Optical Characteristics of Forest-Fire Smoke Observed with Two-Wavelength Mie-Scattering Lidars and a High-Spectral-Resolution Lidar over Japan

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Abstract

Smoke plumes originating from a forest fire in northern Mongolia were observed with a two-wavelength (1064 nm, 532 nm) polarization (532 nm) lidar in Nagasaki at altitudes of 12 to 14 km and 3 to 10 km on June 10, 2007. Smoke from the same region was also observed in Tsukuba with a 532 nm high-spectral-resolution lidar (HSRL) at altitudes of 15 to 15.5 km on June 12, 2007. A two-wavelength data analysis method was applied to the Nagasaki data, and the extinction-to-backscatter ratio (the lidar ratio) at 532 nm was estimated to be 65 ± 5 sr (50 ± 5 sr) for the smoke at 12 to 14 km (3.5 to 4.5 km) altitudes. The particle depolarization ratio (PDR) was 0.14 ± 0.03 (0.12 ± 0.03), and the backscatter-related Angstrom exponent (BAE) between 532 nm and 1064 nm was 1.1 ± 0.2 (0.9 ± 0.1) for the high (low) altitude smoke. The optical thickness of the high (low) altitude plume was approximately 1.0 (0.03). The lidar ratio of the smoke in Tsukuba measured with the HSRL at 15 to 15.5 km was 75 ± 5 sr, and the PDR was 0.15 ± 0.04. The optical thickness was 0.03. The lidar ratio was comparable to those reported previously for forest-fire smoke in the lower troposphere. However, the PDR in the present case was two times higher, and the BAE was slightly lower. A possible explanation of the results involves mixing with solid particles such as those of ash and/or mineral dust in the strong convection found with pyrocumulonimbus. A discussion on lidar methods for characterizing smoke aerosols is also provided.

1. Introduction

In the spring, large forest fires often occur in East Siberia and northern Mongolia. Forest fires, along with dust storms and volcanic eruptions, are important sources of aerosols that can be transported over a long range, affecting the radiative properties of the atmosphere (Fiebig et al. 2002). It is consequently important to understand the transport and the optical characteristics of forest-fire smoke.

We observed an optically thick aerosol plume in the upper troposphere on June 10, 2007, with a two-wavelength (1064 nm, 532 nm) polarization (532 nm) lidar in Nagasaki (32.78°N, 129.86°E; altitude 17 m) that is one of the continuously operated lidars in the NIES Lidar Network (Sugimoto et al. 2008). The aerosol plume was situated at altitudes of 12 to 14 km and it had a high depolarization ratio. We often observe dust layers in the upper troposphere, but the backscatter coefficient of the above-mentioned plume was unusually high (more than ten times) compared with the upper dust layers that are usually observed. Also, the temporal variation was unusually rapid. The same aerosol plume was also observed with satellite sensors MODIS and OMI, and it was reported that the plume was forest-fire smoke lifted by pyrocumulonimbus (Fromm et al. 2007) (see Supplement 1). A smoke plume from the same region was also observed at NIES in Tsukuba (36.05°N, 140.12°E; 30 m) with a high-spectral-resolution lidar (HSRL) at altitudes near the tropopause. In this paper, we report the optical characteristics of smoke

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3. Optical characteristics of forest fire smoke observed with the lidars

Since the observed plume layer was isolated in the profile, we applied the two-wavelength method (Sasano and Browell 1989) to the lidar data in Nagasaki. In this method, we search for a set of optimum lidar ratios at 1064 nm and 532 nm so that the resulting backscattering coefficient profiles are similar at the two wavelengths. The assumption used is that of homogeneity in the optical characteristics of the aerosols in the layer. We searched for optimum values of $S_1$ in the range of 30 to 90 sr for both 1064 nm and 532 nm.

Figure 3 presents example plots of the backscattering coefficients and of the PDR, BAE, and Angstrom exponent (AE) with assumed $S_1$ values. Figure 3a is for the high-altitude plume, and Fig. 3b is for the low-altitude plume. We applied forward (backward) integration to the high (low) altitude plume with a boundary condition at 6 km. We searched for optimum $S_1$ values at 532 nm and 1064 nm such that the backscattering coefficient profiles at the two wavelengths are similar (i.e., AE or BAE is constant in the layer). As the result of the search, $S_1$ at 532 nm was determined to be 65 ± 5 sr (50 ± 5 sr) for the smoke at 12 to 14 km (3.5 to 4.5 km) altitudes. The corresponding $S_1$ at 1064 nm was 60 ± 20 sr (50 ± 20 sr). The error in $S_1$ at 1064 nm was large because the extinction at 1064 nm was small and the method was not sensitive. The PDR at 532 nm was 0.14 ± 0.03 (0.12 ± 0.03), and the BAE was 1.1 ± 0.2 (0.9 ± 0.1) for the high-altitude (low-altitude) plume. The optical thickness of the plume was approximately 1.0 (0.03).

Figure 4 presents the results obtained with the HSRL in Tsukuba (Tatarov et al. 2006). The Mie-to-Rayleigh scattering ratio, the total and particle depolarization ratios, and $S_1$ are plotted in the figure. $S_1$ for the smoke plume at 15 to 15.5 km was 60 ± 20 sr (50 ± 20 sr). The error in $S_1$ at 1064 nm was large because the extinction at 1064 nm was small and the method was not sensitive. The PDR at 532 nm was 0.14 ± 0.03 (0.12 ± 0.03), and the BAE was 1.1 ± 0.2 (0.9 ± 0.1) for the high-altitude (low-altitude) plume. The optical thickness of the plume was approximately 1.0 (0.03).

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4. Discussion

Smoke plumes originating from a forest fire in northern Mongolia were observed in the upper troposphere in Nagasaki and Tsukuba on 10 to 12 June 2007. $S_1$ at 532 nm for the plume in Nagasaki was $65 \pm 5$ sr, and it was $75 \pm 5$ sr in Tsukuba. The PDR was $0.14 \pm 0.03$ in Nagasaki and $0.15 \pm 0.04$ in Tsukuba. The BAE was $1.1 \pm 0.2$ in Nagasaki. It should be noted that the optical thickness of the plume was extremely high ($1.0$) in Nagasaki, and it is considered that fresh smoke was captured in the upper troposphere.

Smoke originating in the same region was also observed in the lower troposphere at altitudes of 3.5 to 4.5 km in Nagasaki. $S_1$ was 50 sr, PDR was $0.12 \pm 0.03$, and BAE was $0.9 \pm 0.1$. Compared with the smoke in the upper troposphere, $S_1$ was smaller, and PDR and BAE were also slightly smaller. This suggests that the particle size was larger and the non-sphericity was lower.

The optical characteristics of forest-fire smoke in the troposphere were reported in previous works (Wandinger et al. 2002; Fiebig et al. 2002; Mattis et al. 2003; Murayama et al. 2004; Amiridis et al. 2009). Murayama et al. (2004) reported an $S_1$ of 65 sr at 532 nm, and a PDR of 0.06 for a Siberian smoke plume at altitudes of 3.2 to 3.8 km. The BAE between 532 nm and 1064 nm read from Fig. 4 of Murayama et al. (2004) is ~1.6. Wandinger et al. and Fiebig et al. reported an $S_1$ of 80sr, a PDR of 0.06–0.11 and a BAE of 1.1 for Canadian smoke observed in Germany at altitudes of 3.5–4 km. The lidar ratio observed in the present study is comparable to that previously reported. The BAE in the present study was also comparable or slightly smaller, but the PDR was higher in the present study.

Non-sphericity of the smoke particles was discussed, for example, in Martins et al. (1998). In the case of long-range transported matured smoke, the optical characteristics are determined mostly by the shape of the carbonaceous aerosols. In the present case, the magnitude of the convection due to pyrocumulonimbus was supposed to be extremely large, and consequently solid particles such as those of ash or mineral dust might be uplifted in the plume. The observed high PDR is consistent with such an explanation. (The PDR for pure mineral dust is typically 0.35, Shimizu et al. 2004).

It is known from previous studies using multi-wavelength Raman lidars (Mattis et al. 2003; Murayama et al. 2004) that the wavelength dependence of $S_1$ is different for smoke and mineral dust. $S_1$ at 355 nm is smaller than $S_1$ at 532 nm for smoke, and $S_1$ is larger at 355 nm for dust. The $S_1$ value at 355 nm would provide information on the mixing of smoke with solid particles, but it was not observed in the present study. Murayama et al. (2004) applied the inversion method to the multi-wavelength Raman lidar data and derived a single scattering albedo of 0.95 and an effective radius of 0.22 μm for a transported matured Siberian forest-fire plume. They also observed water vapor and reported a high relative humidity of 70% at the smoke layer.

In the present case, radiosonde data in Jeju 0000 UT of June 10, 2007, indicated that the relative humidity was less than 15% at both altitude ranges of the smoke plumes. The lower relative humidity may partly explain the higher PDR in the present case, but it may not explain the lower BAE. Mixing with solid particles
can therefore better explain the present results. Another possible explanation of the high PDR is existence of ice particles. Fromm et al. (2008) discussed formation of ice in pyrocumulonimbus and sublimation of ice in smoke plume. The temperature at the upper (lower) smoke layer in the present case was −54 to −62°C (7 to 1°C) in Jeju. Existence of ice may explain the high PDR in the upper smoke layer, but it doesn’t explain the high PDR in the lower smoke layer.

The high PDR of the smoke layer may raise a problem in aerosol-type classification methods using the depolarization ratio for detecting mineral dust. In a simple method using a single-wavelength backscattering signal and the depolarization ratio (Sugimoto et al. 2002; Shimizu et al. 2004), smoke is classified as an external mixture of dust and spherical aerosols. The situation is similar with the method for estimating the contributions of aerosol components (water-soluble aerosols, mineral dust, and sea salt) from the backscattering coefficients at 532 nm and 1064 nm and the depolarization ratio at 532 nm (Nishizawa et al. 2010). A high-PDR smoke is described as an external mixture of dust and spherical water-soluble aerosols. In a method that includes an independent extinction coefficient measurement at 532 nm (Nishizawa et al. 2008), it is described as an external mixture of black carbon, water-soluble aerosols, and dust. This would probably better describe the observed optical characteristics, though the assumed aerosol components may not necessarily represent the actual aerosol components. This kind of data-analysis method for estimating the concentration of aerosol components will be useful for comparing lidar observations with aerosol chemical-transport models where the same aerosol models are used, because the descriptions of the optical characteristics are consistent. However, we need to take care in interpretation of the results. It would be essential to understand the physical and chemical characteristics of externally and/or internally mixed aerosols in smoke in future studies.

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Supplements

1. The MODIS RGB composite image for 0501 UT on June 10, 2007, taken from the Institute of Industrial Science, University of Tokyo www page (http://webmodis.iis.u-tokyo.ac.jp) is given in Supplement 1.
2. Time-height indicators of the lidar attenuated backscattering coefficient at 532 nm observed in Fukue and Nagasaki are given in Supplement 2.
3. A biomass burning emission map for 0600 UT on June 8, 2007 taken from the FLAMBE’ www page is given in Supplement 3.
4. The CALIPSO/CALIOP image and a HYSPLIT trajectory are given in Supplement 4.

References


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