Depolarization properties of cirrus clouds from polarization lidar measurements over Hefei in spring

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A new polarization lidar has been developed for detecting depolarization characteristics of aerosol and cirrus over Hefei (31.90°N, 117.16°E), China. The fundamental principle of polarization lidar is briefly introduced. Overall structure and specifications of the polarization lidar, as well as measurement method, are described. The observational results of depolarization ratio for cirrus over Hefei from February to May in 2005 − 2007 are presented and discussed. The exploring temperatures by radiosonde during the spring of 2005 are also presented and analyzed. The results show that the cirrus generally presents in the altitude from 7 to 12 km, and the depolarization ratio varies from 0.2 to 0.5. At the meanwhile, depolarization ratio appears a climbing tendency with the increasing height and the decreasing temperature.

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Cirrus cloud is one of the most commonly occurring cloud types globally. It forms in the upper part of troposphere, due to synoptic scale lifting, or as a result of moisture transport by deep convection. Satellite data show that cirrus clouds cover nearly 30% of the Earth's surface[1−3]. Because they absorb long-wave outgoing radiation from Earth surface and reflect incoming solar radiation, cirrus clouds play an important role in the Earth's radiation budget. Therefore, knowledge of geometrical and optical properties of the cirrus clouds is essential for climate models. Lidar offers an excellent way to obtain high accurate cirrus data (height, shape or optical properties) with high spatial and temporal resolution. So far, a number of authors have reported the lidar processing methods and observational results of the cirrus clouds[4−10]. However, up to now, there still are few data sets of lidar observed cirrus clouds over the East Asia area.

In general, polarization lidar technique detects cloud particles by depolarization properties of their backscattering signals. The depolarization ratios are related to microphysics and ice compositions of cirrus clouds. So, we developed a new polarization lidar for detecting depolarization characteristics of aerosol and cirrus over Hefei (31.90°N, 117.16°E), China. This paper describes statistical characteristics of cirrus from the polarization lidar measurements at Hefei. Structures and depolarization properties of these cirrus are presented. Meteorological data from nearby radiosonde measurements are used to analyze the lidar observed results.

A form of the lidar equation[11] describing the backscattered power P incident upon the receiver as a function or height z is given by

$$P_{\rm rp}(z)=\frac{k_{\rm p}P_{\rm t}}{z^2}\beta_{\rm p}(z)\exp(-2\int_0^z\tau_{\rm p}(z){\rm d}z), \quad (1)$$

$$P_{\rm rs}(z)=\frac{k_{\rm s}P_{\rm t}}{z^2}\beta_{\rm s}(z)\exp(-\int_0^z(\tau_{\rm p}(z)+\tau_{\rm s}(z)){\rm d}z), \quad (2)$$

where $P_{\rm t}$ is the transmitted power, $P_{\rm rp}(z)$ and $P_{\rm rs}(z)$ are the returned powers in parallel and perpendicular directions relative to the outgoing laser beam, $k_{\rm p}$ and $k_{\rm s}$ are system gain factors (constant) in parallel and perpendicular channels, $\beta(z)$ and $\tau(z)$ are the volume backscatter and extinction coefficient of the atmosphere, and subscriptions p and s represent parallel and perpendicular direction, respectively. The depolarization ratio $\delta(z)$ is defined as

$$\delta(z)=\frac{P_{\rm rs}(z)/k_{\rm s}}{P_{\rm rp}(z)/k_{\rm p}}=\frac{\beta_{\rm s}(z)}{\beta_{\rm p}(z)}\exp(\int_0^z(\tau_{\rm p}(z)-\tau_{\rm s}(z)){\rm d}z). \quad (3)$$

Generally, $\tau_{\rm p}(z)=\tau_{\rm s}(z)$[12], if defining $k=k_{\rm p}/k_{\rm s}$, then

$$\delta(z)=\frac{\beta_{\rm s}(z)}{\beta_{\rm p}(z)}=k\frac{P_{\rm rs}(z)}{p_{\rm rp}(z)}, \quad (4)$$

where k is the gain ratio of system gain factors in parallel to perpendicular channels, which can be got by experimental methods. The depolarization ratio is related to the ice-crystal habits that are largely unknown for a specific type of crystal. For spherical particle and pure air, $\delta(z)$ should be nearly 0. However, different shape or phase ice has dissimilar depolarization ratio[13−15].

A polarization lidar has been developed for detecting depolarization characteristic of dust-aerosol and cirrus-cloud since June, 2004. The lidar system is mainly composed of a Nd:YAG laser transmitter, a receiving optics, a signal receiver and a data-acquisition system. The laser used in this system is a flashlamp pumped Nd:YAG laser with polarization purity of 98% and beam divergence of 0.5 mrad. The output energy is 180 mJ at 532 nm. Pulse repetition rate is 10 Hz in this system. The receiver telescope is Schmidt Cassegrain with diameter of 250 mm. The field of view of the receiver is typically 1 mrad. The polarizer is CVIPBS-532-100 and the pass band of interference filter is 0.3 nm. The photomultiplier tubes (PMTs) are Hamamatsu H7680 modules and the amplifier is Philips 777. The data acquisition PC is Pentium IV 2.4 GHz with an analog-to-digital (A/D) card (GAGE 1610). Figure 1 shows the schematic diagram of

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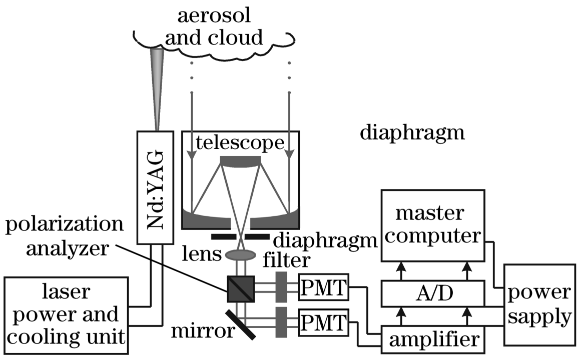

Fig. 1. Schematic diagram of polarization lidar.

the lidar system.

All the performance parameters of the lidar must be tested after being assembled and aligned. The gain ratio k of two polarization channels is most important. In the lidar system, a 1/2 wave plate is fixed between the lens and the polarization analyzer. Choosing a clean and clear day, the polarization directions of the atmosphere backscattering light and the fired laser are adjusted to be identical. By turning the 1/2 wave plate, two sets of returned signals from parallel and perpendicular channels will be received and recorded in each 5000 laser pulses. Then the gain ratio k is just the specific value of two returned signals.

The cirrus clouds were detected whenever we found cirrus clouds by eyes or by using another way, such as Mie lidar's regular measurements of tropospheric aerosol. For each measurement, 5000 laser shots were fired to get two vertical profiles of returned signals in parallel and perpendicular directions. And the specific value of k is given as $k = 1.19$ by foregoing experimental method. So, we can get one profile of depolarization ratio from Eq. (4).

These cirri mostly were thin cirri, including some subvisual or threshold visible cirri. Their optical attenuation is weak, the laser pulse can penetrate through the cirrus completely and the signal transition from the top of the cirrus to the clear air can be detected. Thus these measurements can give depolarization characteristic of some certain cirri but do not cover all kinds of them.

Figures 2(a) and (b) show the profiles of depolarization ratio for cirrus clouds and aerosol over Hefei, China. On May 9, 2005 (Fig. 2(a)), depolarization ratio had two peaks at the height of $7-8.5$ km and $10-10.5$ km. The peak values are 0.33 and 0.3 respectively, which shows that the two layers of cirrus clouds contain ice-crystal and water-drop. On April 12, 2007 (Fig. 2(b)) there was one peak at 11.5 km with the peak value of 0.4 including lots of ice-crystal[14,15]. And it occurred two aerosol layers under 8 km with the depolarization ratio larger than 0.1. One maybe contains a little of ice-crystal at about 7 km with peak value of 0.17, the other caused by dust aerosol has the maximal value of 0.21 at 3 km. The depolarization ratio of aerosol is about 0.05 at the other heights in Fig. 2, which shows that depolarization properties of pure atmosphere aerosol are not obvious.

Figure 3(a) shows the observation results of depolarization ratio (upper line) for cirrus clouds and corresponding height (lower line) of them from February to

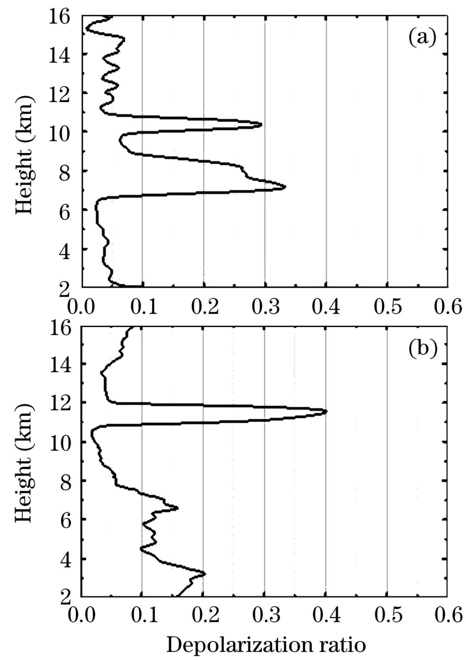

Fig. 2. Profiles of depolarization ratio for cirrus clouds and aerosol over Hefei.

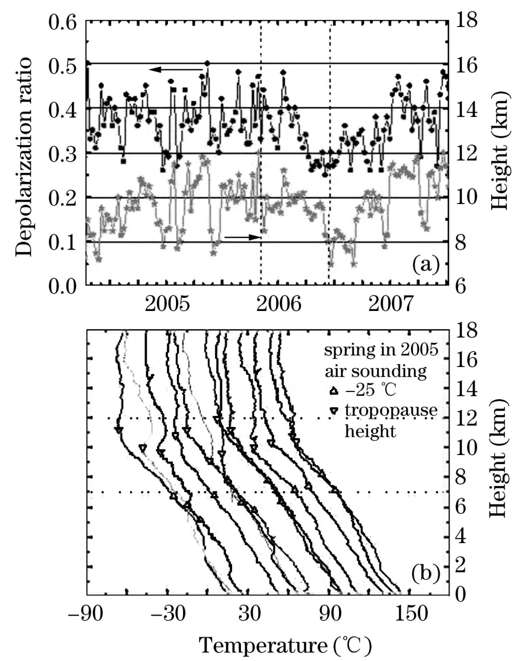

Fig. 3. Statistical results of (a) peak value of depolarization ratio and corresponding height of cirrus over Hefei and (b) profiles of temperature by radiosonde.

May in $2005-2007$. It can be seen that the cirrus clouds generally present in the altitude from 7 to 12 km with average 9.63 ± 1.22 km, which is well compared with 10.90 km determined by the Stratospheric Aerosol and Gas Experiment (SAGE) satellite data at altitude of 25°N[2], and the depolarization ratio varies from 0.2 to 0.5 average 0.36 ± 0.06.

Figure 3(b) shows profiles of temperature by radiosonde during the spring in 2005. It indicates that the location of height of tropopause (∇) and altitudes with

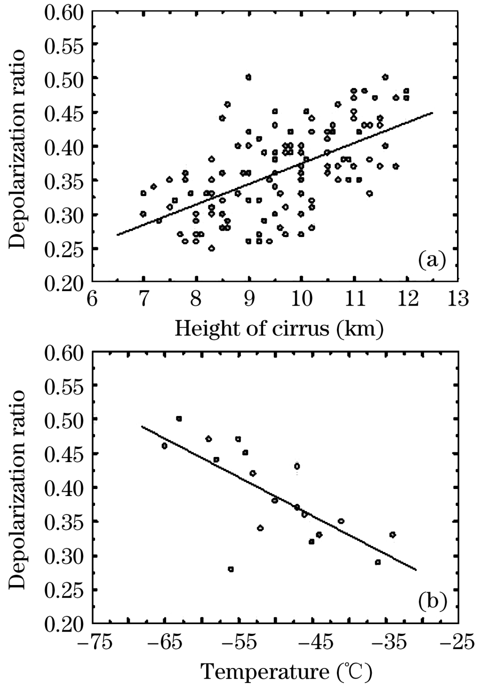

Fig. 4. (a) Relativity between peak value of depolarization ratio and corresponding height (February to May in 2005−2007) and (b) relativity between peak value of depolarization ratio and corresponding temperature (February to May in 2005) for cirrus clouds over Hefei.

−25 °C (Δ).

Comparing Fig. 3(a) with Fig. 3(b) indicates that there are some relationships between the location of the peak altitudes of the cirrus and the tropopause. As for the variability of both the peak altitude of the cirrus and the tropopause height, the former tended to track the latter. Besides, the most cirrus layers were situated in an air mass with a temperature lower than −25 °C. The −25 °C threshold has been recognized as an indicator of cirrus[1].

Figure 4(a) presents the height dependence of peak value of depolarization ratio. The values of depolarization ratio for cirrus clouds are scattered; however, a tendency for depolarization ratio to increase with height between 7 and 12 km is observable. Except for some dispersed dots, depolarization ratio values tend to increase from approximately 0.25 to 0.5.

In order to study the relationship between peak value of depolarization ratio and corresponding temperature, we got some air-sounding data together with exploring results of cirrus by polarization lidar simultaneously (Fig. 4(b)). It still shows some certain relativity, though we only have temperature profiles in 2005. The depolarization ratio values tend to decrease with the temperature varying from −70 to −30 °C. The temperature of cirrus cloud at a higher place is cooler comparatively, and the content of ice-crystal is bigger, thus the corresponding depolarization property is heavy.

This paper has presented polarization lidar observation results of cirrus clouds in spring over Hefei, the southeastern part of China. The following conclusions can be drawn on the basis of the lidar observed data sets. The cirrus cloud layers were situated within 7−12 km altitude range, where the air temperature was lower than −25 °C. The peak altitudes of the cirrus clouds were modulated by the altitude of the tropopause. The mean altitude was 9.63 ± 1.22 km. The depolarization ratio of cirrus clouds varied from 0.2 to 0.5 and the depolarization ratio of aerosol was about 0.05. The depolarization ratio appeared a climbing tendency with the increasing height and the decreasing temperature. The foregoing results may offer an important reference for sand-dust and cirrus cloud detection using airborne lidar[16].

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