A scanning Raman lidar for observing the spatio-temporal distribution of water vapor

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ARTICLE INFO

ABSTRACT

We have constructed a scanning Raman lidar to observe the cross-sectional distribution of the water vapor mixing ratio and aerosols near the Earth's surface, which are difficult to observe when a conventional Raman lidar system is used. The Raman lidar is designed for a nighttime operating system by employing a ultra-violet (UV) laser source and can measure the water vapor mixing ratio at an altitude up to 7 km using vertically pointing observations. The scanning mirror system consists of reflective flat mirrors and a rotational stage. By using a program-controlled rotational stage, a vertical scan can be operated with a speed of 1.5°/s. The beam was pointed at 33 angles over range of 0–48° for the elevation angle with a constant step width of 1.5°. The range-height cross sections of the water vapor and aerosol within a 400 m range can be obtained for 25 min. The lidar signals at each direction were individually smoothed with the moving average to spread proportionally with the distance from the laser-emitting point. The averaged range at a distance of 200 m (400 m) from the lidar was 30.0 m (67.5 m) along the lidar signal in a specific direction.

The experimental observations using the scanning lidar were conducted at night in the Shigaraki MU radar observatory located on a plateau with undulating topography and surrounded by forests. The root mean square error (RMSE) between the temporal variations of the water vapor mixing ratio by the scanning Raman lidar and by an in-situ weather sensor equipped with a tethered balloon was 0.17 g/kg at an altitude of 100 m. In cross-sectional measurements taken at altitudes and horizontal distances up to 400 m from the observatory, we found that the water vapor mixing ratio above and within the surface layer varied vertically and horizontally. The spatio-temporal variability of water vapor near the surface seemed to be sensitive to topographic variations as well as the wind field and the temperature gradient over the site. From the wide-range cross-sectional observations of the water vapor mixing ratio and the backscatter ratio of aerosols within a 2000 m range, we can detect small-scale water vapor structures on a horizontal scale of several hundred meters in the atmospheric boundary layer.

1. Introduction

The atmospheric boundary layer (ABL) present in the lowest part of the Earth's atmosphere plays an important role in the energy cycle between the Earth's surface and the atmosphere. Strong turbulence in the ABL can perturb flow, temperature, and moisture which characterizes the regional atmosphere (Beniston and Schmetz, 1995). Most of the energy driven by heat from solar radiation is absorbed by the Earth's surface and is subsequently radiated back into the atmosphere.

Groundcover, such as forests, grassland, urban districts, and oceans, varies greatly over the surface. The spatio-temporal distribution of minor atmospheric constituents within the ABL also varies widely because the state of ABL is directly affected by groundcover type (Meixner et al., 1999).

Water vapor, which is one of the most variable atmospheric constituents, plays an important role in the atmospheric processes, such as the atmospheric energy budget, the global water cycle, and the atmospheric chemistry. The distribution of water vapor is associated

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with that of clouds and rainfall through the vertical stability of the atmosphere caused by a large amount of latent heat related to the phase changes of water (Trenberth et al., 2003). Therefore, water vapor is a key parameter for understanding of the localized extreme weather events associated with severe weather disasters such as torrential rain and floods. Meanwhile, the interaction of atmospheric aerosol particles with water vapor is related to the cloud condensation nuclei activity, which is a fundamental mechanism for climate change (e.g., Rood et al., 1987; Randriamiarisoa et al., 2006). The hygroscopic properties of aerosols remain one of the largest sources of uncertainty in climate models (e.g., IPCC, 2013). Significant hygroscopic growth of particles is observed under the high relative humidity (RH) conditions. Katata et al. (2014) investigated the impact of hygroscopic growth on dry deposition onto forest canopies using a numerical simulation and suggested that the deposition velocity of wet particles was much as five times greater than that under dry conditions when RH exceeded 95%. The simultaneous observation of the water vapor and the aerosol distribution is important in order to understand of the dry deposition process of particles under high RH conditions, including during the night, as well as the variability in their properties related to the active convection during the daytime in the ABL.

Raman lidar, which uses Raman scattering effects of atmospheric molecules, can be used to observe various atmospheric parameters by detecting the backscattered light from the atmospheric molecules and particles using a telescope. Raman lidar applications are based on measurements of weak inelastic scattering of light by molecules with frequency shift characteristics as a function of the distance (range) from the lidar. The first attempt to observe water vapor using Raman scattering was made by Melfi et al. (1969) and Cooney (1970). The usefulness of Raman lidar has since been demonstrated in numerous studies (Strauch et al., 1972; Pourny et al., 1979). As reported by Whiteman et al. (1992), the lidar technique is a well-established tool for measuring the water vapor mixing ratio in the atmosphere. Ansmann et al. (1992) demonstrated simultaneous measurements of the water vapor mixing ratio and aerosol optical parameters. Navas-Guzman et al. (2014) showed the capability of obtaining accurate RH profiles from the combination of Raman lidar and microwave radiometer measurements.

An ultra-violet (UV) Raman lidar using solar-blind wavelengths was proposed to conduct daytime observations with Raman lidar originating under strong sky radiance (Renaut et al., 1980). Numerous studies have subsequently focused on daytime water vapor observations using UV Raman lidar (Cooney et al., 1985; Renaut et al., 1988). Recently, the improved performance of the UV optical components has led to the development of enhanced UV Raman lidar systems, and the system is now as highly sensitive and cost-effective as the visible system. With regards to eye safety, the UV laser has an advantage over the wavelengths in the visible range because the maximum permitted exposure in the UV region is larger than in the visible region (International Electrotechnical Commission, 2007).

Highly eye-safe UV Raman lidar systems are expected to be able to measure the cross-sectional structure of water vapor profiles. An onboard-type scanning Raman lidar for water vapor observations within the ABL has also been developed (Eichinger et al., 1999). Behrendt et al. (2009) demonstrated 3-dimensional (3-D) observations of atmospheric humidity with a very high accuracy and the high spatio-temporal resolution using a scanning water vapor lidar based on the differential absorption lidar (DIAL) techniques. Späth et al. (2016) showed a 3-D water vapor field in the atmospheric boundary layer observed with a scanning DIAL system by applying range–height indicator scans, conical scans, and low elevation scans. For the lidar scanner, Spuler and Mayor (2005) developed a two-mirror beam-steering unit for the Raman-Shifted Eye-Safe Aerosol Lidar (REAL). Radlach et al. (2008) employed this scanner type and demonstrated the high-resolution measurements of the temperature fields in the atmospheric boundary layer and the lower free troposphere using a scanning

eye-safe lidar based on the rotational Raman technique at 355 nm.

Several Raman lidar systems have been developed for measuring the water vapor content at the Research Institute for Sustainable Humanosphere (RISH) in Kyoto University. Rayleigh Raman lidar, which was installed at the Shigaraki Middle and Upper Atmosphere (MU) Radar Observatory, carried out high-sensitivity water vapor measurements at a height of 1.5–10 km using a high-power visible laser and a large telescope (Behrendt et al., 2002; Luce et al., 2010). Other systems include a portable Raman lidar, which can be transported using a one-box-type vehicle and is used to study water vapor distribution in the lower troposphere in regions including volcanoes and forests (Nakamura et al., 2008). These Raman lidar techniques employ a visible laser.

For a better understanding of the spatio-temporal water-vapor distribution, we have developed a UV scanning Raman lidar system by applying the scanning mirror system to a lidar for observing the vertical direction. By pointing a laser beam at different angles in various scanning directions with respect to the ground surface, a ground-based lidar system can provide a spatio-temporal distribution of water vapor and aerosols in the atmosphere. The scanning Raman lidar technique provides a unique opportunity for obtaining high-resolution spatial information on water vapor and aerosols with the added advantage of high temporal resolution.

2. Methodology

2.1. Water vapor profiles from Raman lidar measurements

The water vapor Raman lidar technique uses the ratio of rotational–vibrational Raman scattering intensities from water vapor to nitrogen molecules. The backscattered laser power at the Raman-shifted wavelengths (λ_x) for the exciting laser wavelength (λ_L) from range R is expressed as

$$P_{x, \lambda_L, \lambda_x}(R) = P_{0, \lambda_L} \frac{K_x O_x(R)}{R^2} n_x(R) \frac{d\sigma_x(\pi)}{d\Omega} \times$$
$$\exp\left[- \int_0^R (\alpha_{A, \lambda_L}(R') + \alpha_{A, \lambda_x}(R') + \alpha_{M, \lambda_L}(R') + \alpha_{M, \lambda_x}(R'))\right.$$
$$\left. dR'\right]. \tag{1}$$

Here, the index x indicates the species of nitrogen (N_2) or water vapor (H_2O), P_0 denotes the laser-emitted power at wavelength λ_L, K_x is the system constant, $O_x(R)$ is the overlap function, $n_x(R)$ is the number density, $d\sigma_x(\pi)/d\Omega$ is the Raman backscatter cross-section, and α_A and α_M are the extinction coefficients, where subscripts A and M refer to the aerosol and molecules, respectively. The molecular absorption, such as that of ozone in the troposphere, is negligible at the Stokes Raman wavelengths of nitrogen and water vapor at the exciting laser wavelengths of 355 nm and 532 nm (Whiteman, 2003a).

The water-vapor mixing ratio is the ratio of the mass of water vapor to the mass of dry air related to the nitrogen concentration, which is constant in the troposphere. By forming the signal ratio $P_{\lambda_{H_2O}}(R)/P_{\lambda_{N_2}}(R)$ and assuming identical overlap for each signal (i.e., $O_{\lambda_{N_2}}(R)/O_{\lambda_{H_2O}}(R) = 1$), we have obtained the mixing ratio of the water vapor relative to dry air:

$$m(R) = K_m \frac{P_{\lambda_{H_2O}}(R)}{P_{\lambda_{N_2}}(R)} \times \frac{\exp\left[- \int_0^R (\alpha_{A, \lambda_{N_2}}(R') + \alpha_{M, \lambda_{N_2}}(R'))dR'\right]}{\exp\left[- \int_0^R (\alpha_{A, \lambda_{H_2O}}(R') + \alpha_{M, \lambda_{H_2O}}(R'))dR'\right]}, \tag{2}$$

where K_m is the calibration constant depending on the percentage of nitrogen in dry air as well as the molecular masses, Raman backscatter cross sections, and system constants of both nitrogen and water vapor. The K_m is commonly evaluated by comparing the results of an