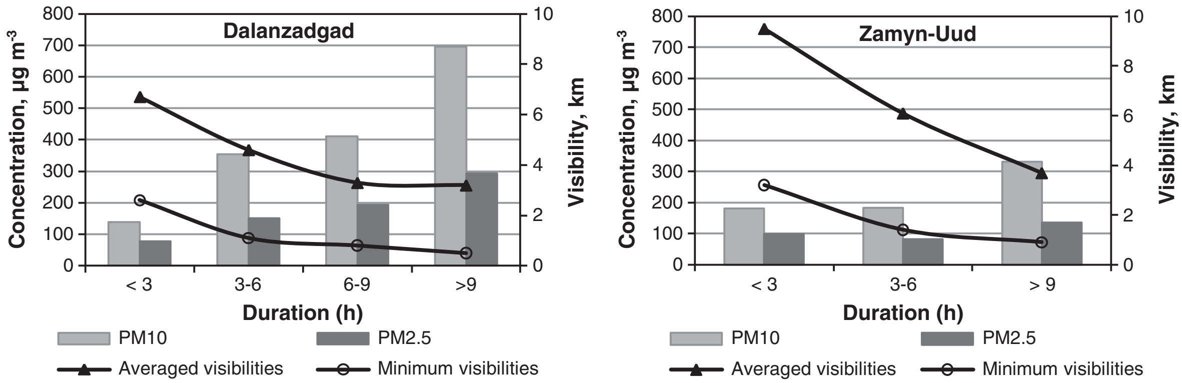

Fig. 5. Relationship between concentration of PM_{10} ($PM_{2.5}$) and visibility with duration of dust storms at Dalanzadgad and Zamyn-Uud in 2009–2010.

correspondingly. Daily mean PM_{10} ($PM_{2.5}$) concentrations, averaged over all dust storms exceeding 6 h at each site, were 198 (115) μg m^{-3} at Dalanzadgad, 64(40) μg m^{-3} at Sainshand, 119 (67) μg m^{-3} at Zamyn-Uud, and 234 μg m^{-3} at Erdene. The maximum daily mean PM_{10} ($PM_{2.5}$) concentrations during dust storm periods were 821 (500) μg m^{-3} at Dalanzadgad, 308 (129) μg m^{-3} at Zamyn-Uud, and 1328 μg m^{-3} at Erdene. Hourly maximum PM_{10} ($PM_{2.5}$) concentrations for all dust events at our four stations during 2009–2010 ranged from 1333 (517) μg m^{-3} to 6626 (2899) μg m^{-3}. The highest of these values was measured at Dalanzadgad.

Averaged duration periods for dust storms were 6.4 h at Dalanzadgad, 4.2 h at Sainshand, 10.1 at Erdene and 5.6 h at Zamyn-Uud. Averaged concentrations of PM_{10} ($PM_{2.5}$) for these duration periods of the dust events varied from 204 (101) μg m^{-3} to 452 (170) μg m^{-3} (Fig. 4). The relationships among the PM mass concentrations, duration of dust storms, and visibility represented by meteorological optical range (MOR) are illustrated for Zamyn-Uud and Dalanzadgad in Fig. 5. PM_{10} and $PM_{2.5}$ concentrations and visibilities were averaged by duration period of dust storms. PM_{10} and $PM_{2.5}$ concentrations increased gradually with dust storm duration. During dust events, averaged visibilities were around 4.2 km at both Dalanzadgad and Sainshand and as high as 7.2 km at Zamyn-Uud. Hourly visibility decreased with increases in PM_{10} and $PM_{2.5}$ concentrations during the dust event period. Frequencies of visibilities less than 1 km during dust storms were 30.6% and 56.3% at Zamyn-Uud and Dalanzadgad, respectively. The lowest visibility values during dust storms for the study period were 37 m at Dalanzadgad on 11 March 2010 and 225 m at Zamyn-Uud on 19 January 2009. Hourly mean wind speeds varied from 6 to 7.5 m s^{-1}, and surface maximum winds were usually 11 to 18 m s^{-1} during dust events, although it sometimes reached 25–26 m s^{-1}, during the study period.

Relative humidity is measured at Erdene only, at the synchronic time with the dust concentration measurement. Fig. 6 shows the relationships between dust concentrations (PM_{10}) and relative humidity (RH) with the dust storm duration period. Minimum relative humidity was varying from 16% to 36% together with the increase in PM_{10} concentrations during dust events at Erdene (Fig. 6). PM_{10} and $PM_{2.5}$ concentrations increased because of dust storms in the Gobi, when the air was very dry. For example, for about 60% of dust events at the Erdene site, relative humidity was less than 20% with the increased PM_{10} concentration.

3.3. Case study: Event of 26–27 May 2008

A severe dust storm accompanied by a snow storm occurred on 26–27 May 2008 in the eastern provinces of Mongolia. A cyclone located over eastern Mongolia on 26 May 2008 deepened to a central pressure of 988 hPa (Fig. 7). This deep cyclone and its associated cold front gave rise to a severe dust storm in eastern Mongolia on 26–27 May.

Fig. 8 shows the Terra/MODIS satellite image over Mongolia at 1216 LST 26 May 2008 with a coverage limited to the most part of Mongolia due to the satellite orbit track. A dust zone appeared in the satellite image as revealed by the yellow color. The dust zone was over the south-eastern part of Mongolia in the rear side of the cold frontal cloud system existing over the eastern region of the country and the south-eastern bordering area between Mongolia and China.

The central areas affected by the dust storm were Khentei and Sukhbaatar provinces, where observed dust concentration data were not available. We analyzed data from Zamyn-Uud, which is close to that area approximately 410 km, while measurements at Sainshand were stopped due to instrumental failures. During the dust event on 26 May 2008, observed PM_{10} concentrations at Zamyn-Uud were as high as 190–1228 μg m^{-3} between 0800 and 1800 UTC, and the visibility ranged from 300 to 700 m between 0600 and 1500 UTC (Fig. 9). Although the weather was stormy with gusty winds of 11 to 24 m s^{-1} at Zamyn-Uud for the whole day, the duration of dust concentration exceeding 100 μg m^{-3} was 11 h and the period of low visibility (<700 m) was 9–10 h.

Lidar observations of tropospheric aerosols (mineral dust and air pollution aerosols) were conducted at Zamyn-Uud during this dust storm. The records of attenuated backscatter coefficients at 532 nm and 1024 nm and the depolarization ratio at 532 nm are shown in Fig. 10, and the extinction coefficient is shown in Fig. 11. The colors in Figs. 10 and 11 show the density of dust layers; the red, green and blue indicate high, medium and low density, respectively. Both figures show that on 26–27 May, the dense dust layer was observed up to 0.5 km above the land surface due to the primary cold front. On next

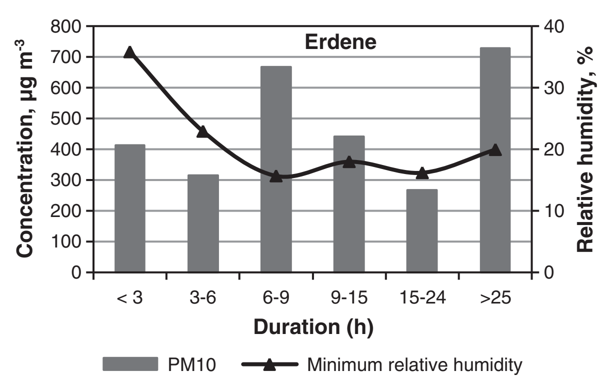

Fig. 6. Relationship between concentration of PM_{10} and minimum relative humidity with duration of dust storms at Erdene in 2009–2010.

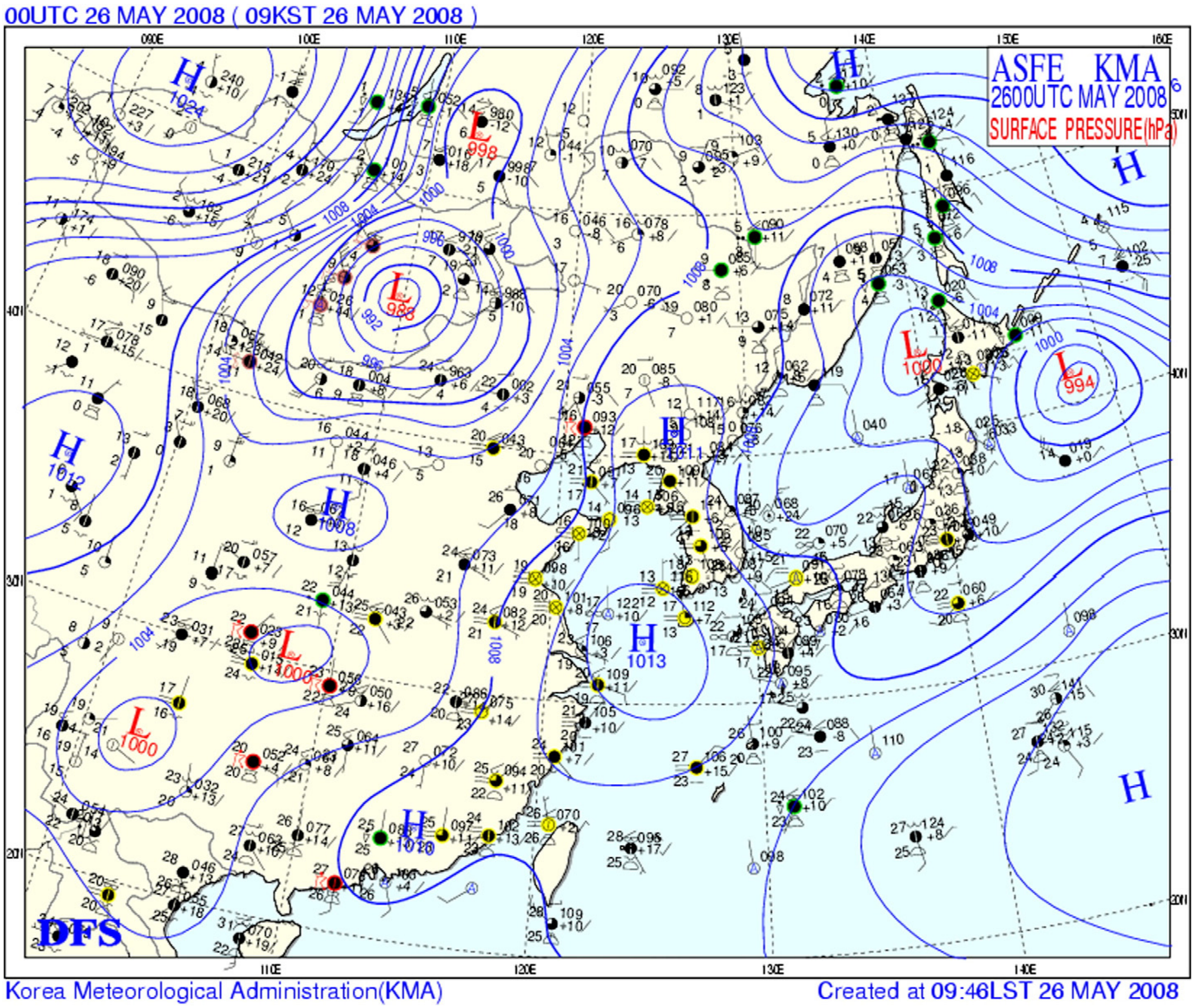

Fig. 7. Surface weather chart over northeast Asia at 00:00 UTC 26 May 2008, from Korea Meteorological Administration.

days (27–28 May), the dust elevated owing to the secondary cold front, reaching about 3 km height (Figs. 10 and 11). The extinction coefficient was larger than 2 km^{-1} during the dust event, indicating a very high concentration of dust during 26–27 May 2008.

4. Discussion

In this discussion, we focused on the following two points. The first is the definition of dust storms using hourly mean PM_{10} concentrations. Our study clearly indicated that the hourly mean PM_{10} concentration increased significantly in the source regions during dust storms; however, there is no universally accepted definition of dust storms in terms of hourly dust concentrations. Previous researchers have classified dust storms by their intensities on the basis of hourly mean PM_{10} concentrations together with wind speed and visibility. The classification system proposed by Hoffmann et al. (2008) is based on the hourly mean PM_{10} concentration in combination with visibility and wind speed as follows: "dusty air" (haze) means hourly mean PM_{10} concentrations higher than 50 $\mu g\,m^{-3}$; "light dust storm", >200 $\mu g\,m^{-3}$; "dust storm", >500 $\mu g\,m^{-3}$; "strong dust storm", >2000 $\mu g\,m^{-3}$; and "serious strong dust storm", >5000 $\mu g\,m^{-3}$ (Hoffmann et al., 2008). Wang et al. (2007) used hourly mean PM_{10} concentrations of <200 $\mu g\,m^{-3}$ for "suspended dust," 200–5500 $\mu g\,m^{-3}$ for "blowing dust," 5500–15,000 $\mu g\,m^{-3}$ for "sand and dust storm", and >15,000 $\mu g\,m^{-3}$ for "severe sand and dust storm". In Taiwan an Asian dust storm event is defined each day that hourly mean PM_{10} concentrations observed at the Yangmingshan station exceed the air quality standard (125 $\mu g\,m^{-3}$) for a period of at least 3 h (Yang et al., 2005). Dust storms are defined in Korea when the measured PM_{10} concentration exceeds 190 $\mu g\,m^{-3}$ for at least 2 h (Chung et al., 2005). The KMA has developed an Asian Dust Warning System with alarm, advisory, and warning levels depending on the dust concentration. Alarms, advisories, and warnings are issued when the hourly mean dust concentrations (PM_{10}) are expected to exceed 300 $\mu g\,m^{-3}$, 400 $\mu g\,m^{-3}$, or 800 $\mu g\,m^{-3}$, respectively, for over 2 h (Chung et al., 2005).

The second point for the discussion is sources of PM_{10} ($PM_{2.5}$) concentrations. The temporal and spatial variations reflect both natural dust storms in the Gobi Desert and anthropogenic aerosols

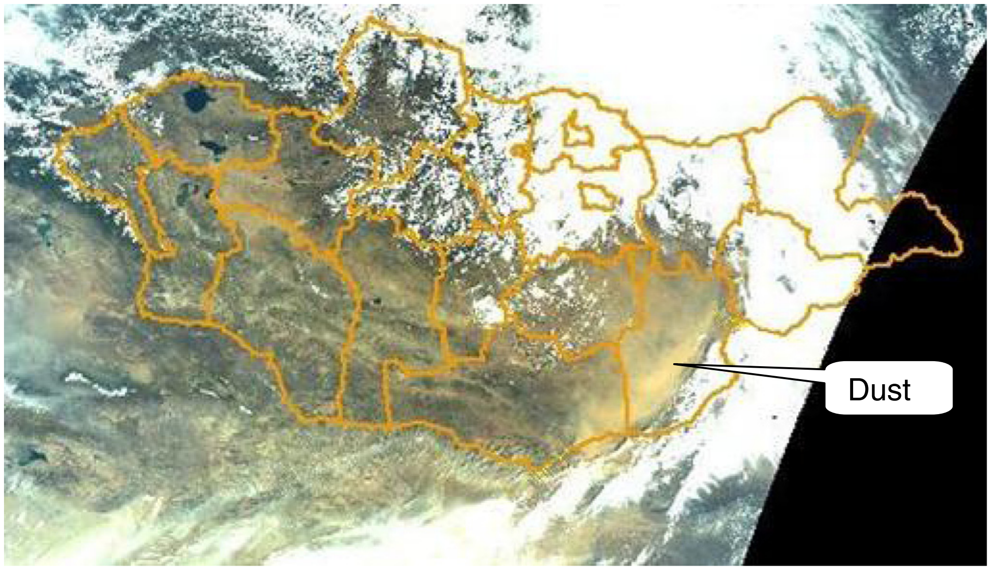

Fig. 8. Satellite image (Terra/MODIS) over Mongolia at 1216 LST 26 May 2008, from Information and Computer Center, National Agency for Meteorology and Environment Monitoring, Mongolia.

in population centers. The dust storms with strong winds are commonly produced by cyclone activities, which are enhanced in the spring (Jugder et al., 2004). As mentioned in Section 3.2, the two sources were distinguished in term of the threshold daily maximum wind speed of 6 m s^{-1}; high concentrations accompanied by the strong winds exceeding the threshold are likely derived from dust storms, while those with calm weather conditions may be due to the anthropogenic aerosols. In addition, climate changes that already have been observed in Mongolia (Mongolia Assessment on Climate Change et al., 2009) are causing substantial effects on the dust storm occurrences in the Gobi Desert areas. As, in 2009, annual mean temperatures at Dalanzadgad, Sainshand, and Zamyn-Uud were higher than normal between 1971 and 2000 by 1.2–1.4 °C. In the same year, annual precipitation at Dalanzadgad was less than normal by 80 mm, while it was near normal at Sainshand and Zamyn-Uud. Such data at Erdene is not available. These temperature and precipitation anomalies appeared to influence increased dust storm occurrences; for example, in 2009, the numbers of dusty day at Dalanzadgad were 2.2 times higher than normal, while it was slightly higher than normal at Zamyn-Uud and close to normal at Sainshand.

Other sources of PM_{10} ($PM_{2.5}$) concentrations were anthropogenic aerosols. Sources of anthropogenic aerosols in population centers were activities such as fossil fuel burning in vehicles, power plants,

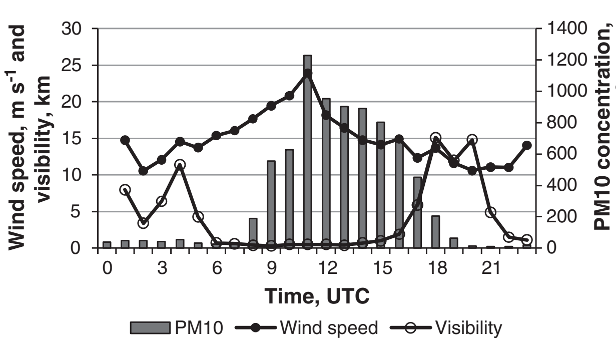

Fig. 9. Maximum hourly wind speeds, minimum hourly visibilities and hourly mean PM_{10} concentrations at Zamyn-Uud on 26 May 2008 (UTC).

and home stoves (Mongolia's Initial National Communication, 2001; Jugder et al., 2008; Mongolia Assessment on Climate Change et al., 2009). Air quality has deteriorated around provincial centers as increasing demand for heat and electricity has caused increased emission of air pollutants from industrial and domestic sources and as other activities have eroded soils. Weather conditions, such as persistent anticyclonic circulation and surface temperature inversions in winter, can also cause increases in air pollutants around population centers (Baasanhuu and Gomboluudev, 1996; Lutgens and Tarbuck, 1998; Jugder and Chung, 2004).

5. Conclusions

The present study showed that annual mean PM_{10} ($PM_{2.5}$) concentrations during 2009 were 47 (34) µg m^{-3} at Dalanzadgad, 49 µg m^{-3} at Erdene, and 9 (5) µg m^{-3} at Sainshand. Monthly mean PM_{10} concentrations were higher in cold months (November to February) and in spring (March to May). Monthly mean PM_{10} ($PM_{2.5}$) concentrations reached a maximum in December 2009 with values of 120 (94) µg m^{-3} at Dalanzadgad, about 60 (38) µg m^{-3} at Zamyn-Uud, 8 (4) µg m^{-3} at Sainshand, and 89 µg m^{-3} at Erdene.

Large amounts of fine dust particles are emitted to the air during the dust storm period in the Gobi Desert of Mongolia. Daily mean PM_{10} ($PM_{2.5}$) concentrations for dust storms exceeding 6 h were 198 (115) µg m^{-3} at Dalanzadgad, 64(40) µg m^{-3} at Sainshand, 119 (67) µg m^{-3} at Zamyn-Uud, and 234 µg m^{-3} at Erdene. Daily mean maximum PM_{10} ($PM_{2.5}$) concentrations were as high as 821 (500) µg m^{-3} at Dalanzadgad, 308 (129) µg m^{-3} at Zamyn-Uud, and 1328 µg m^{-3} at Erdene during dust storms. The highest hourly mean PM_{10} ($PM_{2.5}$) concentration during the study period was 6626 (2899) µg m^{-3} at Dalanzadgad. The observed data at the sites showed dust storms representatively in the Gobi Desert in each season.

During the heavy dust storm period of 26–27 May 2010, measurements at Zamyn-Uud showed that PM_{10} concentrations reached 1228 µg m^{-3}, visibility ranged from 300 to 700 m, gusty winds reached 24 m s^{-1}, and the dense dust layer was observed up to 0.5 km above the land surface due to the primary cold front. On next days (27–28 May), the dust elevated owing to the secondary cold front, reaching about 3 km height. The records of attenuated backscatter coefficients, the depolarization ratio and the extinction

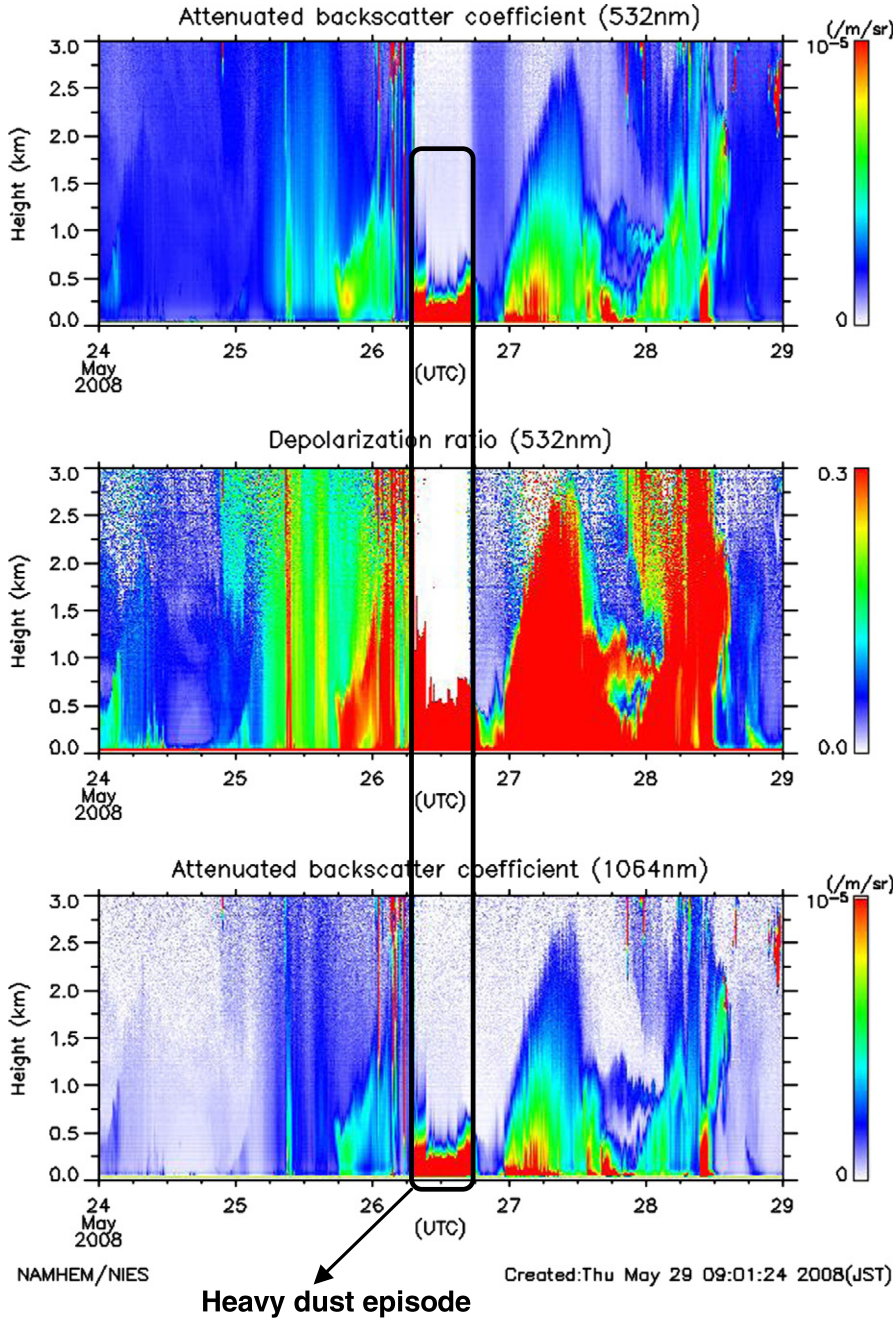

Fig. 10. Lidar observations below 3 km elevation at Zamyn-Uud, 24–29 May 2008 (UTC).

coefficient indicated a very high concentration of dust during 26–28 May 2008.

High concentrations of PM_{10} and $PM_{2.5}$ were related to both natural and anthropogenic sources of particulate matter. The two sources were distinguished in term of the threshold daily maximum wind speed of 6 m s^{-1}; high concentrations accompanied by the strong winds exceeding the threshold wind are likely derived from dust storms, while those with calm weather conditions may be due to the anthropogenic aerosols. A natural source was dust storms developed by the passage of cyclones accompanied by cold fronts. Anthropogenic aerosols were found to be high around Dalanzadgad and Zamyn-Uud, and natural dust particles were high around Erdene. However, the number of dusty days at Dalanzadgad in 2009 was considerable higher than normal. Anthropogenic sources may include burning of coal in population centers. The maximum PM_{10} and $PM_{2.5}$ concentrations occurred in the morning and evening, coinciding with coal usage in private houses. It is evident that human activities can affect local air quality around urban localities in the Gobi of Mongolia. Afternoon peaks in PM_{10} and $PM_{2.5}$ concentrations appear to be due to dust storms.

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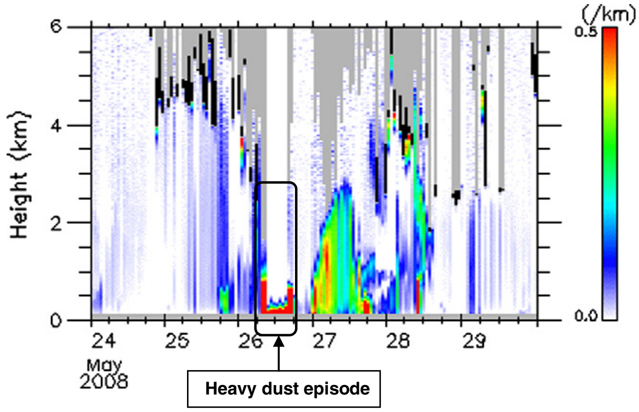

Fig. 11. Extinction coefficients in Zamyn-Uud in late May 2008 (time in UTC).

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