3.4 Odd Observation in High Altitude Clouds with Depolarization Measurement Lidar

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1. Introduction

In the remote detection of physical characteristics of clouds, aerosols, and other particulates, a depolarization measurement lidar is an attractive tool. Although there had been depolarization measurements on the clouds and precipitations with radars and lidars before 1970, K. Sassen would be one of the earliest pioneers in the lidar depolarization measurement of the clouds (Schotland et al. 1971, Sassen 1974). The early study of the depolarization with water cloud and ice cloud showed a distinctive difference in the depolarization ratio (Schotland et al. 1971, Sassen 1974). The laboratory measured depolarization ratio (ratio of the cross-polarization signal to the co-polarization signal) from the water cloud was lower than 10 % while the randomly oriented ice crystals generate a depolarization ratio higher than 30 %. The depolarization originates from the spherical asymmetry of the scattering sources. Thus the depolarization ratio is a good parameter of non-sphericity of the scattering source.

Most high altitude clouds are cirrus clouds and cover the Globe about 30 % on average at a fixed time (Wylie et al. 1999). Cirrus clouds contribute to the Earth energy balance positively and negatively. Cirrus clouds reflect the solar radiation to decrease the insolation to the ground in the day time, but they help to retain the long wave infrared within the atmosphere near the ground in the night time. Cirrus clouds are made of mainly ice crystals formed from the supercooled water. Although water droplets can be supercooled below -40°C if the purity is high and the diameter of the droplets is less than 1 μm (Pruppacher 1995), the water droplet becomes ice through homogeneous nucleation at a temperature below about -33°C (Sassen et al. 1988, Heymsfield et al. 1989). The water droplets of temperature significantly lower than 0°C but higher than -33°C become ice through heterogeneous nucleation on various nuclei (Fletcher 1969, Kanji et al. 2008). When the air temperature is lower than -20°C, more than 90 % of water is in the ice form.

In this report, very unusual observations of high altitude clouds with a depolarization measurement lidar are presented. The observed odd clouds are considered to be composed of highly spherical particles judging from their low depolarization ratio and the particles seemed to be very non-interactive with the surrounding ice crystals.

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2. Lidar Observation

The depolarization measurement lidar is located at 39°10’44” N, 76°48’10” W, and the height of the lidar site from the mean sea level (MSL) is about 100 m. The lidar is located at 11.5 km west of the Thurgood Marshal Baltimore Washington International (BWI) airport. Due to the frequent take-off and landing of the jet airliners above the lidar site, the near ground atmosphere shows very complicated structure. The airline traffic in the high altitude above the lidar site is also very busy since many jet airliners are running from northeastern airports such as New York, Newark, and Boston to Atlanta, Dallas, and Miami back and forth over the lidar site. The radiosonde stations near the lidar site are IAD (station # 72403, Sterling, VA; 60 km southwest from lidar site), APG (station # 74002, Aberdeen Proving Ground, MD; 65 km northeast from lidar site), and WAL (station # 72402, Wallops Island, VA; 185 km southeast from lidar site). The depolarization measurement lidar was operated initially for about 2 hours when the sky was covered with cirrus clouds.

The detail of the used lidar was described in ref. (Lee et al. 2006). The laser used in this observation is a Nd:YLF laser at 1,047 nm instead of the green laser used in ref. (Lee et al. 2006). The lidar system is eye-safe according to the ANSI Z136.1-2007 by using a highly repetitive (5 kHz) low pulse energy (~10 μJ) laser. Since the field of view (FOV) of the receiver is less than 100 μrad, the detected multiple scattering is negligible. The spatial resolution of the used lidar was 7.5 m and the data was averaged in 10 s interval.

Fig. 1. The observed sky of 10 June 2010. High altitude clouds were spread in the sky and odd clouds were detected by the depolarization measurement lidar. The lidar was at an elevation angle of 65°

The sky was as shown in Fig. 1 when the measurement was performed on 10 June 2010. In the previous observations with the lidar, the cirrus clouds were detected at the lidar site in the range from 7 km to 16 km depending on the sky condition. The lidar was at an elevation angle of 65° to avoid the possible specular reflection from the ice sheets and was pointing to northwest. Typical cirrus clouds were spread at an altitude from 8 to 10 km as shown in the lidar time-altitude display of Fig. 2.

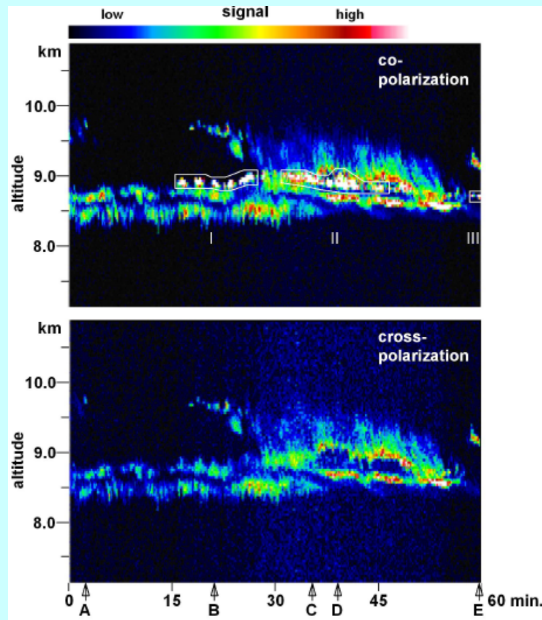

Fig. 2. When the observation started at 0943 EDT, typical cirrus clouds were detected as shown in this time-altitude display. About 15 minutes later, an odd cloud with very low depolarization ratio came in the FOV of the lidar. The cloud was very localized and had very distinctive characteristic.

Although a few jet liners were observed during the lidar observation in the high altitude, none of the jet liners generated contrails directly above the lidar. When the lidar was started, three layers of clouds were detected. The top layer cloud at about 9.5 km altitude disappeared about 4 minutes after the beginning of observation. Fig. 3 shows the lidar backscatter signals for the co-polarization and the cross-polarization at time B in Fig. 2. From the average depolarization ratio of about 50%, the main composition of the cirrus cloud can easily be assumed to be ice crystals for all 3 layers. But the odd cloud at 8.7 km altitude shows a depolarization ratio below 10 %. The low depolarization ratio of the cloud indicates that the cloud particles in the cloud are highly spherical. The odd clouds in the white box II of Fig. 2 are imbedded in the regular ice crystal cloud. Although the odd cloud is intermixed with the ice crystals, the cloud maintained its characteristics persistently.

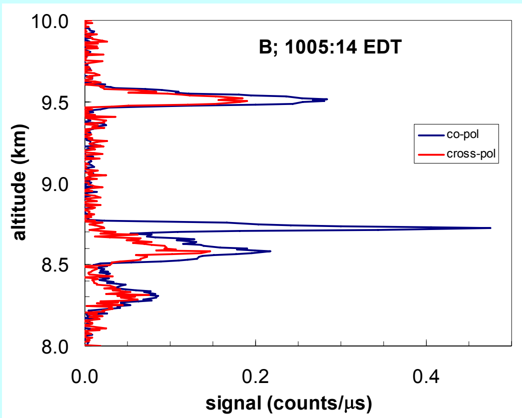

Fig. 3. An odd cloud appeared in the FOV of the depolarization measurement lidar at about 0959 EDT (Eastern Daylight Saving Time). The depolarization ratio of the odd cloud was lower than 10 % and very unusual for such high altitude clouds. This backscattered signal was taken at 1005:14 EDT (time B in Fig. 2.).

The temperatures and the relative humidity measured by 2 radiosondes (IAD and APG, 1200 UTC, 10 June 2010) about 1 hour 43 minutes before the lidar start are shown in Fig. 4. The temperature in the altitude range from 8 km to 10 km was in between -20°C and -40°C from 2 stations data and the temperature at the odd layer of cloud is -30°C. The relative humidity at APG station was peaked to 65 % at 8.5 km altitude. IAD station reported a relative humidity of 50 % from 8 km to 9 km altitude and the humidity reduced over 9 km altitude. The high relative humidity range by the radiosondes measurement coincides with the cirrus cloud altitude in the lidar measurement.

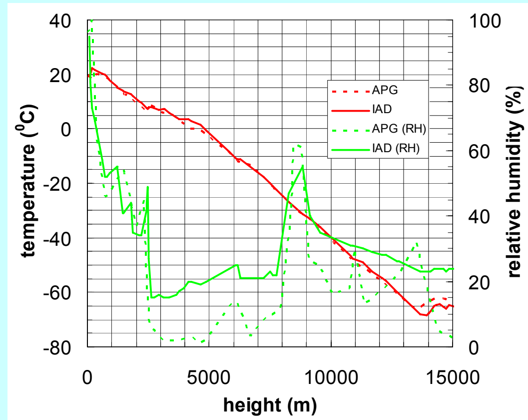

Fig. 4. Temperature and relative humidity reported by radiosonde stations around the lidar site at 1200 UTC, 10 June 2010. High relative humidity was reported at altitude of about 8 km from both stations. The temperature of the odd cloud altitude is about -30°C.

After 10 June 2010 observation of high altitude clouds with highly spherical particles, SESI depolarization lidar is in operation for daytime continuously except rainy days. During 5 months observation period, the odd clouds were observed 2 ~ 3 times a month. In most cases, the odd cloud lasted for 10 ~ 20 minutes at longest. But another unusual observation was happened on 3 November 2010 afternoon. The sky was covered by low clouds (altitude ~1 km) up until 1630 EDT. The low lying clouds started to break after 1630 EDT and the high altitude clouds were observed by the lidar. The ice clouds were falling from 7.2 ~ 7.6 km altitude to 5.0 km as shown in Fig. 5. Just after 1630 EDT, two patches of the odd clouds were detected by the lidar, but each patch lasted only about 30~40 seconds in the lidar FOV. A significantly large patch of odd cloud approached to the lidar FOV at 1713 EDT. The cloud altitude was 6.4 km and the temperature of the cloud was about -20°C from the radiosonde information. The cloud patch was detected for 4 minutes. Another layer of the odd cloud appeared in the lidar FOV at 1720 EDT. The altitude of the cloud was 7.8 km and the temperature of the cloud was -31°C. This cloud lasted for more than one hour in the lidar FOV. Since the wind speed at 8 km altitude was about 80 knot/hour, the cloud must be covering wider than 150 km region.

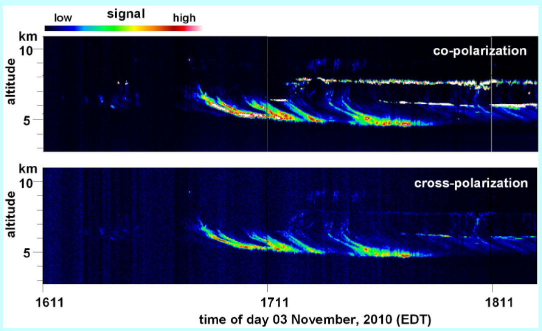

Fig. 5. Time-altitude presentation of 2 hours 20 minutes depolarization lidar display. Two layers of clouds with highly spherical particles were observed for longer than one hour. The geographical coverage of the cloud extends to about 150 km or wider.

3. Discussions

From the depolarization measurements of the high altitude clouds with a lidar, very abnormal layers of cloud were observed. Since the observed odd cloud layers are in the altitude of cirrus cloud, most of the cloud should be ice crystals or aggregation of ice crystals and should show very significant depolarization ratio. The cloud observed on 23 June 2010 was at 10 km altitude and the temperature at the altitude was -36.5°C which is below the homogeneous nucleation temperature of water droplets. The low depolarization ratio indicates that the constituents of the odd clouds are materials with high spherical symmetry. The existence of clouds of highly spherical scattering object in such a high altitude is very unusual since the expected clouds in such a high altitude is mostly ice crystals with very poor spherical symmetry. The average depolarization ratio of the surrounding cirrus clouds was about 40~60 %. However, the depolarization ratio of the odd clouds was less than 10 %. This level of low depolarization ratio is usually observed from the low lying water droplet clouds.

There were studies for the specular reflection of the lidar laser light from cirrus clouds (Platt 1978) and concluded that the specular reflection from horizontally aligned ice crystals is possible when the zenith angle of the laser beam is within about 8.2° (Platt et al. 1978). K. Sassen observed the strong lidar co-polarization signal from high altitude clouds with very low depolarization ratio and considered that the layer of cloud was composed of horizontally oriented ice crystals or plates (Liou 1986) as the same as claimed in ref. (Platt 1978, Platt et al. 1978). As mentioned previously, the zenith angle of the present lidar observation is 25°, and the specular reflection from the odd cloud is not relevant to explain the low depolarization ratio of the odd clouds measured in the present observation.

The possible scattering sources of laser light with high spherical symmetry would be either frozen water droplet or some other material droplet with freezing temperature below -40°C. Highly contaminated water can also be in liquid form at a very low temperature and can be spherical light scatter particles. Among the three possibilities, the frozen water droplet is the least plausible since the formation of frozen water droplet requires a fast temperature drop (Shaefer 1962). The substance that can become droplet form at such a low temperature is the hydrocarbons with a low melting point such as jet fuel that has insufficiently combusted and ejected in fine droplet form. Jet fuel currently used for commercial airliners is Jet A-1, and its melting point is -47°C.

A report on the field measurement of the transition from contrail to cirrus clouds shows that the fresh contrail of ice crystal with mean diameter about 1 μm transforms into young cirrus cloud with relatively spherical particle diameter about 10 μm in about 1 hour (Schröder 2000). The report implied that the spherical particle grows much bigger and irregular particles of cirrus clouds thereafter. The result of the report does not explain very well the present observation since the many of the observed clouds in the present study do not seem to originate from contrails.

4. Conclusions

High altitude clouds with very unusual lidar depolarization characteristics were observed with a depolarization measurement lidar and a very low depolarization ratio was measured from the clouds. The clouds were located near the tropopause. The lidar zenith angle was set at 25° to avoid the possible specular reflection from the high altitude clouds. The measured depolarization ratio of the odd clouds is less than 10 %, and the cloud particles appear highly spherical. Since the surrounding temperature of the cloud is well below -20°C and the cloud particles are expected to be ice crystals, the low depolarization ratio measurement is very difficult to explain. The cloud sustains its physical characteristics persistently once the cloud is formed. Currently, the constituents of the cloud cannot even be guessed. It is not clear whether the odd cloud is a local phenomenon or a global phenomenon since this observation is the first of its kind to the authors' knowledge. An orchestrated field campaign may be needed to determine the constituents of the cloud with an array of depolarization measurement lidars arranged with a distance of about 10 km between lidars and well equipped high flying aircrafts, and to understand the development mechanism and sustainment of the clouds. Only the orchestrated field campaign can provide relevant information of the clouds on the environmental influence and on the influence to the global climate.

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