# TWO-YEAR-OBSERVATIONS OF OPTICAL PROPERTIES OF THE TROPOSPHERIC AEROSOL AND CLOUDS BY A HIGH-SPECTRAL-RESOLUTION LIDAR OVER TSUKUBA, JAPAN


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## ABSTRACT

This paper reports the results of lidar determination of the atmospheric aerosol and cloud optical properties in the troposphere over Tsukuba, Japan (140.12°E, 36.05°N, 27 m ASL). A high-spectral-resolution lidar based on an iodine absorption filter was used to perform the study. The lidar system gives possibility of independently obtaining the profiles of the backscattering and extinction coefficients, and the profile of the depolarization ratio. The results of the measurements carried out from 2003 to 2005 are presented including the mean values, distributions, and the altitude dependences of the lidar ratio for clouds and aerosols. The variations of the daily averaged lidar ratio are given as well.


## 1. INTRODUCTION

To assess the impact of aerosols on the local and global climate the knowledge of the optical properties, temporal and spatial distributions of aerosols is essential. A lidar can provide measurements of the extinction and backscatter coefficients with high spatial and temporal resolutions. However, the retrieval of the optical properties from a conventional backscatter lidar suffers from the well-known problem that two quantities have to be determined from one measured parameter. The assumption of the lidar ratio (aerosol extinction to backscatter coefficients ratio, S1) is consequently needed to solve the lidar equation. The lidar ratio usually depends on the height and on aerosol type and can be only roughly estimated from climatology. The lidar ratio is strongly dependent on microphysical characteristics of the aerosol namely the complex refractive index and size distribution. Thus, the independent observation of the extinction to backscatter ratio is essential. High-spectral-resolution lidars (HSRL) [1, 2] and Raman lidars [3] both have ability of measuring the lidar ratio profile independently.

In this paper, the results of the determination of backscatter and extinction coefficients, lidar ratio, and depolarization ratio for tropospheric aerosols and high altitude cirrus clouds in a period of two years (from 2003 to 2005) are presented.

## 2. METHODS AND APPARATUS

The High-Spectral-Resolution Lidar developed at the National Institute for Environmental Studies is in operation from 1999 in Tsukuba, Japan (140.12°E, 36.05°N) [2]. Main characteristics of the lidar system are summarized in Table 1.

Table 1. The lidar system main parameters

| | |
|---|---|
| **Transmitter** | |
| Gain medium, Conditions | Nd:YAG, Q-switched, injection-seeded, frequency-locked, linearly polarized |
| Wavelength | 532.24 nm |
| Line width, FWHM | <0.003 $cm^{-1}$ |
| Pulse energy | up to 400 mJ at a duration of <8ns |
| Repetition rate | 30 Hz |
| Divergence | 0.1 mrad (using a 5x expander) |
| **Receiver** | |
| Telescope | Cassegrain, f/13.5, 560 mm |
| Detectors | 3x photomultipliers Hamamatsu R3235 |
| Detections and wavelength separators | |
| elastic, 532 nm | Cross and parallel polarizations, 3 nm FWHM Interference filter (IF) |
| Rayleigh, 532 nm | 40 cm long $I_2$ cell, 3 nm FWHM IF |
| **Data acquisition and processing set** | |
| Accusation unit | Licel transient recorder, three channels. Simultaneously record by 12 bit, 20 MHz A/D converter and photon-counter |
| Computer | standard PC |

Aerosol backscatter coefficient profiles were measured for the altitudes above 300 m, whereas the extinction measurements were restricted to the heights above 1 km. Optical properties of the aerosols and clouds were derived employing the methods described in [1, 2, 4, 5]. The optical properties of atmospheric gasses were calculated using pressure and temperature profiles, obtained from routine radiosonde observations at Tateno Aerological observatory (140.13 E, 36.05 N, 27 m ASL).

## 3. RESULTS AND DISCUSSION

Regular HSRL observations at NIES, Tsukuba started on 1 August 2003. Till the end of December 2005, the measurements with a total duration of more than 2500 hours were accomplished. The mean duration of a measurement was about 6 hours per day, including both day- and night-time observations. Observations during mineral dust advections were also performed. The raw lidar data were recorded with time and spatial resolutions of 2 minutes and 3.75 meters respectively. Vertical profiles of the lidar ratio and the aerosol/clouds optical parameters have been derived from the raw data by averaging over 30 min in time and 150 m in range.

All available lidar data are clustered into three basic categories: clouds, spherical aerosols, and nonspherical aerosols. For the purpose we used a procedure based on the values of backscatter ratio, depolarization ratio and the gradient of the lidar signal value. Determination of cloud presence is performed taking into account the range-square-corrected lidar signal and the values of backscatter ratio obtained for each profile. When the vertical gradient of the lidar signal intensity and backscatter ratio exceed a certain threshold value the profile is categorized as “cloud presented” and the lowest (by height) point is recognized as the cloud base height. In the points/volumes detected as “clouds free” the aerosol is considered. To split spherical on nonspherical aerosol, values of the total depolarization ratio are used.

Based on the all available lidar ratio data the mean values of lidar ratio and their distributions were obtained. In Fig. 1, the probability distributions of the lidar ratio for clouds, spherical aerosols and nonspherical aerosols are shown in a step of 2 sr. The obtained mean values and standard deviations are as follow: S1=18.2±12.5 sr for clouds, S1=68.6±39.8 sr for spherical aerosols, and S1=48.5±27.1 sr for nonspherical aerosols. One can see the distribution of the lidar ratio for clouds is significantly different from the both kinds of aerosols. The typical values for clouds are approximately three times smaller than those for aerosols. Also, the distribution for clouds has an apparent peak with a maximum probability of 0.12 at S1=14 sr, while the lidar ratios for spherical and nonspherical aerosols have broader distributions. The standard deviation quantitatively represents this characteristic – 12.5 sr for cloud and 39.8 sr and 27.1 sr for spherical and nonspherical aerosol. The primary reason for the smaller mean value and standard deviation for clouds is the significantly larger particle size compared to spherical and nonspherical aerosols. Another reason could be the composition of aerosols, which may contain optically absorptive substances.

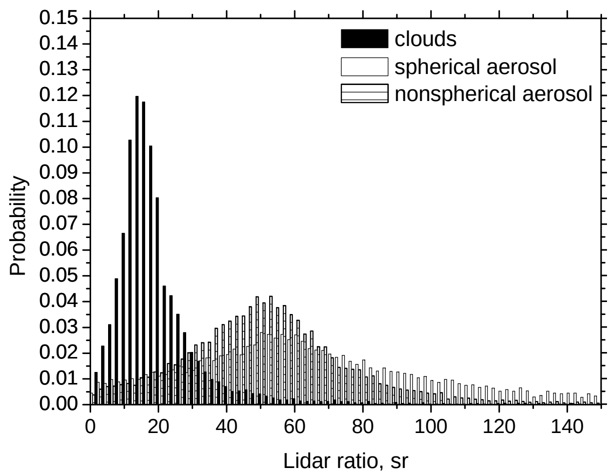

Fig. 1. Histograms of point by point distributions of lidar ratio values for clouds, spherical-shape aerosol and nonspherical-shape aerosol in steps of 2 sr.

The results in Fig. 1 also show a difference between the statistical parameters of the lidar ratio for spherical and nonspherical aerosols. The mean value of the lidar ratio for spherical aerosols (S1=68.6 sr) is larger at about 20 sr than that for nonspherical aerosols. The lidar ratio values between 80 sr and 140 sr were more frequently observed for spherical aerosols. In contrast, for nonspherical aerosol particles, values between 30 sr and 70 sr were more frequently observed. Likewise, the maximum probability for spherical aerosol - 0.025 is about two times smaller than that for nonspherical aerosols.

As a whole, the lidar ratio distribution is broader for spherical aerosol particles than for nonspherical aerosol particles. The possible reasons for the differences between spherical and nonspherical aerosols are the size distribution and the absorption. The reason for larger variability in spherical aerosols is the fact that spherical aerosols includes many different kinds of aerosol particles, for examples, haze, low density fog, air pollution aerosols, photochemical aerosols, aerosols originated from the ocean and sea, etc. Each one of these kinds of aerosols has different microphysical properties, and accordingly has a different extinction-to-backscatter ratio. Another factor for the variability of the lidar ratio is relative humidity.

Figure 2 presents mean vertical profiles of the lidar ratio (squares), particle depolarization ratio (stars), and extinction coefficient (circles) for clouds. To construct these curves 6945 data points in the altitude range from 4 km to 15 km in all seasons are used. The vertical spatial resolution is 150 m.

One can see the almost constant value of the lidar ratio S1≈20 sr is obtained in the wide vertical range from 5.5 km to about 13 km. In the same height range, the particle depolarization ratio indicating the nonsphericity of the particles is almost constant with a value of 48%.

Smaller values of the lidar ratio, from S1=15 sr to S1=20 sr are observed at the altitudes from 4 km to 5.5 km. Probably, these smaller values indicate presence

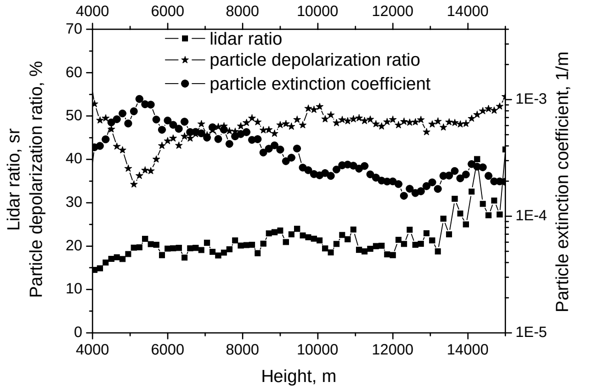


Fig. 2. Dependences of the lidar ratio, particle depolarization ratio, and extinction coefficient on height in case of clouds.

of liquid water. Relatively smaller values of the depolarization ratio are consistent with the suggestion. In addition, the increase of the lidar ratio is observed at higher altitudes (near to the tropopause). S1 changes from 20 sr at 13 km to 40 sr at 15 km.

The profile of extinction coefficient generally reveals a decrease with height. The extinction coefficient $\alpha_p$ changes from $10x10^{-4}m^{-1}$ at 5 km to $2x10^{-4}m^{-1}$ at 15 km. Considering from the nearly constant values of the lidar ratio and particle depolarization ratio, similar microphysical parameters (shape, composition and size distribution of cloud's particles) are expected in the wide altitude range from 6 km to 13 km.

Fig. 3 shows the dependences of optical parameters on the cloud temperature. Radiosonde data are used for the

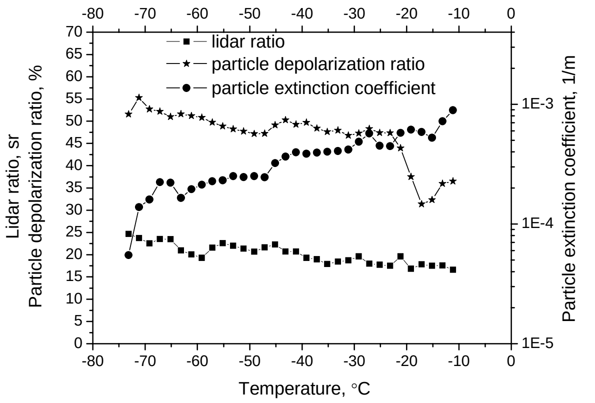


Fig. 3 Dependence of the lidar ratio, particle depolarization ratio, and extinction coefficient on temperature.

temperature. The optical parameters are averaged in the temperature intervals of 2°C. One can see the decrease of the lidar ratio and the depolarization ratio with increasing cloud temperature. The change suggests the dependence of the structure of cloud particles on temperature. Contrariwise is the behavior of the extinction coefficient, which increases with increasing of the temperature.

Profiles of the lidar ratio, depolarization ratio and extinction coefficient obtained for aerosols (both spherical and non-spherical) are presented in Fig. 4. For

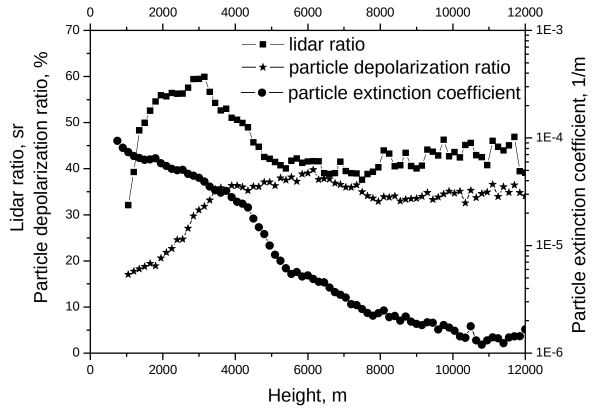


Fig. 4. Dependences of the lidar ratio, particle depolarization ratio, and extinction coefficient on height in case of aerosols.

this plot, data in the altitude range from 1 km to 12 km in all seasons are used. The vertical spatial resolution is 150 m. The lidar ratio is about 55 sr in the height range from 1 km to 3 km. At higher altitudes, it decreases to 40 sr at 5 km and nearly constant up to 12 km. In the depolarization ratio profile, one can see the increase of the values from 15% at 1 km to 35% at 4 km, and it is nearly constant up to 12 km. The behavior of the depolarization coefficient indicates the presence of spherical aerosols and mixture of spherical and nonspherical aerosols at altitudes between 1 km and 4 km. In the same height range the lidar ratio has relatively higher values. The profile of the extinction coefficient decreases with altitude over entire range of height.

Variation of daily averaged mean values of the lidar ratio for the middle and high attitude clouds are shown in Fig.5. In this plot, data of 91 days are used. A sliding fit by 5 points is also shown in the same figure. One can see higher values of the lidar ratio are observed in the period from December to February. This trend can be clearly seen in the sliding curve. On some of days in the spring and summer, low lidar ratio values of about 10 sr are measured. Such low values are not observed in the winter time.

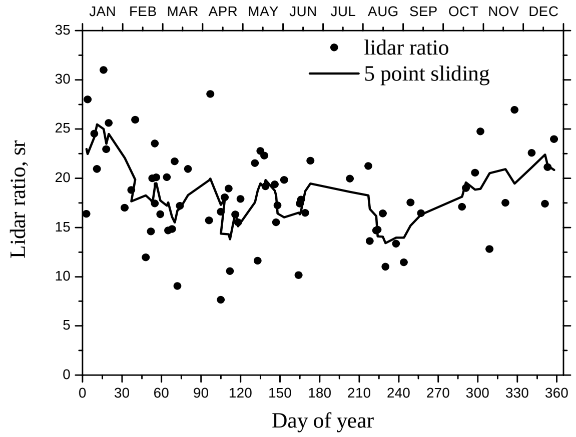


Fig. 5. Variation of daily averaged values of the lidar ratio in clouds in middle and high troposphere.

The annual cycle of the mean lidar ratio of aerosols (both spherical and nonspherical particles) is shown in Fig. 6. The data of 183 days are used in the plot. A five point sliding average is also plotted. For most days, the lidar ratio has values between 30 sr and 70 sr. However, a significant number of days with the lidar ratio larger than 70 sr are seen in the figure. The relatively higher

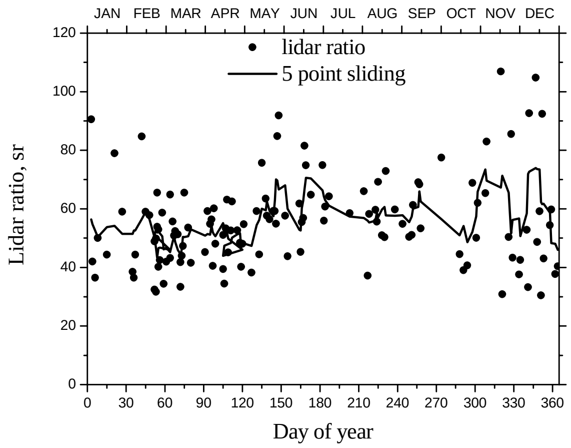


Fig. 6. Variation of daily averaged values of the lidar ratio of aerosols.

values are observed in the winter months as well as in the early summer. The probable reason for such increase is the predominance of particles with sub-micron size over the rest aerosol on such days. The sliding average curve shows only small seasonal variations of the daily averaged lidar ratio, a weakly pronounced "summer maximum" is seen between May and September.

## 4. CONCLUSIONS

Based on the HSRL measurements performed in the period from 2003 to 2005, mean values of the lidar ratio and particle depolarization ratio was obtained. The differences between statistical properties of the lidar ratio for clouds, spherical and nonspherical aerosols are studied. In the case of clouds, the vertical profile of the lidar ratio shows almost constant value of S1≈20 sr in the wide range of altitude from 4 km to 13 km. The decrease of the lidar ratio and the depolarization ratio with increase of cloud temperature is also observed. For aerosols, higher values of the lidar ratio are measured in altitudes up to 4 km.

## ACKNOWLEDGMENTS

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