ONE YEAR HIGH-SPECTRAL-RESOLUTION LIDAR OBSERVATIONS OF THE LIDAR RATIO AND THE DEPOLARIZATION RATIO OF TROPOSPHERIC AEROSOLS AND CLOUDS

Boyan Tatarov, Nobuo Sugimoto, Ichiro Matsui, Atsushi Shimizu
National Institute for Environmental Studies, Tsukuba, 16-2 Onogawa, Tsukuba, Ibaraki 305-0053, Japan
E-mail:boyan.tatarov@nies.go.jp

ABSTRACT

The work reports on some results of the one year systematic measurements of the particle optical properties (extinction and backscatter coefficients) and especially the lidar ratio and depolarization ratio in the troposphere over Tsukuba, Japan. The measurements were performed using a high-spectral-resolution lidar based on iodine absorption filter. We present results from sounding in cases of troposheric aerosol layers and cirrus clouds.

1. INTRODUCTION

The tropospheric aerosols and clouds play significant role in Earth radiation budget through the scattering and absorption of sun and earth radiation. Lidar has proven to be a very effective tool in aerosol characterization experiments. Lidar measurements of particle optical properties with high resolution in time and space give detailed information on occurrence, extent, and development of aerosol structures. From the independent detection of particle extinction and backscattering properties, an optical characterization of aerosols is possible. The extinction-to-backscatter ratio, or lidar ratio, is a parameter strongly related to the microphysical properties of the aerosols depending on the aerosol type and aerosol size distribution; moreover, lidar ratio is important in estimating the climate impact of aerosols. For this reason a statistically significant data set of systematic lidar ratio measurements is a very powerful tool for the study of tropospheric aerosols.

The work presents results from one yaer measurements of the tropospheric aerosol properties by high-spectral-resolution lidar (HSRL) techniques on Tsukuba. During the experiments presented here, the lidar was placed into the National Institute for Environmental Studies (NIES), Tsukuba, Japan (36.05°N, 104.12°E, 27 m above sea level). Experimental data were acquired from August 2003 till Jully in 2004.

2. METHODS AND APPARATUS

The HSRL of the National Institute for Environmental Studies (Liu et al. 1999) use a Nd:YAG laser with a maximum pulse energy of 400 mJ at 532 nm and a repetition rate up to 30 Hz. The pulsed Nd:YAG laser is injection-seeded for single-mode operation with a monolithic, diode-pumped, continuous-wave Nd:YAG laser, so that the laser has a spectral bandwidth of <0.003 cm^{-1}. The laser beam is collimated with a 5× expander.

The backscattered photons are collected with a 0.56 m diameter Cassegrain telescope.The signal is divided into three parts. A non-polarizing beamsplitter divides into two equal parts first. One part, that contains both the narrow-line particle backscattering and the Doppler-broadened molecular backscattering, is separates the parallel- and cross-polarized components by a polarizing beamsplitter. The other one passes a thermally stabilized iodine-vapor absorption cell of 40-cm length. In this manner, the absorption line of iodine at the center wavelength of 532.26 nm leads to a suppression of the particle backscattering of approximately a factor of 1000, whereas, due to the absorption line width of 1.7 GHz, the wings of the molecular return with a Doppler width of 2.6 GHz at 293 K can pass the cell. Therefore the detector behind the absorption cell measures the molecular response mainly. In this manner we separate lidar returns for aerosol and molecular scattering. Three R3235 photomultiplier tubes, equipped with interference filters with a bandwidth of 3 nm at the working wavelength, were used for lidar return detection. A diameter-adjustable iris is located at the focal point of the telescope to determine the field of view from 0.2 mrad to 0.8 mrad for different measurements.
For data acquisition and processing is using a three channel Licel transient recorder with 12 bit, 20 MHz A/D converters and photon-counters; and standard PC. The lidar system configuration ensures maximum spatial and time resolutions of 3.75 m and 0.033 s respectively.

Optical properties are derived by methods developed by Shimizu et al. (1983), Piironen et al. (1994), Liu et al. (1999). Aerosol backscatter coefficient is obtaining as product of molecular backscatter coefficient and ratio between aerosol to molecular signals. Aerosol extinction coefficient is calculating as differential from natural logarithm of range corrected, molecular backscatter normalized molecular return. In addition we measure total depolarization ratio (depolarization coefficient), defined as ratio between lidar responses with polarizations parallel and perpendicular with respect to polarization of the laser source.

The molecular backscatter and extinction profiles are obtained by routine radiosonde observations at Tateno Aerological observatory (36.05°N, 140.13°E).

3. RESULTS AND DISCUSSION

Regular HSRL measurements have been performed in NIES, Tsukuba three times a week starting on 1 August 2003. Additional observations have been performed in case of Kosa events. The average duration of a measurement is about 6 hours per day, including daily and night-time observation. In Table 1, the measurement statistics can be seen. For this statistics, only measurements from days without low clouds (cloud base < 3000 m) are taken. The typical resolution of raw data is 2 min in time and 3.75 m in space. Usually, for the extinction coefficient profiles calculation, the data are averaged over 30 min and vertically over 150 m.

From the all collected data we select to the statistical analysis only points for which the measurement uncertainties is less than 50% for lidar ratio S_p and 20% for depolarization ratio δ_p. The data that has unrealistically values were also excluded.

Mount	Aug'03	Sep'03	Oct'03	Nov'03	Dec'03	Jan'04	Feb'04	Mar'04	Apr'04	May'04	Jun'04	Jul'04	**Total**
Number of days	11	14	7	10	11	8	7	10	10	15	14	10	**127**
Duration, hours	66	96	38	59	82	47	54	79	75	83	109	60	**848**
Number of days with ice clouds	6	5	4	5	3	4	4	5	5	10	10	3	**64**

Tab. 1. Measurements statistics by months over the period 1 August 2003 – 31 July 2004

Figure 1 presents results from a typical case of HSRL measurements of aerosol layer in low troposphere and ice cloud on 22 July 2004. The vertical profiles of particle extinction (α_p) and backscatter (β_p) coefficients, backscatter

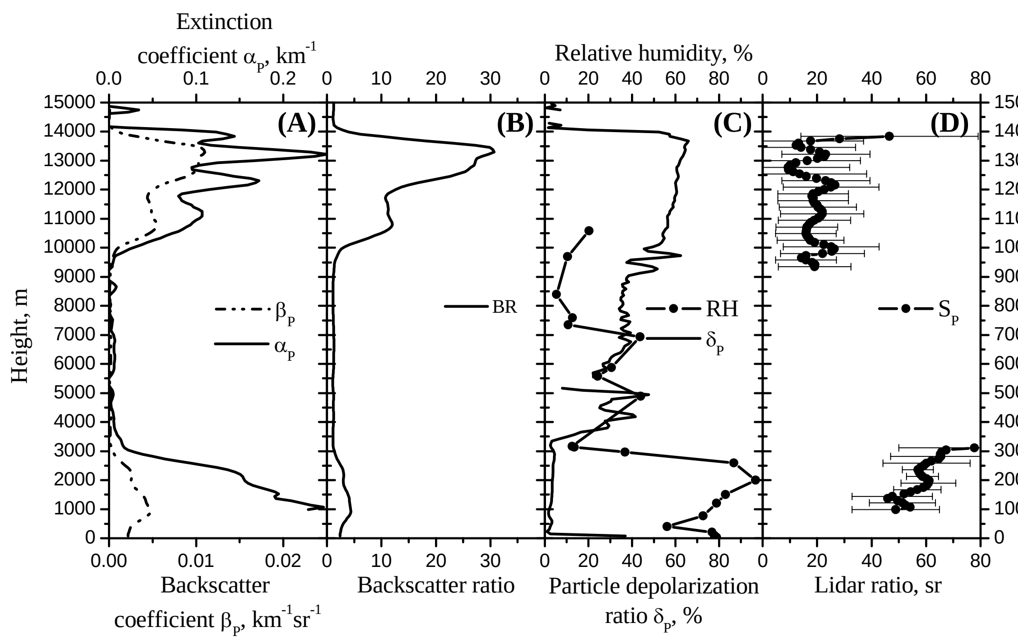


Fig. 1. Vertical profiles of optical properties averaged over 06:00-07:00 UTC on 22 July 2004.
(A) - particle extinction coefficient (solid curve) and particle backscatter coefficient (doted curve); (B) – backscatter ratio; (C) - particle depolarization ratio (solid curve) and relative humidity (doted curve).

ratio (BR), particle depolarization ratio (δ_p) and lidar ratio (S_p) are showed. A profile of the relative humidity obtained by routine radiosonde observation at Tateno on this day (12:00 UTC) is also presented in the figure. Lidar signals were averaged by 108 000 laser shots during the time period of 06:00-07:00 UTC. The vertical resolution is 76 m for BR and δ_p and 380 m for S_p.

The extinction coefficient profile ($\alpha_p(R)$) decreases into the ground layer from α_p~0.24 km^{-1} at 1000 m to α_p<0.01 km^{-1} after 4000 m. The profile of backscatter coefficient in this range has similar behavior. The optical thickness is about 0.28 within in the range 1000÷4000 m. The particle depolarization ratio has values about δ_p~5% below 3500 m. Such values are typical for scattering from spherical particles. The profile of depolarization is in good agreement with this of the relative humidity - up to 3000 m the values of the RH are more than 60%. Lidar ratio varies from 48 sr at 1400 m to 77 sr at 3200 m, as height-averaged value is S_p=58 sr.

The extinction and backscatter coefficients increase between altitudes 9500 m and 14000 m indicating presence of a cloud in this range. The values of α_p showed maxima α_p≈0.25 km^{-1} at height about 13200 m. The optical depth is ≈0.5 between 9500 m and 13200 m, considerably larger than in grounded aerosol layer. The δ_p values are in range of 40÷65% indicating scattering from nonspherical particles - ice crystals. Into the cloud the lidar ratio values vary between 9 and 46 sr in the cloud, as height-averaged value is S_p=19 sr.

In Figure 2 the results from a typical case of HSRL measurements of Asian dust layer on 30 April 2004 are presented. The temporal and vertical resolutions are same as previous case. The vertical profile of backscatter ratio shows a presence of several aerosol layers up to 6000 m altitude, and an ice cloud layer between 7000 m and 12000 m. For the range up to the cloud, three aerosol layers can clearly be distinguished characterized by behavior of the backscatter coefficient and particle depolarization ratio. The first one spans the distance from lidar location to approximately 1000 m, the second one lies between 1000 m and 3000 m and the third one envelops altitudes from

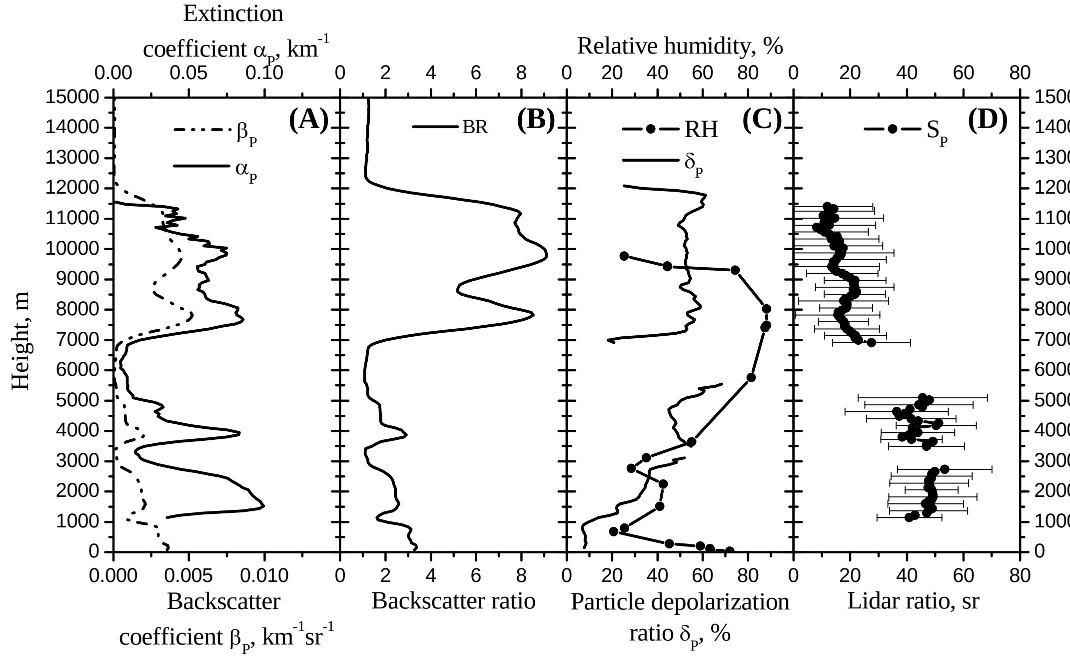


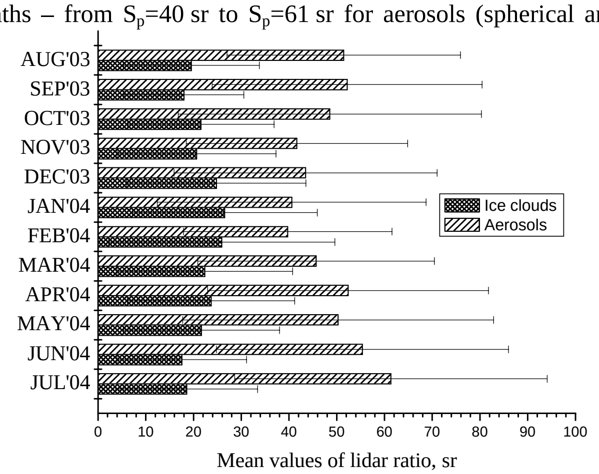
Fig. 2. Same as Fig. 1. but averaged over 05:00-06:00 UTC on 30 April 2004.

3500 m to 5500 m. Into the lowest aerosol layer the backscatter coefficient has values β_p~0.005 km^{-1}sr^{-1} and particle depolarization ratio is lower than 10 %, which indicates that this layer mostly consists of spherical particles. Since, as the geometric factor of the used lidar system is not constant below 1000 m, we can't retrieve the extinction coefficient and lidar ratio for this layer. For another two layers the extinction coefficient α_p has peaks with magnitude - α_p~0.01 km^{-1} at 1500 m and α_p~0.008 km^{-1} at 4000 m. The particle depolarization ratio has mean values δ_p~32 % between 1000 m and 3000 m and δ_p~52 % between 3500 m and 5500 m. The lidar ratio has mean values S_p=48 sr and S_p=44 sr, respectively. The relatively low values of backscatter ratio (BR<3) and the high depolarization exhibit, that these two particle layers contains mineral dust. The most probable distinctions of the values of the depolarization and lidar ratios for the two dusts layer are gives rise to presence of some spherical aerosols in range from 1000 m to 3000 m.

In the range of the cloud, the extinction coefficient has a mean values α_p=0.56 km^{-1}. The height-averaged values of the particle depolarization ratio and lidar ratio are: δ_p=52% and S_p=18 sr, respectively.

The mean values and standard deviation of the lidar ratio separated by months are reported in Tab. 2. These results show similar values of the lidar ratio in the months – from S_p=40 sr to S_p=61 sr for aerosols (spherical and

	Aerosols		Ice clouds	
	Lidar ratio, sr	St.dev., sr	Lidar ratio, sr	St.dev., sr
AUG'03	51.46	24.46	19.56	14.23
SEP'03	52.18	28.28	17.98	12.54
OCT'03	48.54	31.75	21.54	15.37
NOV'03	41.66	23.19	20.66	16.64
DEC'03	43.47	27.56	24.78	18.76
JAN'04	40.56	28.16	26.54	19.35
FEB'04	39.73	21.82	25.91	23.68
MAR'04	45.68	24.78	22.35	18.39
APR'04	52.38	29.39	23.67	17.54
MAY'04	50.28	32.56	21.65	16.37
JUN'04	55.36	30.58	17.54	13.58
JUL'04	61.35	32.75	18.56	14.87



Tab. 2. Mean values and standard deviations of the lidar ratio by months

nonspherical) and from S_p=18 sr to S_p=27 sr for clouds. One can see that during the winter months (December, January and February) the lidar ratio has smaller values in case of aerosols in comparison with summer months (June, July, August). For example mean value of lidar ratio is S_p=43.47±27.56 in December 2003 and S_p=61.35±32.75 in July 2004. In contrast, for ice clouds lidar ratio is bigger for the winter months – S_p=24.78±18.76 in December 2003 and S_p=18.56±14.87 in July 2004.

We clustered the collected data into three categories – ice clouds, spherical aerosols, and non-spherical aerosols. First one is obtained for values of α_p>0.5 km^{-1}, δ_p >10% and presence of the sharply increasing of the lidar signal (cloud base). Second one, we separate by δ_p <10%, α_p<1 km^{-1} and absence of cloud base. For the determination of third type δ_p >10%, α_p<1 km^{-1} and absence of cloud base are used. In Fig. 3 histograms on the distributions of the values of lidar ratio for these categories are present.

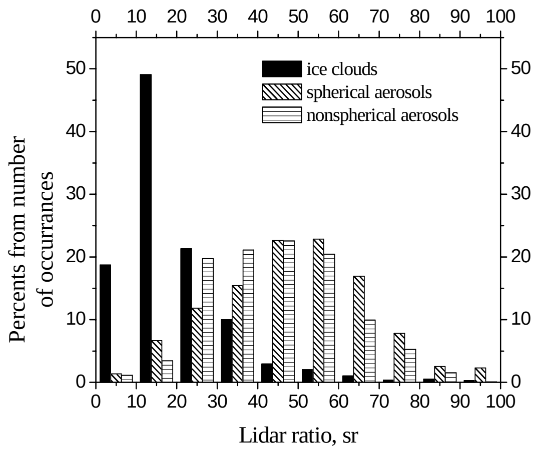


Fig. 3. Histograms of the lidar ratio values for ice clouds, spherical aerosols and non-spherical aerosols

One can see that for ice clouds has a peak in occurrence at range 10–20 sr, and approximately equal number of occurrences for 0–10 sr and 20–30 sr. The mean value for the all data range is S_p=22±15 sr. Significantly greeter mean values are observed other two categories - S_p=49±23 sr for spherical aerosols and S_p=43±20 sr for nonspherical aerosols. Although the mean value and standard deviations are similar, one can observe that in case of spherical aerosols more frequently values of the lidar ratio between 50–80 sr are observed. In contrast, for nonsoherical aerosol, values between 20–40 sr more often are observed.

Figure 4 shows the mean lidar ratio depending on the relative humidity in case of spherical aerosol. In the figure results for HSRL measurements and model results based on Mie numerical calculation by Ackermann (1998) are presented. For this dependence only lidar ratio values for spherical aerosols, observed from 11:00 to 13:00 UTC are taken. Lidar data from 63 days in this time period are used. The values of relative humidity are derived from radisonde measurements at 12:00 UTC. To agreement of the vertical resolution a linear extrapolation of the radiosonde data is used.

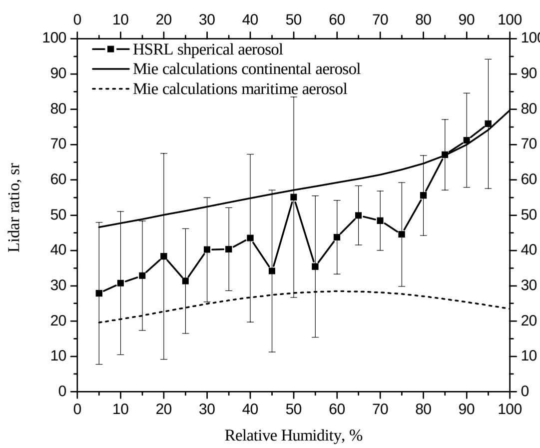


Fig.4. Dependence of the lidar ratio on the relative humidity for spherical aerosols

As a whole, the lidar ratio rises with increasing of the relative humidity from S_p=27 sr. at RH=5 %, to S_p=76 sr at RH=95%. For higher relative humidities (85%-95%), one can see a very good agreement of the experimental points with model calculation for continental aerosol. For relative humidities up to 80 % the lidar obtained values of the lidar ratio are lower than continental aerosol model data and larger than continental aerosol model data.

4. CONCLUSIONS

We have carried out high-spectral-resolution lidar measurements of the vertical distributions of the particle optical and polarization properties in the troposphere over Tsukuba, Japan. The temporal and vertical cross section of the lidar ratio, depolarization ratio, extinction and backscatter coefficients over the one year period August 2003-Jully 2004 have been obtained. The measured values of the lidar ratio ranged mostly from 10 sr to 30 sr for clouds and from 30 sr to 70 sr of aerosols.

ACKNOWLEDGMENTS

This work has been supported by the Ministry of the Environment, Tokyo, Japan.

REFERENCES

Liu, Z., I. Matsui, N. Sugimoto, High-spectral-resolution lidar using an iodine absorption filter for atmospheric measurements, *Opt. Eng.* 38, 1661-1670, 1999.

Shimizu, H., S. A. Lee, and C. Y. She, High spectral resolution lidar system with atomic blocking filters for measuring atmospheric parameters, *Appl. Opt.*, Vol. 22, 1373--1391, 1983.

Piironen, P. and E. W. Eloranta, Demonstration of a High-Spectral-Resolution Lidar based on a Iodine Absorption Filter, *Optics Letters*, Vol. 19, 3, 234-236, 1994.

Ackermann J., The Extinction-to-Backscatter Ratio of Tropospheric Aerosol: A Numerical Study, *J. of Atm. And Oceanic Techn., 15*, 1044-1050, 1998.