# The Taklimakan Dust acting as Ice nuclei observed by dual wavelength and polarization lidar

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## Abstract

A ground-based lidar observation was carried out at Aksu, Xinjian province, China to reveal the behavior of the dust acting as ice nuclei over the Taklimakan Desert on 23 - 25 March 2009. Aerosols such as dust directly affect on the Earth’s radiation budget through scattering and absorption and indirectly affect it through condensation and the formation of ice nuclei. However, the temporal and spacial variations of the dust and the possibility of the dust acing as ice nuclei over the Taklimakan Desert have not been understood yet. In this study, we used the lidar because it can measure the vertical distribution of the aerosol at high resolution temporally and spacially, and the cloud phase using the depolarization ratio. A simultaneous lidar observation between the ground-based (Aksu-lidar) and space-borne lidar (CALIOP) was conducted on 24 March (LST) at which the satellite CALIPSO passed the nearest region from the Aksu-lidar in the three days. First, we investigated the diurnal variation of the dust layer height (DLH). The DLH rapidly rose to 6-7 km at 22 LST and keep the height until 09 LST, and gradually sank from 09 LST to 22 LST. This phenomenon is considered to be attributed to the local circulation. The jump of the DLH at the 22 LST was attributed to the advection of the dust from the south west of the Taklimakan Desert because the 500 hPa wind direction was the south west and the CALIOP captured the aspect of the advection. We suggested that the super cooled cloud fraction decreased due to the dust acting as ice nuclei according to the relationship between the VDR and temperature.

## 1. Introduction

Kosa (Yellow sand or Asian dust) is known as a spring phenomena in Japan. The sources of the Kosa are desert and semi-desert regions of inner China such as the Gobi and Taklimakan Desert. When the dust is eroded by a strong wind over those regions, it soars into the atmosphere and affects the human activity (e.g. health damage, crops production and transport facilities). Moreover, when the dust is lifted up to westerly dominant, it is transported for a long distance eastward. This phenomenon was observed over the American continent beyond the Pacific Ocean as well as the East Asia (e.g. Husar et al., 2001; Uno et al., 2001). Uno et al., (2010) reported that the dust from the Taklimakan Desert was transported around the globe.

The aerosol such as dust affects the Earth’s radiation budget directly through scattering and absorption of the solar radiation. It concerns the cloud formation acting as the condensation and ice nuclei. The albedo is increased if the cloud is formed. The aerosol also affects the Earth’s radiation budget indirectly. However, IPCC was reported that the radiation forcing due to the aerosol indirect effect has the large uncertainty (IPCC, 2007). This uncertainty is attributed to the lack of the knowledge for the role of the aerosol in the Climate system. Because the aerosol

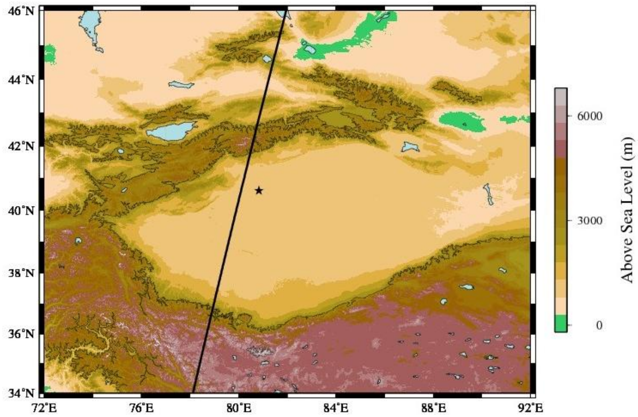


Fig. 1 Location of the Taklimakan Desert and the CALIPSO grand track on 24 March 2009 (LST). The star symbol indicates the location of the ground-based lidar station used in this study.

has the various chemical compositions and particle size distributions as well as the large temporal and spatial variations in the atmosphere, it makes the observation of the three dimensional aerosol distributions difficult.

In order to investigate the behavior of the aerosol over the Taklimakan Desert, we introduced the lidar that can measure the vertical distribution of the aerosol at high temporal and spatial resolutions. The Taklimakan Desert is located in the north west of China (Fig. 1) and the largest desert in China. It is the huge basin surrounded by the high mountains and plateaus exceed 5000 m, north to the Tian Shan Mountain, west to the Pamir Plateau and south to the Kunlun Mountain. The dust is stagnated all of the time due to the closed topography (Liu et al., 2008) and picked up to 5 km due to the local circulation (Tsunematsu et al., 2005). For this reason, the Taklimakan dust is very possible to act as ice nuclei rather than the other deserts. However, there is no example about the indirect effect of the dust by the observation on the Taklimakan Desert.

In the present study, we used the data of the space-borne lidar CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization) onboard CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) as well as the ground-based lidar data to make a simultaneous observation (Winker et al., 2006). The space-borne lidar is effective instrument for global distribution of the cloud and aerosol (McCormick et al., 1993) and used for the validation of the aerosol transport model (e.g. Yumimoto et al., 2009). We used the CALIOP level 1B data in this study for the findings of the three dimensional distribution of the aerosol.

## 2. Lidar observation and analysis method

We used CALIPSO data only on 23 March 2009 because

CALIPSO passed within 100 km circle from ground-based lidar station. The ground track of CALIPSO on that day is shown in Figure 1.

*2.1 Ground-based Lidar Observation*

A ground-based lidar observation was carried out during 23 - 25 March 2009 at the Aksu Water Balance Experimental Station of the Xinjiang Institute of Ecology and Geography of the Chinese Academy of Science. The station is located in the northern part of the Taklimakan Desert (40.62°N, 80.83°E, 1,028 m above sea level) as shown in Figure 1. We call the ground-based lidar as Aksu-lidar afterward.

The Aksu-lidar employs a Nd:YAG laser (pulse energy: 300 mJ, pulse repetition rate: 10 Hz) for the light source. The wavelengths of the laser used in this study are the fundamental and second harmonics (i.e. 532 and 1064 nm). The laser is polarized linearly and collimated at 0.2 mrad by beam expander and emitted to the atmosphere vertically.

The 14-inch Schmidt-Cassegrain telescope is used for collection of the scattering light and set coaxial to the laser. The collected light is dispersed to 532 and 1064 nm by the dichroic filter. Because the 532 nm light is split the parallel and perpendicular components to the laser polarization plane by the polarizer, we can measure polarization that index the non sphericity. The photomultiplier tubes and avalanche photodiode are used for return signal detection at 532 and 1064 nm, respectively.

The Aksu-lidar can measure the vertical profile from the telescope to a height of 120 km every five minutes with a vertical resolution of 7.5 m. In order to make the vertical resolution of the Aksu-lidar conform to that of CALIOP, we averaged the profiles vertically over 30 m.

*2.2 Analysis Method*

We use the CALIOP data of the total attenuated backscattering coefficient to investigate the spacial distribution of the aerosol and calculated the color ratio (CR) to get the size information. For Aksu-lidar, we calculated the volume depolarization ratio (VDR) to investigate non sphericity of the aerosol. The VDR is also used to detect the dust layer height (DLH). The VDR is defined as follows.

$$\delta_v(z) = \frac{P_\perp(z)}{P_{//}(z)} = \frac{\beta_{1,\perp}(z) + \beta_{2,\perp}(z)}{\beta_{1,//}(z) + \beta_{2,//}(z)} \quad (1)$$

Where P is the detected signal and subscript $\perp$ and // are the perpendicular and parallel components to the laser polarization plane, beta is the backscattering coefficient and subscript 1 and 2 are the Mie and Rayleigh scattering components, respectively. The DLH is defined at the height where the VDR is 0.1 (Kim and Kai, 2009). The CR provides us the particle size information and is defined as the equation below.

$$\chi(z) = \frac{\beta_{1,1064}(z)}{\beta_{1,532}(z)} \quad (2)$$

The backscattering coefficient was calculated using the Fernald inversion method (Fernald 1984). The backward inversion method was applied to the Aksu-lidar and the forward inversion method was applied to the CALIOP. Then, we estimated the backscattering coefficient using performance functions that minimize the difference of the backscattering coefficient for Aksu-lidar and CALOP (see Jin et al., 2010 a, b). The lidar ratios used in this study were 41.97 and 45.86 sr at 532 and 1064 nm, respectively.

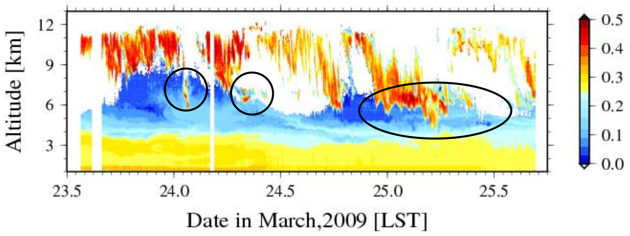


Fig.2 Time-cross section of the VDR observed by the Aksu-lidar in March 2009 (LST). The circles depicted in the figure show that the dusts were observed around the clouds.

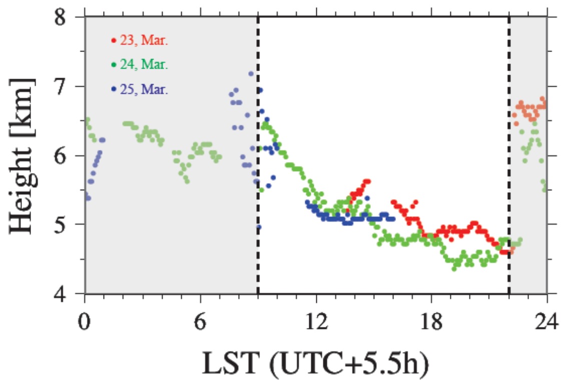


Fig. 3. Diurnal variation of the dust layer height (DLH). It is defined of the height at which the VDR is 10 %. The hatched areas correspond to the high DLH

## 3. Results and discussion

*3.1 Spacial distribution of the dust over the Taklimakan Desert*

The time-cross section of the VDR is shown in Figure 2. The VDR of the boundary layer dust (below 4 km), the tropospheric dust and the cloud were more than 0.25, less than 0.25 and from 0.3 to 0.5. However, less than 0.1 of the VDR for the cloud was observed from 09 LST to 12 LST. According to the reanalysis data of the ECMWF interim, the temperature of the cloud was about -10℃ and it was considered that this cloud was the supercooled water cloud or 2D plate ice cloud. Interestingly, the dust was observed around the cloud shown by the circle in the figure. It means that the dust was mixed with the cloud and possibly acting as ice nuclei.

We examined the diurnal variation of the DLH derived from the Aksu-lidar which is shown in Figure 3. The hatched region is the period of time at which the high DLH was observed. The DLH rose rapidly at 22 LST and was high until 09 LST on the next day, then gradually sank until 22 LST. This high and low DLH in the night and day are attributed to the local circulations of which are the updraft with the convergence of the mountain winds from the Pamir Plateau and Tian Shan Mountain in the night, and the downwind with the divergence of the valley winds from there in the day (Kim and Kai, 2009).

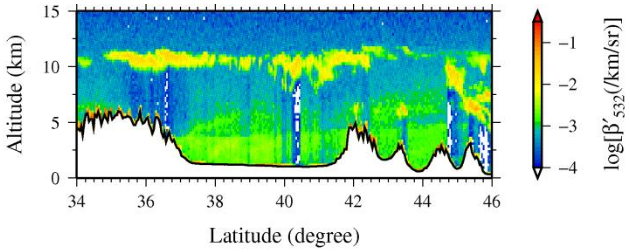


Fig. 4 Total attenuated backscattering coefficient Location of the Taklimakan Desert and the CALIPSO grand track on 24 March 2009 (LST). The star symbol indicates the location of the ground-based lidar station used in this study.

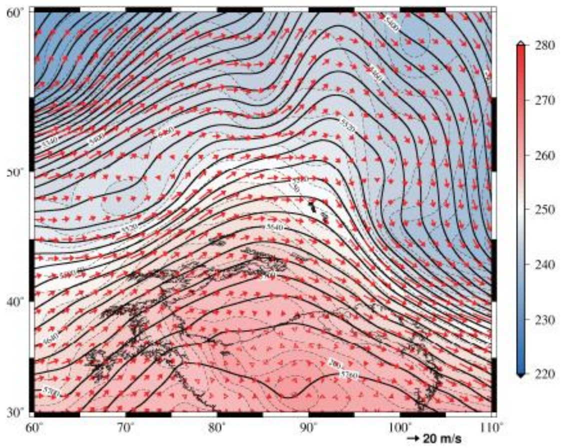


Fig. 5. Wind , geopotential height and temperature from the reanalysis data of the ECMWF interim at 2330 LST 23 March, which are indicated by arrow, solid line and dotted line. The thick line in (b) indicates the trough.

The time-cross section of the total attenuated backscattering coefficient derived from CALIOP on 24 March 2009 (LST) is shown in Figure 4. The region enclosed by red dashed line is the area that is used to make the simultaneous lidar observation with the Aksu-lidar. As you can see in the figure, the double layered structure of which the dust is from ground to 6 km and the cloud is about 10 km, is observed over the Taklimakan Desert. The region that the signal is small at below the cloud indicates the strong attenuation of the laser by the thick cloud.

The jump at 22 LST of the DLH was possibly attributed to the advection from other place. Figure 5 shows the 500 hPa wind, geopotential height and temperature that were derived from the reanalysis data of ECMWF interim. As you can see in figure, the wind direction over the Taklimakan Desert was south west due to the high pressure over the Tibetan Plateau at 2330 LST on 24 March. The CALIOP data in Figure 4 at 0230 LST shows that the dust flew out from the boundary layer at the south of the Taklimakan Desert. If we combine the CALIOP with ECMWF data, the dust was possibly transported from the south west to north east and it seems that the jump at 22 LST of the DLH was resulted in the advection of the dust from south west.

This jump of the DLH at night was also observed by Aksu-lidar in spring 2003 and 2004. To reveal the regularity of the phenomena, we need a long term lidar observation and the numerical experiment to understand the upper wind fields over the Taklimakan Desert.

*3.2 The possibility of the duct acting as ice nuclei*

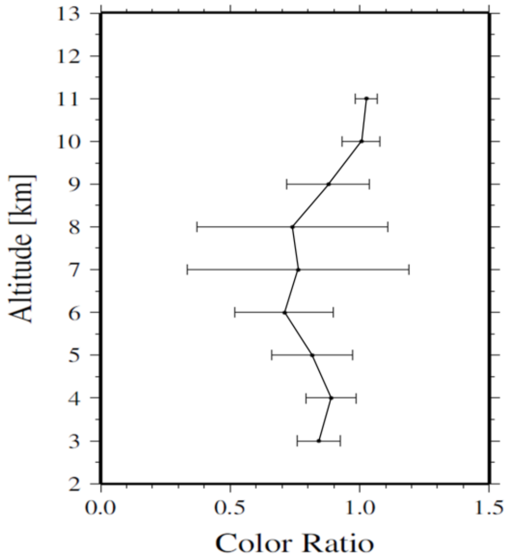


Fig. 6. Vertical distribution of the CR when the simultaneous lidar observation was made between Aksu-lidar and CALIOP. The error bar of the CR indicates the standard deviation.

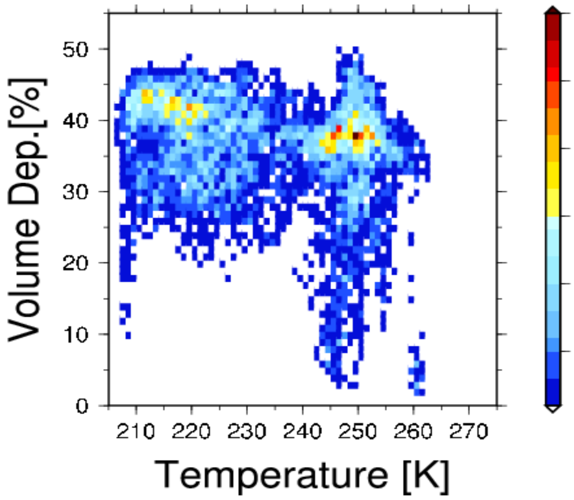


Fig. 7. Frequency of occurrence as the functions of the VDR and temperature.

We examined the vertical distribution of the CR to investigate the dust height when the simultaneous lidar observation was made between Aksu-lidar and CALIOP and shown in Figure 6. The error bar of the CR indicates the standard deviation. In this profile, the cloud base and top height were 7.5 and 11.5 km, respectively according to the total attenuated backscattering coefficient. Because more than 0.7 of the CR was observed just below the cloud, it suggests that there was the dust at the cloud base height and the dust possibly affected on the cloud phase change by acting as ice nuclei and mixing.

To investigate the cloud phase, we examined the frequency of occurrence as the function of the temperature and VDR of the cloud using the method of Hu et al., (2009). Figure 7 shows the result observed by the Aksu-lidar. For less than -40℃, the large depolarization was observed more than 0.3 and decreased with increasing the temperature. This means that the ice cloud was observed because the supercooled water cloud fraction in the cloud is low for that temperature (Seinfeld and Pandis 2001). The negative correlation with the temperature is attributed to the change of the ice habit (Platt and Dilley, 1981).

For more than -40℃ and less than 0℃, it is considered that the ice, supercooled water and 2D plate ice clouds existed and less than 0.3 of the depolarization ratio was observed by the CALIOP for this temperature (Hu et al., 2009). It is attributed to the characteristics of the clouds of which the ice cloud has high depolarization ratio and the water and 2D plate ice clouds have low depolarization. However for the Aksu-lidar, the high VDR was observed for that temperature about 0.4 and it indicated that there were a lot of ice particles in the cloud. It suggested that the supercooled water cloud fraction decreased due to the dust acting as nuclei.

Choi et al., (2010) revealed that the supercooled cloud fraction over the Taklimakan Desert was less than 30 % at -20 ℃ and smaller than other regions. It is consistent with our results, but this study is the first result to suggest that the dust act as ice nuclei over the Taklimakan Desert.

## 4. Conclusion

The ground-based was carried out during 23 – 25 March 2009 in the north west of China to investigae the behaviors and optical properties of the aerosols over the Taklimakan Desert. First, we examined the diurnal variation of the dust layer height (DLH). The DLH rapidly rose to 6-7 km at 22 LST and keep the height until 09 LST, and gradually sank from 09 LST to 22 LST. This phenomenon is considered to be attributed to the local circulation. The jump of the DLH at the 22 LST was attributed to the advection of the dust from the south west of the Taklimakan Desert because the 500 hPa wind direction was the south west and the CALIOP captured the aspect of the advection. The high VDR of the cloud was observed at more than -40℃. We suggested that the super cooled cloud fraction decreased due to the dust acting as ice nuclei according to the relationship between the VDR and temperature.

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## References

Choi Y.-S., R. S. Lindzen, C.-H. Ho, and J. Kim 2010: Space observation of cold-cloud phase change. *Proc. Natl. Acad. Sci.*, **107**(25), 11211-6.

Hu, Y., D. Winker, M. Vaughan, B. Lin, A. Omar, C. Trepte, D. Flittner, P. Yang, S. L. Nasiri, B. Baum, W. Sun, Z. Liu, Z. Wang, S. Young, K. Stamnes, J. Huang, R. Kuehn, and R. Holz, 2009: CALIPSO/CALIOP Cloud Phase Discrimination Algorithm, *J. Atmos. Ocean Tech.*, **26**, 2293-2309.

Husar, R. B., D. M. Tratt, B. A. Schichtel, S. R. Falke, F. Li, D. Jaffe, S. Gasso, T. Gill, N. S. Laulainen, F. Lu, M. C. Reheis, Y. Chun, D. Westphal, B. N. Holben, C. Gueymard, I. McKendry, N. Kuring, G. C. Feldman, C. McClain, R. J. Frouin, J. Merrill, D. Dubois, F. Vignola, T. Murayama, S. Nickovic, W. E. Wilson, K. Sassen, N. Sugimoto, and W. C. Malm, 2001: Asian dust event of April 1998, *J. Geophys. Res.*, **106**, 18317-18330.

IPCC, 2007: Climate Change 2007: The Physical Science Basic, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge and New York, 996pp.

Jin Y., K. Kai, T. Shibata, K. Zhang, and H. Zhou, 2010a: Validation of the Dust Layer Structure over the Taklimakan Desert, China by the CALIOP Space-borne Lidar Using Ground-Based Lidar, *SOLA*, **6**, 121-124.

Jin Y., K. Kai, T. Shibata, K. Zhang, and H. Zhou, 2010a: Validation of the Dust Layer Structure over the Taklimakan Desert, China by the CALIOP Space-borne Lidar Using Ground-Based Lidar – Part Ⅱ －, *SProc. of SPIE,* **7856**, 785609-1-785609-10.

Kim H.-S., and K. Kai 2007: Recent Dust Outbreaks in the Taklimakan Desert and their Relation to Surface Wind and Land Surface Condition, *SOLA*, **3**, 69-72.

Liu Z., D. Liu, J. Huang, M. Vaughan, I. Uno, N. Sugimoto, C. Kittaka, C. Trepte, C. Hostetler, and D. Winker, 2008: Airborne dust distributions over the Tibetan Plateau and surrounding areas derived from the first year of CALIPSO lidar observations. *Atmos. Chem. Phys.*, **8**, 5045-5060.

McCormick M. P., D. M. Winker, E. V. Browell, J. A. Coakley, C. S. Gardner, R. M. Hoff, G. S. Kent, S. H. Melfi, R. T. Menzies, C. M. R. Platt, D. A. Randall, and J. A. Reagan, 1993: Scientific Investigations Planned for the Lidar In-Space Technology Experiment (LITE), Bull. *Amer. Meteor. Soc.*, **74**, 205-214.

Platt C. M. R., and A. C. Dilley 1981: Remote Sounding of High Clouds. IV: Observed Temperature Variations in Cirrus Optical Properties, *J. Atmos. Sci.*, **38**, 1069-1082.

Seinfeld J. H. and Pandis S. N. 2001: Atmospheric Chemistry and Physics: From Air Pollution to Climate Change, *J. Wiley*, New York.

Tsunematsu N., K. Kai, and T. Matsumoto 2005: The influence of synoptic-scale air flow and local circulation on the dust layer height in the north of the Taklimakan Desert, Water, Air, and Soil Pollution: *Focus*, **5**, 175-193.

Uno I., H. Amano, S. Emori, K. Kinoshita, I. Matsui, and N. Sugimoto, 2001: Trans-Pacific yellow sand transport observed in April 1998: A numerical simulation, *J. Geophys. Res.*, **106**, 18331–18344.

Uno I., K. Eguchi, K. Yumimoto, T. Takemura, A. Shimizu, M. Uematsu, Z. Liu, Z. Wang, Y. Hara, and N. Sugimoto, 2010: Asian dust transported one full circuit around the globe. *Nature geosciences*, **2**, 557-560.

Winker D. M., C. A. Hostetler, M. A. Vaughan, and A. H. Omar, 2006: CALIOP Algorithm Theoretical Basis Document Part 1: CALIOP Instrument, and Algorithms Overview. available at http://www-calipso.larc.nasa.gov/resource/project-documentation.php.

Yumimoto K., K. Eguchi, T. Takemura, Z. Liu, A. Shimizu, and N. Sugimoto, 2009: An elevated large-scale dust veil from the Taklimakan Desert: Intercontinental transport and three-dimensional structure as captured by CALIPSO and regional and global models, *Atmos. Chem. Phys.*, **9**, 8545-8558.