Observations of Water Vapor Mixing Ratio Profile and Flux in the Tibetan Plateau Based on the Lidar Technique

Songhua Wu (a), Guangyao Dai (a), Xiaoquan Song (a), Bingyi Liu (a) and Liping Liu (b)
(a) Ocean Remote Sensing Institute, Ocean University of China
Qingdao, 266100, China
(b) Laboratory of Severe Weather, Chinese Academy of Meteorological Science
Beijing, 100081, China
wash@ouc.edu.cn

Abstract: As a part of the third Tibetan Plateau Experiment of Atmospheric Sciences (TIPEX III) in China, a Raman water vapor, cloud and aerosol lidar and a coherent wind lidar were operated in Naqu (31.48°N, 92.06°E) with a mean elevation of more than 4500 m above MSL in summer of 2014. During the field campaign, the water vapor mixing ratio profiles were obtained and validated by radiosonde observations. The mean water vapor mixing ratio in Naqu in July and August was about 9.4 g·kg\(^{-1}\) and the values vary from 6.0 to 11.7 g·kg\(^{-1}\) near the ground according to the lidar measurements. Furthermore, using concurrent measurements of vertical wind speed profiles from the coherent wind lidar, we calculated the vertical flux of water vapor that indicates the water vapor transport through updraft and downdraft. The fluxes were for a case at night with large-scale non-turbulent upward transport of moisture. It is the first application, to our knowledge, to operate continuously atmospheric observations by utilizing multi-disciplinary lidars at the altitude higher than 4,000 meters, which is significant for research on the hydrologic cycle in the atmospheric boundary layer and lower troposphere in the Tibetan Plateau.

Keywords: Raman lidar, Coherent Doppler lidar, water vapor mixing ratio and flux, Tibetan Plateau.

1. Introduction

Water vapor has a significant impact on the determination of weather and climate due to the fundamental role in the radiative energy transfer, hydrological cycle, and atmospheric chemistry processes. It influences the radiative budget of the planet both directly and through coupling with clouds [1]. Moreover, because of its strong absorption and emission bands, especially in the infrared, water vapor is the most significant greenhouse gas. Aiming at the detection of water vapor, the most commonly used method is radiosonde. However, the humidity sensors in radiosonde detect changes in resistance or dielectric constant resulting from absorption or adsorption of water. Lidar (LIght Detect And Ranging) has the advantage of high temporal and spatial resolution, and high-frequency observations. Two lidar techniques have been applied to the detection of water vapor profile: the Differential Absorption Lidar (DIAL) and the Raman lidar technique. In this paper, the lidar system applies Raman technique. The process of Raman scattering is characterized by a wavelength shift of the scattered radiation in respect to the exciting wavelength. The shift is uniquely associated with the internal transitions between the rotational-vibrational energy levels of the molecules [2], and is used for identification of the scattering molecules.

The Tibetan Plateau is a vast elevated plateau in the middle of the Eurasian Continent with averaged elevation above 4500 m MSL, and has important roles in global and regional climate system [3]. The Tibetan Plateau has great impact on the water vapor budget of area around. The water vapor transportation based on the plateau-monsoon interaction affects the drought and flood of Asia and even the whole north...
hemisphere [4]. Even though the altitude is high, a relatively wet condition is maintained over the Tibetan Plateau and the hydrological cycle is active during the monsoon season [3].

This paper introduces the lidar techniques to provide vertical profiles of water vapor mixing ratio and wind speed with the advantages of high spatial resolution and updating rate. The observations of lidars during the TIPEX III are described. The methodology of the water vapor mixing ratio, wind field and vertical water vapor flux are introduced in section 2 and the results and case studies are provided in section 3. More technique details and observation data can be found in a full length research paper [5].

2. Lidar technology and methodology

The lidar observations in summer of 2014 as a part of the TIPEX III were performed in Naqu (31.48°N, 92.06°E, 4508 m MSL), located in the north central part of the Tibetan Plateau. During this campaign, the vertical profiles of water vapor mixing ratio were measured by a WAter vapor, Cloud and Aerosol Lidar (WACAL) based on the Raman lidar technique and the horizontal and vertical wind profiles were detected by a pulsed Coherent Doppler lidar (CDL). Moreover, the temperature, pressure and relative humidity were detected by radiosonde twice a day (00:00 and 12:00 UTC). Combining the data products of the three systems, the water vapor flux can be calculated.

The principle of WACAL is introduced briefly in this section and the detailed design is described in a separated paper [6]. The system is based on the second and third harmonic frequency of a compact, pulsed Nd:YAG laser, which emits pulses of 400, 120 and 710 mJ output energy at 355, 532 and 1064 nm, respectively, at a 30 Hz repetition rate. The optical receiver consists of four 308 mm diameter Newtonian telescopes. Five Hamamatsu 10721P-110 photomultipliers and one Hamamatsu G8931-20 APD are used to detect the lidar signals at wavelengths of 355, 387, 407, 532 (parallel), 532 (perpendicular) and 1064 nm. The acquisition system bases on a six-channel LICEL (12bit AD, 40MHz) and the photon counting (250MHz) modes. The spatial and temporal resolutions of the signal are 3.75 m and 30s, respectively. Several smoothing procedures are applied to the raw data when retrieving the optical properties.

According to lidar equation, the backscatter signal of $N_2$ and $H_2O$ are obtained as $P(z,\lambda_{N_2})$ and $P(z,\lambda_{H_2O})$. The water vapor mixing ratio can be calculated by Eq. (1)

$$w(z) = C \frac{P(z,\lambda_{H_2O})}{P(z,\lambda_{N_2})} \exp\left(-\int_{z'}^z [\alpha(z',\lambda_{N_2}) - \alpha(z',\lambda_{H_2O})]dz'\right),$$

where $C$ is the calibration constant and can be obtained by the validation of lidar data and radiosonde data, the $\alpha(z',\lambda_{N_2})$ and $\alpha(z',\lambda_{H_2O})$ are calculated by Raman method [7]. The calibration constant is retrieved using linear regression to a vertical water vapor mixing ratio profile obtained by a reference radiosonde.

In addition to the water vapor content measurements, the wind profiles were measured by a compact CDL to calculate the water vapor flux. The CDL takes advantage of the fact that the frequency of the backscatter signal is shifted compared to the local-oscillator light because of the Doppler effect which occurs from backscattering of aerosols. The details of the CDL system is described in a separated paper [8]. The Doppler shift in the frequency of the backscattered signal is analyzed to calculate the line-of-sight (LOS) velocity component of the air motion. The Doppler shift $f_D$ can be obtained as follows:

$$f_D = 2|\bar{V}_{LOS}|/\lambda,$$

where $\bar{V}_{LOS}$ is the line-of-sight (LOS) velocity, $\lambda$ is the laser wavelength, 1550 nm in this lidar.

Once the LOS velocities in four directions $\bar{V}_{LOS,E}$, $\bar{V}_{LOS,W}$, $\bar{V}_{LOS,S}$ and $\bar{V}_{LOS,N}$ are measured, the vertical wind speed can be computed by Eq. (3)
\[ V_{\text{ver}} = \left( V_{\text{LOS,E}} + V_{\text{LOS,W}} + V_{\text{LOS,S}} + V_{\text{LOS,N}} \right) / 4 \sin \theta, \]

where \( \theta \) is the elevation angle.

With the concurrent observations of the profiles of water mixing ratio and vertical velocity, the vertical water vapor flux \( \text{Flux}_{\text{WV,ver}} \) can be calculated by Eq. (4),

\[ \text{Flux}_{\text{WV,ver}}(T) = W_{\text{Lidar}}^{\text{Cal}} \left| V_{\text{ver}} \right|, \]

where \( W_{\text{Lidar}}^{\text{Cal}} \) and \( V_{\text{ver}} \) are the time serials of the mean vertical air movements and moisture transports in the water vapor mixing ratio and the vertical wind speed. The bar represents the temporal average over the time interval \( T \).

### 3. Observation results and discussion

The nighttime water vapor mixing ratio measured by the WACAL is provided in Figure 1. The trend of \( W_{\text{Lidar}}^{\text{Cal}} \) is shown and two dry or low water vapor content time periods are found. Figure 2 (b) provides the profiles of mean water vapor mixing ratio and fluctuation range of water vapor mixing ratio from 10 July to 16 August 2014 measured by WACAL.

One case sturdy about vertical wind velocity and vertical water vapor flux on 15 August 2014 is presented in Figure 2 and Figure 3. The fluxes are for a case at night with large-scale non-turbulent upward transport of moisture. The time serials of water vapor mixing ratio shown in Figure 2 (b) indicates that the water vapor content inside clouds located at the height of 0.82 km to 1.2 km at time period from 21:52 LST to 22:06 LST is \( 5.77 \pm 0.41 \text{ g kg}^{-1} \), higher than that of the ambient atmosphere. In figure 3, the mean vertical air movements and moisture transports are provided. It can be found in Figure 3 (a) that it started to rain at about 22:00 LST. It is also worth to mention that the water vapor transported both by the updraft and downdraft and the flux was about \( 0.78 \pm 1.38 \text{ g kg}^{-1} \text{ m s}^{-1} \) between 21:03 and 22:00 LST before the rain. Meanwhile, in the process of rain, the water vapor inside the clouds kept transporting downwards and the flux is about \(-3.91 \pm 1.74 \text{ g kg}^{-1} \text{ m s}^{-1}\). Note that because of the coverage of raindrops on the optical windows of WACAL, the water vapor mixing ratio measured between 22:05 LST and 22:10 LST were removed by data quality control. Nevertheless, a small-scale water vapor cycling can be recognized, in which the ascending and descending of the water vapor were monitored.
Figure 2 (a). Time serials of combined water vapor mixing ratio measured by WACAL and radiometer; (c). Time serials of vertical velocity profiles.

Figure 3 Time serials of vertical water vapor flux from 21:03 LST to 22:25 LST.

4. References


