Seasonal variability of cirrus depolarization properties derived from CALIPSO lidar measurements over Beijing in China

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The seasonal variability of cirrus depolarization ratio and its altitude at the region of Beijing (39.93°N, 116.43°E, the capital of China) are presented. From the results obtained from the cloud aerosol lidar and infrared pathfinder satellite observations lidar measurements, it appears that the values of depolarization ratio and altitude of cirrus are generally higher in autumn and summer than those in spring and winter, and the cirrus altitude is modulated by the height of tropopause. Additionally, the depolarization ratio tends to linearly vary with the increase of altitude and the decrease of temperature.

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Knowledge of the radiation budget of atmosphere is crucial for our understanding of the earth's climate. Cirrus cloud, one of the most common types of cloud covering the globe, plays an important role in the radiation budget of the earth, since it would either cool or warm the earth's surface[1−3]. Typical values of the physical properties of cirrus clouds obtained from different techniques were reported by various authors[4−7]. It can be inferred from these typical values that the properties of cirrus depend greatly on the temporal and spatial scales. To date, the satellite lidar is considered as a very powerful tool to characterize the time and spatial evolution of atmospheric aerosols, as well as to investigate chemical and physical properties of clouds.

Based on the experiences of lidar in-space technology experiment (LITE) and geoscience laser altimeter system (GLAS), the cloud aerosol lidar and infrared pathfinder satellite observations (CALIPSO) satellite was successfully launched on April 28, 2006[8]. The first polarization lidar on board of CALIPSO simultaneously provides two backscatter 532-nm signals polarized parallel and perpendicular to the outgoing beam. The information on the vertical distributions of aerosols or clouds and cloud ice or water phase can be retrieved from the two backscatter signals. In this letter, we describe the seasonal variability of cirrus depolarization ratio and its altitude at the region of Beijing (39.93°N, 116.43°E, the capital of China).

For the polarization lidar, the range scaled, energy and gain normalized return signals $X(z)$ for the parallel and perpendicular channels are defined as[9−11]

$$\left\{\begin{array}{l} X_{\mathrm{p}}(z)=C_{\mathrm{p}}\beta_{\mathrm{p}}(z)T^2(z) \\ X_{\mathrm{s}}(z)=C_{\mathrm{s}}\beta_{\mathrm{s}}(z)T^2(z) \end{array}\right., \tag{1}$$

where C is the lidar calibration constant, $\beta(z)$ is the total (aerosol and molecular) volume backscattering coefficient at altitude z. The subscriptions "p" and "s" represent the parallel and perpendicular directions, respectively. $T(z)$ is the one way transmittance from the lidar to altitude z expressed as

$$T(z)=\exp(-\int_{\mathrm{z}}^{z_{\mathrm{s}}}\alpha(z')\mathrm{d}z'), \tag{2}$$

where $\alpha(z')$ represents the total volume extinction coefficient, and z_{s} is the space-borne lidar calibration altitude[12]. $\delta(z)=\beta_{\mathrm{s}}/\beta_{\mathrm{p}}$ is defined as the total volume depolarization ratio. The polarization analysis and adjustment of the polarization lidar can be found in Refs. [13, 14]. From the CALIPSO level 1 products[10] and the definition of $\delta(z)$, the total volume depolarization ratio can be directly obtained as

$$\delta(z)=\frac{\beta'_{532,\mathrm{s}}(z)}{\beta'_{532,\mathrm{Total}}(z)-\beta'_{532,\mathrm{s}}(z)}, \tag{3}$$

where $\beta'_{532,\mathrm{Total}}(z) = [\beta_{532,\mathrm{p}}(z)+\beta_{532,\mathrm{s}}(z)]T^2_{532}(z)$ and $\beta'_{532,\mathrm{s}}(z) = \beta_{532,s}(z)T^2_{532}(z)$ are the total attenuated and perpendicular attenuated backscatter coefficients at the wavelength of 532 nm, which are the profile products archived upon the completion of the level 1 processing.

In order to increase the signal-to-noise ratio for data retrieved from the CALIPSO level 1 profiles, an integration of profiles was performed[15]. From June 2006 to February 2009 there were about twenty measurements for each season, and for these measurements the mean shortest distance between Beijing and CALIPSO ground track was about 50 km. Therefore, for each measurement case we averaged 326 profiles (∼16 seconds) corresponding to the nearest distance between the CALIPSO ground track and the location of Beijing for our analysis of cirrus optical properties.

The depolarization ratio related to both its altitude and temperature over Beijing is shown in Fig. 1. The altitude of cloud layer in Fig. 1 is reported in the CALIPSO

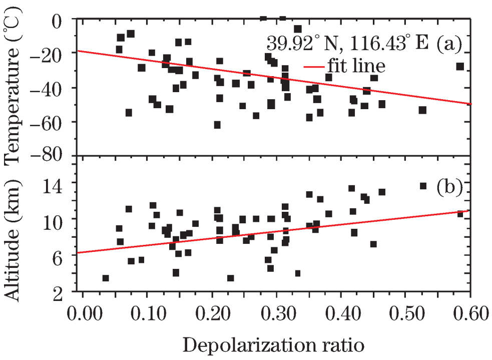

Fig. 1. Relation between (a) depolarization ratio and temperature and (b) depolarization ratio and altitude. The black squares stand for the actual measurements from June 2006 to February 2009.

level 2 5-km horizontal cloud data product[3]. The temperature profile archived in the CALIPSO level 1 products is a function of altitude z. The temperature shown in Fig. 1 is the mean value at the cloud layer altitude. The values of depolarization ratio reported in the CALIPSO level 2 5-km horizontal cloud products are scattered. The fit line is linear fitting corresponding to the entire scattered points. As shown in Fig. 1(a), it appears that the values of depolarization ratio tend to decrease with the temperature varying from −60 to −20 °C. The content of ice-crystal, which would lead to an increased value of depolarization ratio, is larger than that of water at lower temperature. As no water can exist in the atmosphere below −40 °C, the points with lower values of depolarization ratio below −40 °C in Fig. 1(a) can only be due to a change in ice crystal habit[16]. A tendency of depolarization ratio increasing with altitude between 7 and 12 km is clearly shown in Fig. 1(b). This can be attributed to the fact that the temperature normally decreases with height in the troposphere.

As shown in Fig. 1, the values of depolarization ratio tend to vary from approximately 0.05 to 0.45, which is probably related to water, ice, or mixed phase clouds. To discriminate water and ice clouds, it may be possible to perform the classification using cloud temperature. If the temperature at cloud base is lower than −45 °C, it can be assumed that the cloud is a cirrus cloud. If the temperature at cloud top is higher than 0 °C, it can be assumed that the cloud is a water cloud[17]. Generally, the cloud situated in an air mass with temperature lower than −25 °C can be recognized as the cirrus cloud[18]. Based on the above assumptions we select the cases where the average temperature is lower than −45 °C as the cirrus samples for our present study.

A summary of mean results about the cirrus depolarization ratio, its altitude, and tropopuase from June 2006 to February 2009 obtained from both the CALIPSO level 1 and level 2 data products is given in Table 1. Figure 2 describes the annual cycle of cirrus depolarization ratio, altitude, and tropopause over the region of Beijing. The error bars show the standard deviation about the mean value. The cirrus altitude from CALIPSO level 1 data products shown in Fig. 2 as black circles is the height above sea level (ASL) corresponding to the maximum value of total attenuated backscatter coefficients and is well compared with the cirrus layer top black squares in Fig. 2 reported in the CALIPSO level 2 5-km horizontal cloud data products. Whenever we observe a cirrus cloud layer in the CALIPSO data set we also take into account the tropopause height reported in the data set and calculate the mean value of the tropopause height through the cirrus layer. From Fig. 2 cassociated with Table 1, it can be easily found that the values of depolarization ratio and cirrus altitude retrieved from the CALIPSO level 1 data are nearly the same as ones reported in level 2 5-km horizontal cloud data products, while the slight differences may be due to the different horizontal average range. It can be concluded from Fig. 2 and Table 1 that the cirrus altitude and depolarization ratio trail after the height of tropopause, namely, corresponding to the higher altitude of tropopause the depolarization ratio and altitude of cirrus are higher as well. The mean altitude of cirrus at the region of Beijing is about 10.1±1.3 km, which are in agreement with 9.5 km and 9.7 km determined from 11 months of Stratospheric Aerosol and Gas Experiment (SAGE) data at latitudes of 45°N and 35°N, respectively[4].

The mean depolarization ratio in spring at the region of Beijing is around 0.26±0.07, which is much lower than the value of 0.36±0.06 obtained from signals received by the ground-based polarization lidar at Hefei (31.90°N, 117.16°E, China)[18]. Besides the nature temporal and spatial variation of cirrus properties and the random errors in separate measurements, the bias may be due to different shapes of ice crystals or different influences of multiple scattering on space-borne and ground-based lidar returns[12]. The value of 0.36±0.06 at temperature around −25 °C indicates that the ice crystals are non-rimed crystal aggregates, with little water present[16]. The mean value of depolarization ratio is 0.28±0.03 at 532 nm, which agrees with 0.33±0.11 at the temperature from 0 to −80 °C at 694 nm[5], and is also consistent with 0.3 at − 40 °C region[16]. Depolarization ratio from ice crystals depends on crystal shape and aspect ratio but is typically in the range from 0.3 to 0.5. Lower values can be obtained when horizontally oriented particles are present[19]. The CALIPSO lidar view angle was changed from 0.3° to 3.0° on 28 November 2007, greatly reducing the effect of specular reflections from horizontally oriented ice crystals. The mean depolarization ratio of cirrus before November 2007 was 0.25±0.07 and after was 0.33±0.09, which could indicate the influence of horizontally oriented ice crystals in 2006 and 2007. As shown in Fig. 2 associated with Table 1, it can be deduced that the values of depolarization ratio and altitude of cirrus are mainly larger in autumn and summer than the ones in spring and winter. Moreover, the frequency of occurrence of cirrus for the entire measurement cases at the region of Beijing is as high as 35% in summer and is approximately 7% in winter, which is consistent with the results of the limb-viewing satellite, which shows a greater amount of cirrus overall with a seasonal peak in the summer[4].

From the statistical analysis of signals received by the CALIPSO lidar at the region of Beijing, we can conclude that the altitude of cirrus is modulated by the height of tropopause, namely, the altitude of tropopause is generally higher in autumn and summer and lower in spring

Table 1. Statistical Mean Values for Cirrus Depolarization Ratio, Altitude, and Tropopause at Beijing

	CALIPSO Level 1		**CALIPSO Level 2**		
Seasons	Depolarization	Altitude (km)	Depolarization	Altitude (km)	Tropopause (km)
Spring(Feb-Apr)	0.26±0.07	9.1±1.1	0.25±0.09	10.0±0.8	11.3±2.1
Summer(May-Jul)	0.30±0.11	11.4±1.2	0.32±0.12	11.7±1.5	12.9±2.0
Autumn(Aug-Oct)	0.31±0.18	11.4±0.7	0.33±0.16	11.6±1.5	13.2±1.8
Winter(Nov-Dec,Jan)	0.24±0.09	8.6±0.9	0.27±0.11	8.7±0.9	9.8±0.1

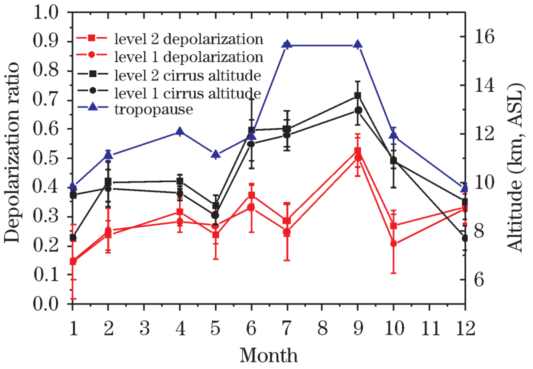

Fig. 2. Illustration of annual cycle of cirrus depolarization ratio, altitude of cirrus layer, and tropopause over the region of Beijing. The red and black squares stand for the depolarization ratio and cirrus layer altitude reported in the CALIPSO level 2 cloud data products. The red and black circles represent the same quantities retrieved from the CALIPSO level 1 profiles. The blue triangles stand for the altitude of tropopause.

and winter, and the altitude of cirrus is found to be higher in autumn and summer as well. The values of depolarization ratio tend to gradually increase with the altitude extended to higher height and decrease with the corresponding increased temperature. Additionally, the temporal variation of tropopause is also quite significant from the results.

In conclusion, the statistical mean values of cirrus altitude and depolarization ratio are 10.1±1.3 km and 0.28±0.03, which are in good agreement with 9.5 km determined from SAGE data at latitudes of 45°N and 0.33±0.11 obtained at 694 nm, respectively. Furthermore, the results we retrieved from the CALIPSO level 1 data products are in good agreement with the ones reported in the CALIPSO level 2 5-km horizontal cloud data products. While the results reported herein are the statistical mean values from June 2006 to February 2009, the data may be still insufficient to support a rigorous statistical analysis. Nevertheless, the results associated with the ones obtained from the ground-based lidar measurements may offer useful information on further studies of local cirrus microphysical and macro-physical properties.

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