Journal of Quantitative Spectroscopy & Radiative Transfer 122 (2013) 3–12

Contents lists available at SciVerse ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

Macrophysical and optical properties of mid-latitude cirrus clouds over a semi-arid area observed by micro-pulse lidar

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ARTICLE INFO

Article history:
Received 3 July 2012
Received in revised form
27 December 2012
Accepted 11 February 2013
Available online 18 February 2013

Keywords:
Mid-latitude cirrus
Micro-pulse lidar
Optical depth
Lidar ratio
Semi-arid area

ABSTRACT

Macrophysical and optical characteristics of cirrus clouds were investigated at the Semi-Arid Climate Observatory and Laboratory (SACOL; 35.95°N, 104.14°E) of Lanzhou University in northwest China during April to December 2007 using micro-pulse lidar data and profiling radiometer measurements. Analysis of the measurements allowed the determination of macrophysical properties such as cirrus cloud height, ambient temperature, and geometrical depth, and optical characteristics were determined in terms of optical depth, extinction coefficient, and lidar ratio. Cirrus clouds were generally observed at heights ranging from 5.8 to 12.7 km, with a mean of 9.0 ± 1.0 km. The mean cloud geometrical depth and optical depth were found to be 2.0 ± 0.6 km and 0.350 ± 0.311, respectively. Optical depth increased linearly with increasing geometrical depth. The results derived from lidar signals showed that cirrus over SACOL consisted of thin cirrus and opaque cirrus which occurred frequently in the height of 8–10 km. The lidar ratio varied from 5 to 70 sr, with a mean value of 26 ± 16 sr, after taking into account multiple scattering effects. The mean lidar ratio of thin cirrus was greater than that of opaque cirrus. The maximum lidar ratio appeared between 0.058 and 0.3 when plotted against optical depth. The lidar ratio increased exponentially as the optical depth increased. The maximum lidar ratio fell between 11 and 12 km when plotted against cloud mid-height. The lidar ratio first increased and then decreased with increasing mid-height.

1. Introduction

In the past two decades, many studies reveal that cirrus clouds play a crucial role in the radiation budget of the earth-atmosphere system [1–3]. The influence of cirrus clouds on the climate of the upper troposphere is important, not only because cirrus appear at high altitudes, but also because they consist of non-spherical ice crystals with complicated absorption and scattering properties. Cirrus clouds are widely dispersed in the upper troposphere and regularly cover about 20% of the total earth's surface [4].

Cirrus clouds play an important part in modulating regional and global climate via two complex processes. One is the albedo effect in which high-altitude cirrus clouds can scatter or absorb solar radiation, cooling the Earth's surface by reflecting solar insolation; the other is the greenhouse effect, which results in atmospheric warming due to the trapping of longwave radiation [5,6]. Liou [1] suggested that tropical cirrus acts as a greenhouse modulator, whereas the albedo effect is more effective in mid-latitude cirrus. Fu and Liou [7] reported

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http://dx.doi.org/10.1016/j.jqsrt.2013.02.006

that thin clouds may cause a positive radiative forcing at the top of the atmosphere, whereas thick cirrus clouds produce cooling. Additionally, cirrus clouds are crucial to the hydrological cycle of the atmosphere and to stratosphere–troposphere exchange (STE) processes for water vapor. The parameterization of cirrus in terms of their macrophysical and optical characteristics at different geographic locations is very important for climate models and particularly in the improvement of the general circulation model (GCM) due to their important roles in climate, radiation balance, and water vapor exchange.

However, significant uncertainties remain regarding the radiative and climatic effects of cirrus clouds [8] and subsequent predictions of the changing global climate. Consequently, studies on cirrus are currently being undertaken worldwide. In an attempt to assess the impact of clouds on the global climate, many experiments such as the First ISCCP (International Satellite Cloud Climatology Project) Regional Experiment (FIRE), Cirrus Intensive Observations (IFO) [9], the European experiments on cirrus (ICE/EUCREX) [10], and the Experimental Lidar Pilot Study (ECLIPS) [11] have been conducted using a variety of techniques to investigate and improve our knowledge of cirrus clouds and their radiative properties in different regions of the globe.

Today, there are several global and regional networks of atmospheric observatories that use lidar as their main monitoring instrument because of the high spatial and temporal resolution it provides. The lidar technique has become a quantitative tool for detecting and characterizing cirrus clouds from the ground (ground-based lidar). Extensive ground-based measurements have been undertaken to study the geometrical and optical properties of tropical high-altitude cirrus and their radiative properties by various research groups in the tropics [12–14]. Similarly, cirrus clouds have also been widely observed at mid-latitudes. A ground-based lidar and a passive radiometer have been used together to remotely sense the gross structure and optical properties of cirrus, both at mid-latitudes and in the tropics [15]. Using a UV Raman lidar at Geesthacht (53.5°N, 10.5°E) in northern Germany, Reichardt [16] reported that cirrus mid-cloud height and temperature yielded distribution maxima between 9 and 10 km and between −50 and −60 °C, respectively. Sassen and Cambell [17] determined the cirrus cloud base/top properties to be 8.79/11.2 km and −34.4/−53.9 °C from 10-yr extensive high-cloud datasets collected from the University of Utah campus (40.8°N, 111.8°E). Xue et al. [18] showed that the peak appearance of high-altitude cirrus over Hefei, Anhui (31.90°N, 117.16°E), observed by L300 Mie lidar ranges from 8 to 11 km. Giannakaki et al. [19] found that cirrus clouds are generally observed over Thessaloniki, Greece (40.6°N, 22.9°E) at heights ranging from 8.6 to 13 km, with mid-cloud temperatures in a range from −65 to −38 °C.

It should be noted that cirrus climatology observed by a ground-based lidar over one particular location cannot be considered globally representative. Although the macrophysical and optical properties of cirrus clouds over north China were described by the lidar observations from the Earth-orbiting Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument on board the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite [20], the ground-based lidar observations could provide more continuously intensive measurements, comparing with the satellite observations of cirrus, so that more accurate properties could be retrieved [21,22].

The semi-arid area of northwest China is still lacking in lidar observations of cirrus clouds. Therefore, to understand the morphology and effects of cirrus clouds in this region, this study was designed to determine the statistical characteristics of cirrus clouds during the period from April to December 2007 by using ground-based micropulse lidar (MPL-4B) measurements at the Semi-Arid Climate Observatory and Laboratory (SACOL, 35.95°N, 104.14°E) of Lanzhou University in northwest China. The macrophysical and optical characteristics of cirrus clouds over SACOL are discussed here in detail and are also compared with other studies made over different geographic locations.

2. Instrumentation

The Semi-Arid Climate Observatory and Laboratory (SACOL) is a permanent cloud-research station located on the western edge of Lanzhou University (35.95°N, 104.14°E) at the top of Tsuiying mountain (about 1965.8 m above sea level). It was established in 2005. This site is approximately 48 km from the city of Lanzhou, which is situated on the southern bank of the Yellow River in the Gansu province in Northwest China [23]. The elastic-scattering MPL-4B system used for performing continuous measurements of suspended aerosol particles and cirrus clouds in this study was installed at SACOL in 2007. Its significant eye-safety feature compared with standard lidar systems is achieved by using low pulse energies and high pulse repetition rates. The lidar is equipped with an Nd: YLF laser pointed vertically, emitting a micro-pulse of 8 μJ output energy at a wavelength of 527 nm and a 2500 Hz repetition rate. The optical receiver is a Cassegrain telescope of 178 mm diameter with a field of view of 0.1 mrad. The vertical resolution of the elastic raw signal at 527 nm is equal to 75 m.

We defined the “effective height” as the height where the number of bins with negative signal intensity is larger than 5 in a 10-point bin. In order to obtain the accurate properties of cirrus, the signal is considered to be too noisy for further analysis when the effective height of the lidar signal falls below 15 km. Moreover, one cloud profile was generated by a one-minute lidar measurement time; hence, a measurement period of a few hours often resulted in hundreds of profiles. Because of the variable nature of cirrus clouds, ten profiles were averaged to produce one lidar ratio for a cirrus cloud. There were 1042 data points in total produced from April to November 2007.

3. Data analysis

Hu et al. [24] have found that the fraction of supercooled water is higher at higher latitudes than at lower latitudes for the same mid-layer cloud temperature. The