LIDAR OBSERVATION OF THE DUST STORM AND ITS REMOVAL PROCESS OVER THE TAKLIMAKAN DESERT, CHINA

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ABSTRACT

In April 2002, a severe dust storm occurred in the Taklimakan Desert during the intensive observation period of the ADEC project (Japan-China Joint Studies on Aeolian Dust Experiment on Climate Impact). A large amount of the dust was lifted up by the dust storm and gradually removed in the following few days. There was a clear diurnal variation of the top of the dust layer after the dust storm. The whole event of the dust storm was observed by the Mie-scattering depolarization lidar at Aksu, China. We try to estimate the backscattering ratio during the severe dust storm by solving the lidar equation directly. The present paper shows the structure of the dust layer and its removal process.

1. INTRODUCTION

The Japan-China Joint Study on Aeolian Dust Experiment on Climate Impact (ADEC) has started since April 2000 in order to clarify mechanism of mineral dust outbreaks from arid regions into the atmosphere and to evaluate its annual variability [1].

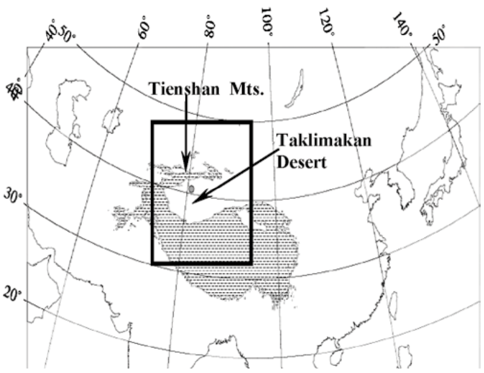

Fig. 1 Location of Taklimakan Desert and Aksu (40.62°N, 80.83°E), Xinjiang, China [2].

As part of ADEC, a Mie - scattering depolarization lidar was operated at the Aksu Water–Balance Station of Xinjiang Institute of Ecology and Geography, CAS in order to investigate the vertical structure of the dust layer over the Taklimakan Desert [3]. Aksu, an oasis city, is located in the northern fringe of the Taklimakan Desert (40.62°N, 80.83°E, 1028 m above the sea level) as shown in Fig. 1.

Kai et al. (2004) and Tsunematsu (2005) reported the strong dust storm over Aksu in April of 2002 [4,2]. But the lidar observation during the dust storm was impossible for several hours because of the absorption of laser beam by the heavy dust. In the present study, we try to estimate the backscattering ratio at the lowest height during the dust storm by solving the lidar equation directly. In addition, the removal process of the dust over the source region is discussed.

2. INSTRUMENTATION

2.1 Lidar system

The lidar system is single wavelength Nd:YAG laser based system and designed to measure the vertical profiles of backscatter and the depolarization of the aerosol particles from near the ground and up to the stratospheric aerosol layer [3]. The pulse energy of the laser is 300mJ at 532nm and the pulse repetition is 10Hz. Two telescopes, which diameter is 200mm and 355mm respectively, are used to expand the dynamic range of the receiving signal strength. Using the A/D conversion and photon counting systems, the system can measure the altitude range from near the ground up to the stratosphere (30km or above). All instruments such as the optical components, data processing instruments and electronics are contained in the environment shelter. Two optical windows are set on the ceiling of the shelter to cover the field of view of the two telescopes. Each optical window have two coated optical glasses to avoid dewing or frosting outside.

2.2 Data processing

The lidar equation, atmospheric transmittance, backscattering ratio, lidar ratio and total depolarization ratio are given by the following equations:

$$V(z) = \frac{K}{z^2} O(z)[\beta_m(z) + \beta_a(z)]T(0,z) \qquad (1)$$

$$T(0,z) = \exp\left\{-2\int_0^z (\sigma_m(z') + \sigma_a(z'))dz'\right\} \qquad (2)$$

$$R(z) = \frac{\beta_m(z) + \beta_a(z)}{\beta_m(z)} \qquad (3)$$

$$\sigma_a(z) = S_1 \beta_a(z)$$

$$\delta_t(z) \equiv \frac{\beta_{a,\perp}(z) + \beta_{m,\perp}}{\beta_{a,\parallel}(z) + \beta_{m,\parallel} + \beta_{a,\perp}(z) + \beta_{m,\perp}} \times 100[\%] \qquad (4)$$

$$= \frac{gP_\perp(z)}{P_\parallel(z) + gP_\perp(z)} \times 100[\%]$$

where z is height above the ground, $V(z)$ is the signal from height z, K is a constant of the lidar, $O(z)$ is the beam overlap factor, $\beta(z)$ is the backscattering coefficient, $\sigma(z)$ is the extinction coefficient, $T(0,z)$ is the atmospheric transmittance, $R(z)$ is the backscattering ratio, $\delta t(z)$ is the total depolarization ratio, $P(z)$ is the output of the photomultiplier, g is the signal gain, S_1 is the lidar ratio, the subscripts a and m refer to the components of aerosol particles and air molecules, the subscripts = and ⊥ refer to the parallel and perpendicular components with respect to the polarization plane of the emitted laser, respectively.

3. RESULTS AND DISCUSSION

3.1 Dust storm event

After the passage of the trough, the strong easterly wind brought the severe dust storm on 13 - 15 April 2002 at Aksu. The easterly wind was separated from the synoptic-scale cold westerly and intruded into the Taklimakan Desert after going around the eastern side of the Tianshan Mountains [2]. The dust storm raised a large amount of the dust into several kilometers in the air.

Fig. 2 shows time-altitude cross sections of backscattering ratio $R(z)$ and depolarization ratio $D(z)$. It was calm and clean on 11 and 12 April before the dust storm. There was a path of upper clouds at height of 10-13 km, which corresponds to the height of the Tianshan Mountains and Pamir Plateau.

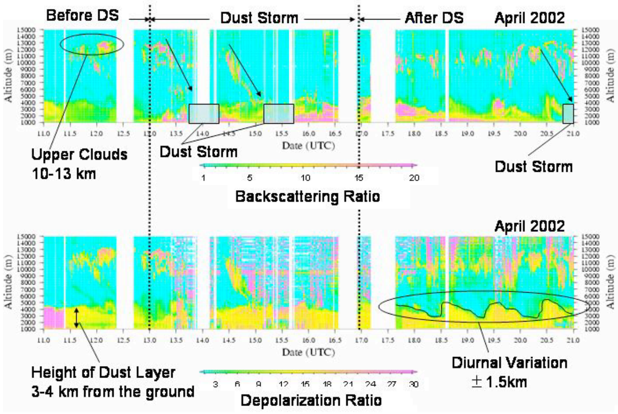

Fig. 2 Backscattering ratio (upper) and depolarization ratio (lower) over Aksu, China during 11 - 21 April 2002.

The dust event occurred on 13 April, and it led to a sudden change of visibility and the other surface meteorological elements. The upper clouds descended from 12 km to 5 km during 13.3 to 13.8 UTC April, and then a strong dust storm occurred at the surface. The surface visibility was less than 1 km. During the strong dust storm, the laser beam was almost absorbed by the heavy dust. The lidar observation was impossible in several hours which were shaded in Fig. 2. Reddish zones near the ground show very high values of $R(z)$ more than 18. A second dust storm occurred during 14.5 and 15.0 UTC April. The dust event continued from 13 to 16 April. After the dust events, the dust layer had higher values of $R(z)$ during 17 to 19 April than before the dust storm. On 20 April, the dust layer weakened. On 21 April, another trough passing over Aksu led to the third dust storm.

Mineral dusts have high values of $D(z)$ because of the non-sphericality. The $D(z)$ is a good indicator to identify the dust layer. In Fig. 2, the depolarization ratio shows the structure of the dust layer more clearly than the backscattering ratio. According to Fig. 2, we can divide the IOP-1 into three sub-periods:

BD : before the dust storm
DS : during the dust storm
AD : after the dust storm

A typical height of the dust layer over Aksu was about 3-3.5km before the dust storm (BD) and became about 4 km during the dust storms (DS). After the dust storms (AD), we can see a clear diurnal variation of the top of the dust layer with amplitude of 1.5 km during 18 and 20 April. It was fine in these days; the characteristic diurnal variation may reflect effects of a meso-scale circulation or a convective mixed layer.

3.2 Estimation of the backscattering ratio during the dust storm

Using Equations (1) – (4), the relationship between the backscattering ratio and the range corrected backscattering signal at the lowest height (187 m) is derived as follows [7]:

$$z^2P(z) = K\beta_m(z)R(z) \exp\left[-2\int_0^z \left\{S_1\beta_m(z')R(z) + \left(\frac{8\pi}{3} - S\right)\beta_m(z)\right\}dz'\right] \quad (5)$$

The lidar system has two telescopes 200mm and 3500mm, of which the smaller one is coaxial for the laser beam. For this case, the above equation is reduced to:

$$z_1^2P(z_1) \sim a_1R(z_1)\exp\left(-a_2R(z_1)\right) \quad (6)$$

$$a_1 = K\beta_{m0}\exp\left(-2\int_0^{z_1}\left(\frac{8\pi}{3} - S\right)\beta_m(z')dz'\right)$$

$$a_2 = 2S_1\beta_{m0}\Delta z \sim 0.018$$

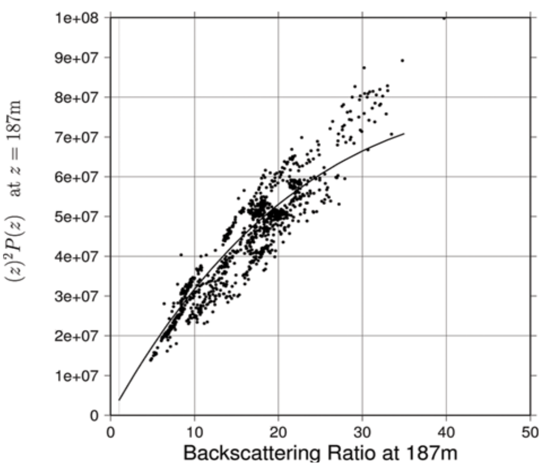

Fig. 3 Relationship between backscattering ratio and range corrected value at 187m.

The range corrected backscattering signals are plotted against the backscattering ratio in Fig. 3. The regression line for Eq.(6) is shown in the figure. The backscattering ratio for the whole IOP-1 was estimated using Eq.(6). Fig. 4 shows the time series of the backscattering ratio during the whole dust storm on 11 – 21 April. On 11-12 April, the backscattering ratio had small value less than 10. After the dust storm on 13 April, it increased to 25. On 18- 20 April, the backscattering ratio decreased gradually. On 21 April, another dust storm occurred.

Fig. 5 shows the relationship between the backscattering ratio at 187 m and the wind speed at 10 m. Before the dust storm and during the dust storm, the backscattering

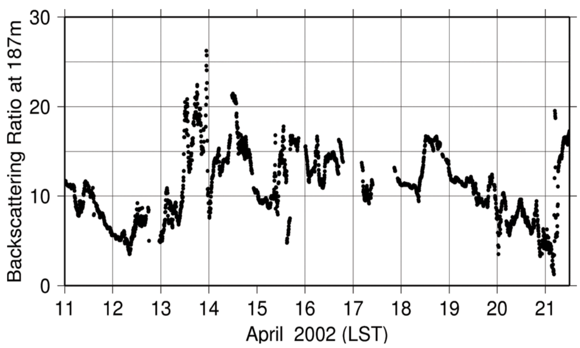

Fig. 4 Backscattering ratio before, during, and after the dust event.

ratio increases with the wind speed, but after the dust storm, the backscattering ratio has a high value even for a weak wind. This means the dust floating above the Taklimakan Desert after the dust storm.

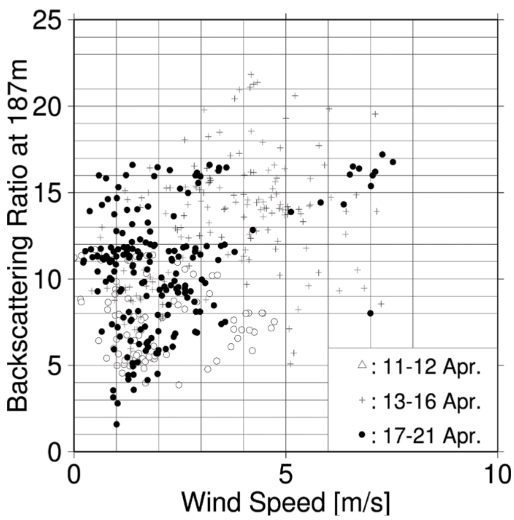

Fig. 5 Relationship between the backscattering ratio at 187 m and the wind speed at 10 m.

3.3 Removal process of the dust

The removal process of the dust lifted up by the dust storm is discussed in this section.

Fig. 6 shows time series of backscattering ratio at heights of 187 m, 1, 2, 3, 4 and 5 km on 18 – 21 April 2002. At first glance, the behaviors of lidar signal at lower heights (187 m and 1 km) are different from those at higher heights (above 2 km). The lidar signals at lower heights gradually decreased during 18-20 April (the post-dust storm period). This result indicates the presence of the gravitational settling of the relatively-large size dust (coarse particles) near the ground.

On the other hand, the lidar signals at 2 – 4 km show a diurnal variation with spike-like peaks from the evening to the midnight. The peaks suggest that the advection of the dust lifted up in the other places by the meso-scale local circulations.

There is no diurnal peak at height of 5 km. This means that the vertical transport of the dust was limited to 4 km. According to the radiosonde data, an inversion layer of temperature at about 4 km capped the top of the dust layer.

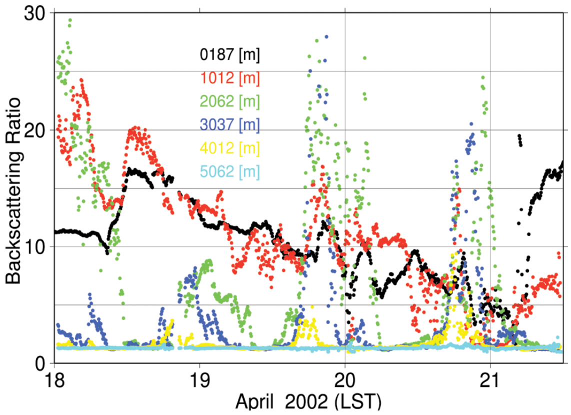

Fig. 6 Time series of backscattering ratio at heights of 187 m, 1, 2, 3, 4 and 5 km on 18 – 21 April 2002.

Using the data of lidar and the sky radiometer during 18 – 20 April, mean diurnal variations of dust layer height and aerosol optical thickness were examined. It is noted that both of the dust layer height (DLH) and aerosol optical thickness (AOT) were going down in the morning and had minimum values near noon. Conversely, DLH and AOT were increasing in the afternoon and had maximum values at night. The behaviors of DLH and AOT are different from those inferred from the development of the mixed layer during the daytime. The behaviors of DLH and AOT suggested that the development of the dust layer over Aksu may be suppressed by the downdraft induced by the meso-scale circulation such as the Tiashan Mountains and valley wind [5, 6].

4. CONCLUDING REMARKS

In April 2002, a severe dust storm occurred in the Taklimakan Desert. It made a sudden change of the surface meteorological elements; visibility became less than 1 km. The whole event of the dust storm was observed by the Mie-scattering depolarization lidar at Aksu, Xinjiang, China. Main results are summarized as follows:

1) A large amount of the dust was lifted up by the dust storm and gradually removed in the following few days. The lidar signals at lower heights (less than 2 km) indicate the gravitational settling of the coarse particles.

2) The lidar signals at 2 – 4 km show a diurnal variation with spike-like peaks from the evening to the midnight.

3) There was the characteristic diurnal variation of the top of the dust layer with amplitude of 1.5 km during the post-dust storm period.

4) The backscattering ratio at the lowest height during the severe dust storm was estimated by solving the lidar equation directly.

The lidar observation shows that the development of the dust layer and its diurnal variation over the Taklimakan Desert may be influenced by the meso-scale circulations. Kim et al. (2006) investigates these phenomena by the numerical simulations in the present conference [8].

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