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Aerosol Extinction Coefficient Continuously Measured with Polarized Mie Scattering Lidar

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Aerosol extinction coefficients of clouds and dust were continuously measured in the year of 2002 with a polarized Mie-scattering lidar controlled by an automatic and remotely operating system utilizing internet services. Measured cloud extinctions were greater than 1.0 km^{-1} below the altitude 6 km, 0.17 - 1.0 km^{-1} between 6 and 10 km, and 0.091 - 0.3 km^{-1} beyond 10km. Extinction of dust were 0.10 and 0.20 km^{-1} for Asian dust and 0.057 km^{-1} for urban dust.

1 INTRODUCTION

Recent years, aerosol has been attracted interests because of its effect on global climate change. Measurement of aerosol optical properties is essential to evaluate the effect. A lidar can measure height distribution of aerosol. Results of lidar measurements of clouds and dust aerosols are reported here. Optical properties have been studied of cirrus[1], stratocumulus[2], and midlevel clouds[3]. Especially much knowledge has been obtained about cirrus. Dust aerosols, e.g., mineral, urban, and maritime dust, were also investigated[4 – 9], whereas other types of clouds are not so much cultivated.

In the previous paper[10], we presented height profiles of depolarization ratio of Asian dust obtained with a polarized Mie-scattering lidar(MLO-II). In this paper, aerosol extinction coefficient of tropospheric clouds, Asian dust, and urban dust in Okayama are investigated. Data were obtained with improved MLO-III and a new lidar operating system.

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2 THEORY AND SYSTEM CONFIGURATION

A polarized Mie-scattering lidar was employed to probe aerosol extinction because of its high sensitivity to detect small particles in the atmosphere and its capability to discriminate categories of interested aerosol. The discrimination of aerosol categories is achieved with the extinction to backscattering ratio, or lidar constant, at the lidar wavelength. A lidar operating system (LiOS) allows operators remote and automatic control of the lidar for continuous aerosol observation over more than a week via the internet.

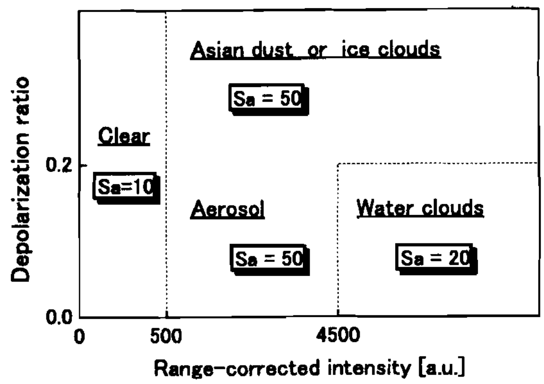


Figure 1: The algorithm to categorize aerosol particles according to intensity of range-corrected lidar returns and depolarization ratios.

2.1 Polarized Mie-Scattering Lidar

Polarized Mie-scattering lidar is able to measure aerosol extinction coefficients. The polarized Mie-scattering lidar employs Nd:YAG lasers 1064 and 532 nm in wavelength. Backscattering coefficient of aerosol particles, which size from submicrons to tens of microns, is large enough at these wavelengths to attain the high sensitivity in aerosol sensing. The capability to discriminate the category of aerosol particles is provided by the polarization of laser. When linearly polarized laser beam is scattered by an aerosol particle, the scattered light involves two polarization components, one is parallel to the polarization of incident laser beam and the perpendicular. The ratio of powers of the perpendicular to parallel, which is called "depolarization ratio", indicates how much aerosol particles are not spherical. The ratio is nearly zero for spherical water droplets, 0.1-0.4 for mineral dust, and 0.1-0.6 for ice clouds. Thus, the category of aerosol particles can be estimated from the depolarization ratio.

A novel inversion method has been developed based on Wei's metnod[12]. It can deal inhomogeneous atmosphere in the calculation of extinction coefficients from lidar returns. Fernald's inversion method is based on the homogeneity condition of the atmosphereFernald 1984. *The* atmosphere in which clouds, fog, dust, or other aerosols exist is, however, not homogeneous, so the inhomogeneity of the atmosphere must be concerned at inversion process. Wei reported an inversion method for inhomogeneous atmosphere to apply multiple boundary conditions to each homogeneous layer. The multi boundary method, however, possesses a difficulty in determining locations where the boundary conditions of each segmented domain should be applied. To avoid this difficulty, we introduced a new inversion method that requires only one boundary condition. This inversion method assumes that aerosol extinction coefficients at a height$z$, $\sigma_{\mathrm{a}}(z)$, is given

$$
\begin{aligned}
\sigma &= -\frac{S_{\mathrm{a}}(z)}{S_{\mathrm{m}}} \\
&\quad + \frac{A}{\dfrac{X(z_{\mathrm{c}})}{\dfrac{S_{\mathrm{a}}(z_{\mathrm{c}})}{S_{\mathrm{m}}}\sigma_{\mathrm{m}}(z_{\mathrm{c}})} + 2\displaystyle\int_{z}^{z_{\mathrm{c}}} \sigma_{\mathrm{m}}(z')dz'} \qquad (1) \\
A &= X(z)\exp\left\{2\left(\frac{S_{\mathrm{a}}}{S_{\mathrm{m}}} - 1\right)\int_{z}^{z_{\mathrm{c}}} \sigma_{\mathrm{m}}(z')dz'\right\},
\end{aligned}
$$

where σ_{m} is the molecular extinction coefficient, X is range-corrected lidar returns, S_a and S_m are the lidar constant of aerosol and molecule respectively, and z_{c} denotes the boundary height. The altitude z_{c} is found by inspecting the received signal so that ratio of signal power to the system noise power should be 10. The function $S_{\mathrm{a}}(z)$ of z represents the inhomogeneity of the atmosphere. In other words, the new inversion method can choose the most appropriate $S_{\mathrm{a}}(z)$ according to the category of aerosol particles existing at z.

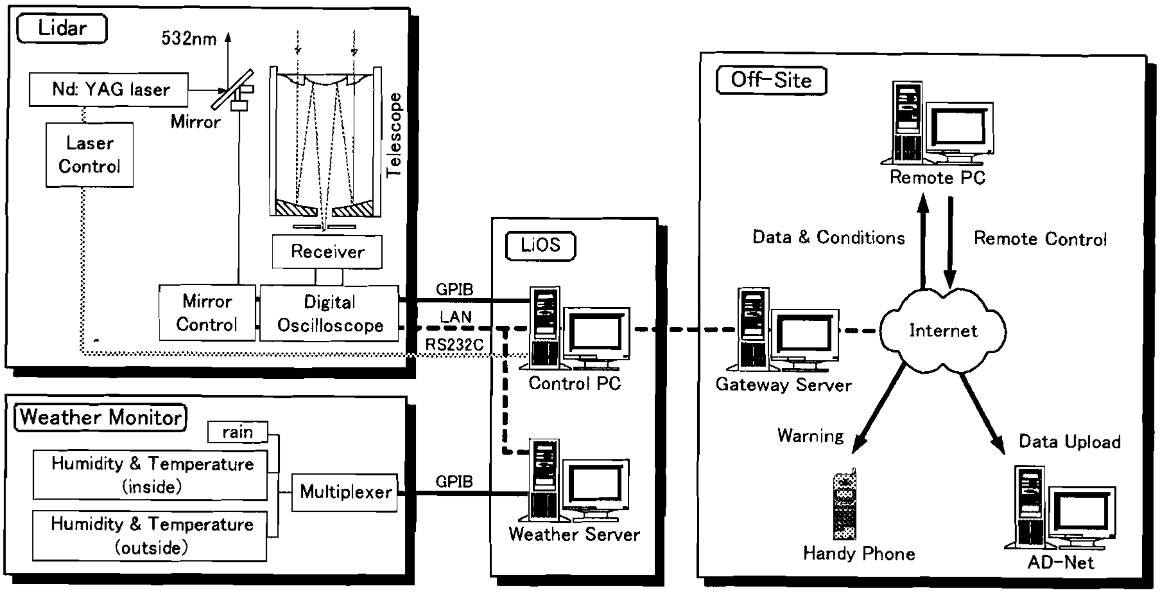


Figure 2: The functions of LiOS.

An algorithm to discriminate aerosol categories determine the lidar constants of aerosols according to the amplitude of $X(z)$ and depolarization ratio, as shown in Fig. 2. The algorithm categorizes aerosol condition into three: clear air, water clouds, and aerosol or mineral dust or ice clouds. Lidar constants for each category are assumed as 10 for clear air, 20 for water clouds[16], 50 for aerosols, Asian dust, and ice clouds[17, 18]. These values can be modified after integration of measured data in future.

2.2 Lidar Operating System

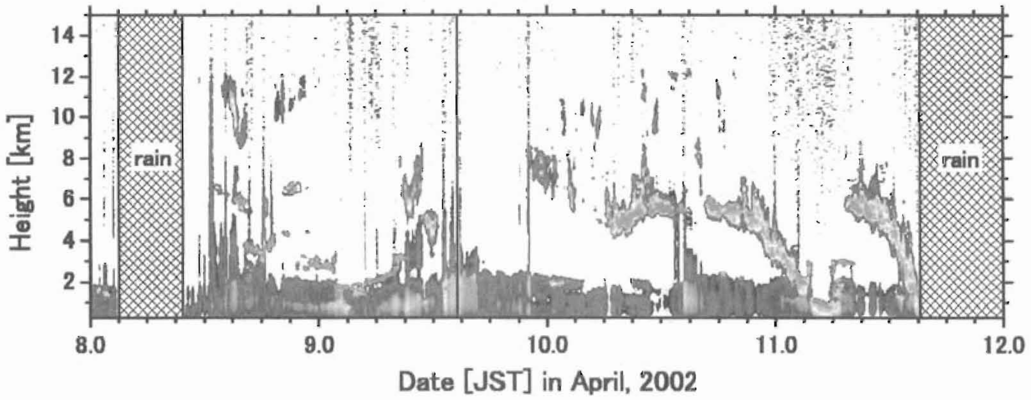
LiOS, lidar operating system, controls MLO-III for continuous aerosol extinction measurements with least human resource. LiOS controls devices of MLO-III automatically according to a predetermined sequence and also monitor the conditions of devices and surrounding condition: temperature, humidity, and rain. Unattended operation is executed over the internet. In detecting some error, LiOS notices the operator on watch who stays away from the site a caution via e-mail. The operator received the error message can solve the trouble on web-browser. These functions of LiOS are shown in Fig. 2.

3 RESULTS AND DISCUSSIONS

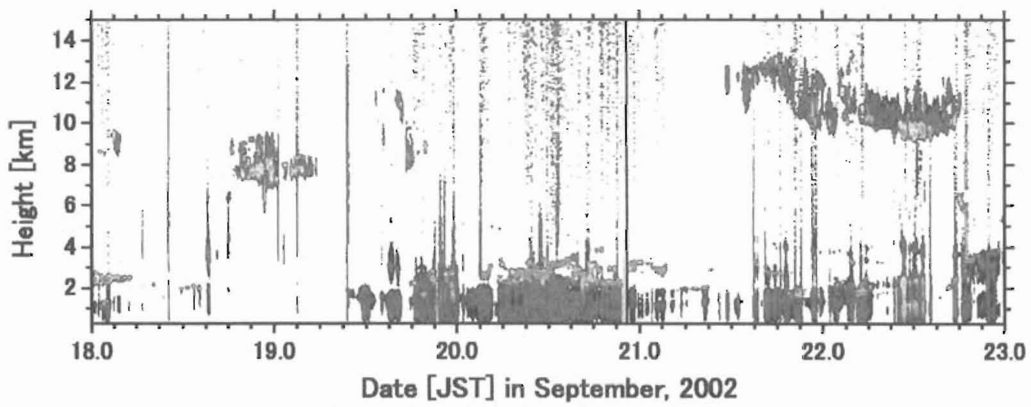
Aerosol extinction coefficients were continuously measured in Okayama University (133.57E, 34.41N) in April, May, September, and November in 2002. The experimental results of aerosol extinction coefficient indicate the height profiles of clouds and dust, see in Fig. 3. In these profiles, clouds appeared at the top of the PBL and in the free troposphere, and dusts sometimes filled the PBL.

Clouds

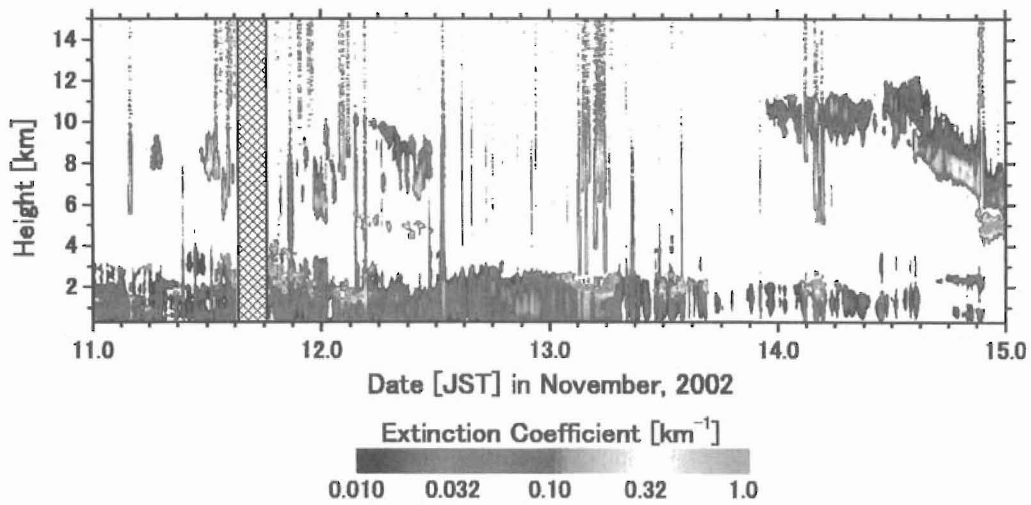
In this paper, clouds are divided into four groups according to their existing range of height. The



(a) April 8 to 11 in 2002.



(b) September 18 to 22 in 2002.



(c) November 11 to 14 in 2002.

Figure 3: The contineous height profiles of aerosol extinctin coefficient from altitude 0.3 to 15 km measured with MLO-III and LiOS in (a)April, (b)September, and (c)November, 2002. During the meshed periods rain interrupted the measurements.

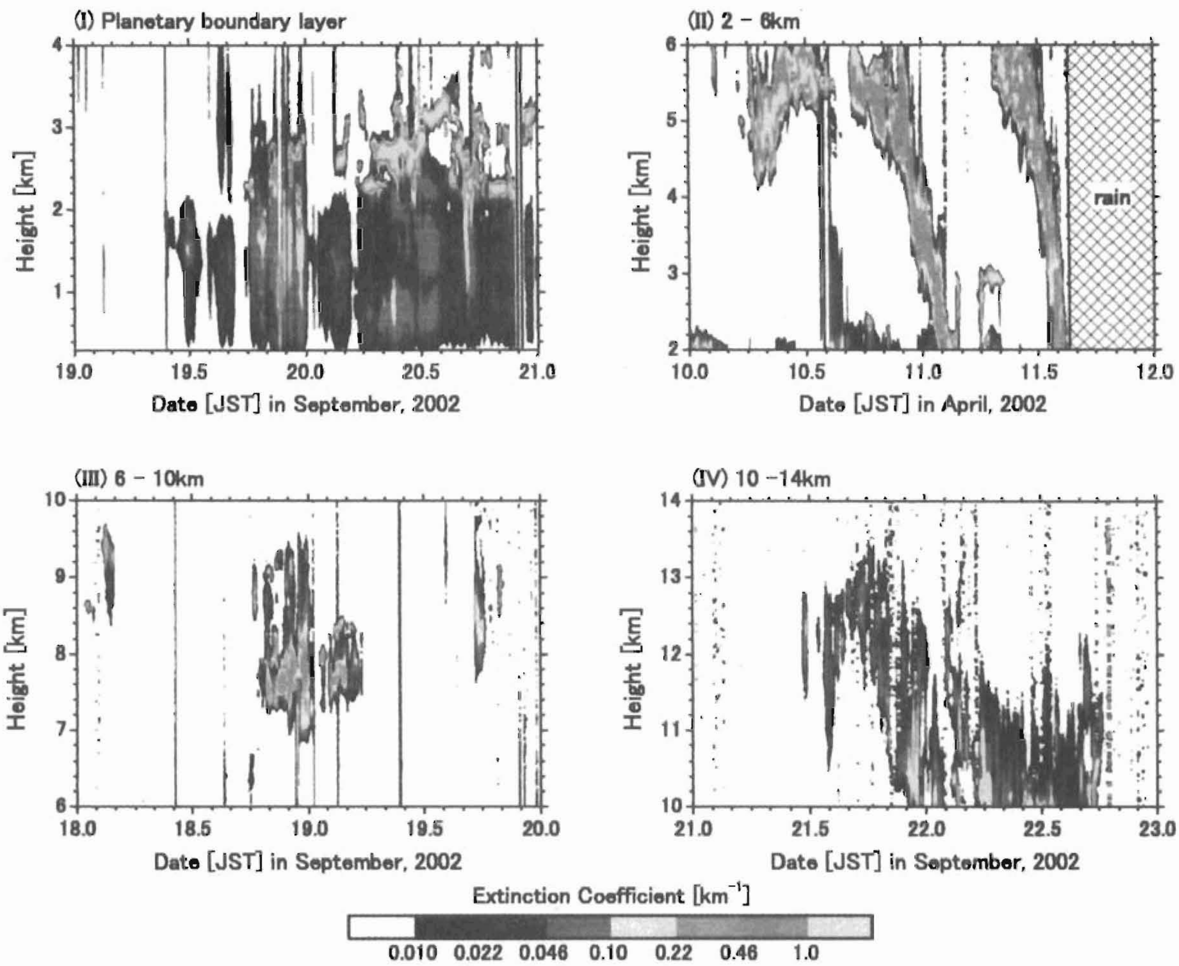


Figure 4: The extinction coefficients of clouds.

groups involve clouds existing (I)in the PBL and the others are in the free troposphere (II)below 6 km, (III)between 6 and 10 km, and (IV) above 10 km in height. The grouping into the PBL and the free troposphere corresponds to the classification of meteorology into micro- and meso-scale respectively. On the other hand, the grouping of (II), (III), and (IV) may not be found in the meteorology where clouds are categorized according to the shape and height into ten types. In lidar measurement, however, clouds cannot be categorized by shape, because lidar see the clouds in one dimension along the laser path, not in three-dimension. Therefore, clouds in the free troposphere are simply grouped according to the height. The boundary heights at 6km and 10km are determined from authors' experience in which clouds of front and depression appeared below 6 km, and the upper clouds existed above that height. Furthermore, the upper clouds between 6 and 10 km show high extinction coefficients compared with those beyond 10 km.

The extinction coefficient of clouds decreases with height. The height profiles of extinction coefficient of the four cloud-groups are shown in Fig. 4. The group (I) indicates more than 1.0km^{-1} of extinction coefficient. The group (II) indicates more than 0.22km^{-1}. The group (III) and (IV) show 0.046-1.0 km^{-1} and 0.022-0.22 km^{-1} in extinction coefficient respectively. These results mean a tendency that the particle density of cloud decreases with height.

Dust

Two types of dust aerosol, one with large depolarization ratio and the other, small, were observed in the PBL as shown in Fig. 5. The large depolarization aerosol could be Asian dust, because research workers participating in the Asian Dust Network (AD-Net)[13] also observed Asian dust even on the ground during the same periods in Japan, Korea, and China. On the other hand, the small depolarization aerosol should be urban dust. Generally, the PBL aerosol involves desert dust, urban dust, and maritime dust[14]. In considering the location of Okayama University which locates in the urban aria of Okayama city, 15 km away from the sea, and more than 2,000 km away from the desert in China, the urban aerosols, not the maritime and desert, should occupy the greater part of the PBL aerosol in Okayama. Furthermore, the urban aerosols indicates smaller depolarization ratio, about 1.5 %, in a previous report[6].

The extinction coefficients of Asian dust are larger than that of urban dust. Mean values of extinction coefficient of Asian dust measured in April 9 and during November 12 and 13, 2002 are 0.10 and 0.12km^{-1}, respectively whereas the mean of urban dust extinction was 0.057km^{-1}. These mean values and the standard deviations are shown in Table 1. Extinction coefficients in Asian dust conditions were reported as 0.03-0.28km^{-1}(Chiba, Japan)[15], 0.05-0.3km^{-1}(Seoul, South Korea), and 0.15-0.6km^{-1}(Hefei, China)[7]. Values found in Okayama, Chiba, and Seoul obtained similar extinction coefficient of Asian dust, which can be convinced to be characteristic to Asian dust. The other, Hefei, showed larger extinction than does the three sites. This difference means the precipitation of Asian dust during its transportation. In the case of urban dust, 0.4-1.3km^{-1} in extinction coefficient, about 10 times as large as our results in Table 1, was reported as a result of lidar measurement in Tokyo[6]. This difference in urban dust may relate to the difference in size of the both cities. In Okayama where is a twentieth less populated than Tokyo, less exhaustion of polluted air should lead the small extinction coefficient even in urban dust condition.

Table 1: The means and standard deviations of extinction coefficient and depolarization ratio.

	σ [km^{-1}]		δ [%]	
	mean	SD	mean	SD
(a)Asian dust	0.12	0.057	28.6	7.3
(b)Asian dust	0.10	0.039	18.7	4.1
(c)Urban dust	0.057	0.028	1.9	2.3

The extinction coefficients of Asian dust are larger than that of urban dust. The mean values of extinction coefficient of Asian dust measured in April 9 and during November 12 and 13, 2002 are 0.10 and 0.12 km^{-1}, respectively: the mean of urban dust extinction is 0.057km^{-1}. These mean values and the standard deviations are shown in Table 1. In previous papers, extinction coefficients in Asian dust conditions were reported as 0.03-0.28km^{-1}(Chiba, Japan)[15], 0.05-0.3km^{-1}(Seoul, South Korea), and 0.15-0.6km^{-1}(Hefei, China)[7]. As com-

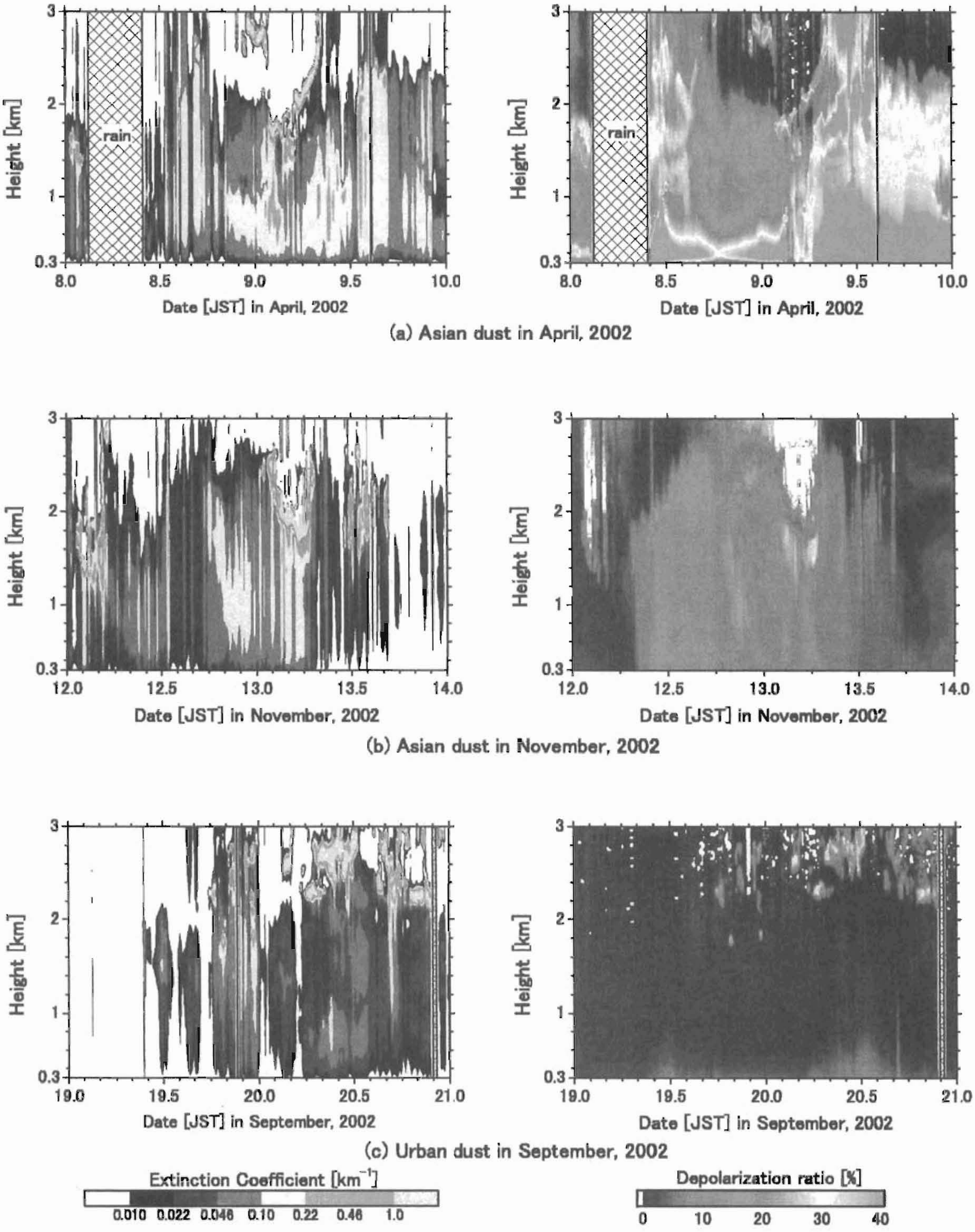


Figure 5: The extinction coefficients (left) and depolarization ratios (right) in the dust conditions.

pared between these four sites, Okayama, Chiba, and Seoul obtained almost same extinction coefficient of Asian dust. The other, Hefei, observed larger extinction than does the three sites. This difference means the precipitation of Asian dust during its transportation. In the case of urban dust, 0.4-1.3 km^{-1} in extinction coefficient, about ten times as large as our results in Table 1, was reported as a result of lidar measurement in Tokyo[6]. This difference in urban dust may relate to the difference in size of the both cities. In Okayama where is a twentieth the population of Tokyo, a little exhaustion of polluted air should lead the small extinction coefficient in urban dust condition.

4 CONCLUSIONS

The continuous measurements of tropospheric aerosol with the polarized Mie-scattering lidar presented the extinction coefficients of clouds and dust aerosol. The extinction coefficients of clouds are found to be greater than 1.0 km^{-1} in PBL and below 6 km in height, 0.17 - 1.0 km^{-1} between 6 and 10 km, and 0.091 - 0.3 km^{-1} beyond 10 km. These results show that cloud extinction coefficients decrease with height in accordance with the decrease of the cloud density. In the dust events, Asian dust indicates large depolarization ratio in PBL which is contrasting to the less depolarization ratio of urban dust there. Extinction coefficients under dust event were 0.10 and 0.20 km^{-1} in the Asian dust periods, and 0.057 km^{-1} in the urban dust period. For global Asian dust, results in Okayama are similar to those in other sites in Japan and South Korea. For local urban dust in Okayama showed, however, extinction coefficient of one tenth as small as that in Tokyo.

A procedure to find proper zc, the altitude to apply the boundary condition, is shown here. It's, however, necessary to examine and add other aspects so that it may give more reliable results and is now still open.

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