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Characteristics of cirrus clouds and tropical tropopause layer: Seasonal variation and long-term trends

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ABSTRACT

In the present study, characteristics of tropical cirrus clouds observed during 1998–2013 using a ground-based lidar located at Gadanki (13.5°N, 79.2°E), India, are presented. Altitude occurrences of cirrus clouds as well as its top and base heights are estimated using the advanced mathematical tool, wavelet covariance transform (WCT). The association of observed cirrus cloud properties with the characteristics of tropical tropopause layer (TTL) is investigated using co-located radiosonde measurements available since 2006. In general, cirrus clouds occurred for about 44% of the total lidar observation time (6246 h). The most probable altitude at which cirrus clouds occurr is 14.5 km. The occurrence of cirrus clouds exhibited a strong seasonal dependence with maximum occurrence during monsoon season (76%) and minimum occurrence during winter season (33%) which is consistent with the results reported recently using space-based lidar measurements. Most of the time, cirrus top was located within the TTL (between cold point and convective outflow level) while cirrus base occurred near the convective outflow level. The geometrical thickness of the cirrus cloud is found to be higher during monsoon season compared to winter and there exists a weak inverse relation with TTL thickness. During the observation period the percentage occurrence of cirrus clouds near the tropopause showed an 8.4% increase at 70% confidence level. In the last 16 years, top and base heights of cirrus cloud increased by 0.56 km and 0.41 km, respectively.

1. Introduction

Cirrus clouds are ubiquitous high level cold clouds predominantly consisting of ice-crystals (Liou, 1986; Lynch et al., 2002). Satellite observations reveal that these clouds cover about 50% of the globe with highest fraction observed over the tropics (Stubenrauch et al., 2010). Tropical cirrus clouds are one of the most vital and complex components of the tropical tropopause layer (TTL) due to their strong radiative feedback (Stephens, 2005) and dehydration in upper troposphere and lower stratosphere (UTLS) regions (Jensen et al., 1996). Based on their formation mechanism, tropical cirrus clouds are of two kinds: remnants of convective anvil and in-situ formed thin cirrus (Pfister et al., 2001). Using daily values of Halogen Occultation Experiment (HALOE) aerosol extinction and Climate Diagnostics Centre (CDC) outgoing long-wave radiation (OLR) data, Massie et al. (2002) showed that half of the cirrus clouds in TTL over the maritime continent are convectively generated while the remaining half are formed through in-situ processes. The net radiative effect at the top of the atmosphere by these two different kinds of cirrus clouds is different. The former are known to cause cooling through solar-albedo effect, while the latter cause warming through green-house effect (Fu and Liou, 1993). The relative magnitude of these two competing radiative effects strongly depends on the cloud coverage, position, thickness, and ice-crystal size and shape distributions (Liou, 1986). Note that all these features of cirrus clouds exhibit large spatial and temporal variations. Thus, a better understanding of their properties at different locations and various time scales is a pre-requisite to quantify their influences on regional and global climate.

Advances in ground and space-based lidars in the past couple of decades have made it possible to provide optical properties of cirrus clouds and their geographical coverage at high accuracy and resolution. Ground-based lidars are best suited to investigate the detailed characteristics of cirrus clouds over a given location with high vertical and temporal resolutions. In the past, many studies of tropical cirrus clouds using ground-based lidar (Comstock et al.,

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2002; Sunil Kumar et al., 2003; Sunil Kumar and Parameswaran, 2005; Seifert et al., 2007; Das et al., 2009) and space-based lidar (Sassen et al., 2008; Virts et al., 2010; Massie et al., 2013) have been made. However, there are only few studies that used long-term data sets and fewer studies that have used collocated radiosonde data. Over Nauru Island (0.52°S, 166.92°E), Comstock et al. (2002) studied the macrophysical and radiative properties of cirrus clouds for a period of 8 months using lidar and radar. They also used radiosonde profiles of temperature to study the thermodynamic characteristics of cirrus clouds. Sunil Kumar et al. (2003) reported the general features (like percentage occurrence, occurrence height, monthly variation, optical thickness and radiative properties) of cirrus clouds over Gadanki (13.5°N, 79.2°E), India, using lidar data from March 1998 to February 2001. The dependence of lidar-derived optical properties of cirrus clouds viz., extinction coefficient, linear depolarization ratio and optical thickness, on the temperature derived from co-located MST radar was studied by Sunil Kumar and Parameswaran (2005). Using the lidar and radiosonde measurements at Hulule (4.1°N, 73.3°E), Maldives, during INDOEX (INDian Ocean EXperiment), Seifert et al. (2007) studied the optical properties of cirrus clouds during two contrasting monsoon seasons. They found that cirrus clouds occur more frequently during south-west (SW) monsoon than north-east (NE) monsoon due to frequent deep convections during SW monsoon. Das et al. (2009) studied the macrophysical and optical properties of cirrus clouds over Chung Li (24.58°N, 121.10°E), Taiwan. Sassen et al. (2008) gave the global distribution of cirrus clouds using initial one year (June 2006–June 2007) of CloudSat/CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) data. Spatial and temporal variation of TTL cirrus clouds was studied by Virts et al. (2010) using 3 years of CALIPSO, ERA-interim and radiosonde data during 2006–2009.

In the present scenario, aerosols in the UT region (some of which serve as ice-nuclei) are increasing (Kulkarni et al., 2008; Vernier et al., 2011a). In addition to this, water vapour in the stratosphere which mainly comes from TTL has been increasing (Rosenlof et al., 2001; Solomon et al., 2010). These long term changes in the distribution of aerosols and water vapour can have significant impact on the long term properties of cirrus clouds at regional and global scales. To understand the qualitative and quantitative impact of climate change on tropical cirrus clouds and hence on the TTL processes, long-term observations of tropical cirrus at regional and global scale are essential. Massie et al. (2013) hypothesized that changes in latitudinal distribution of water vapour and temperature will change the distribution of TTL cirrus clouds and hence they can be used for climate diagnostic parameter.

In this study, we present 16 years (from 1998 to 2013) climatology of cirrus cloud properties like percentage occurrence, altitude distribution, physical thickness and their long-term trends obtained using ground-based lidar over a tropical location, Gadanki. Its association with the characteristics of TTL like convective outflow level, cold point tropopause altitude and TTL thickness observed using co-located radiosonde launches is also investigated.

2. Instrumentation and data description

2.1. Site description

The present study is carried out using a Rayleigh–Mie lidar located at National Atmospheric Research Laboratory (erstwhile National MST Radar Facility), Gadanki. Gadanki is a tropical rural site situated at 13.5°N, 79.2°E and an altitude of 375 m above mean sea level in southern India, about 130 km west of Bay of Bengal. The laboratory is surrounded by agricultural fields, forests and hills. Gadanki has typical tropical wet climate. Surface meteorology over Gadanki has been reported in our previous studies (Jagannadha Rao et al., 2003; Basha and Ratnam, 2009). The weather over Gadanki has a strong seasonal variation. During the period from January to March, sky is mostly clear. June–November is rainy season marked by two monsoons namely SW monsoon during June-September and NE/post-monsoon during October–November. We have divided the year into four different seasons viz. winter (December–February), pre-monsoon (March–May), monsoon (June–August) and post-monsoon (September–November) to characterise the cirrus properties. Note that the September month is a transition period from SW to NE monsoon and for ease of description we have grouped it with post-monsoon.

2.2. System description

The Rayleigh–Mie lidar was installed in 1998 to study the middle atmospheric (30–80 km) temperature and upper-tropospheric aerosols and clouds. The laser unit of system was replaced with a new laser in January 2007. It is a monostatic biaxial system which uses Nd:YAG laser as a light source and two telescopes as receivers. Laser pulses of wavelength 532 nm are transmitted at the rate of 20 Hz (50 Hz since 2007) in the atmosphere. Each pulse has pulse duration of 7 ns and a maximum energy of about 550 mJ (650 mJ since 2007). The laser beam has a diameter of 8 mm which is broadened to 80 mm using a beam expander before transmitting into the atmosphere. The backscattered photons from the atmosphere are collected by two independent telescopes. One of the telescopes is designed to collect the backscattered photons from the air molecules above 30 km in the atmosphere (called Rayleigh receiver) while the second telescope is designed to collect the backscattered photons from altitude below 30 km to study aerosols and clouds (called Mie-receiver). The Mie-receiver is a 35.5 cm diameter Schmidt Cassegrain telescope with a field of view of 1 mrad. To eliminate unwanted background noise from the received signal, a narrow band interference filter with wavelength centred at 532 nm and a full-width at half-maximum of 1.1 nm is placed in front of a polarizing beam-splitter. The polarizing-beam splitter splits the beam into parallel and perpendicularly polarized beams which are then detected by two identical orthogonally aligned photomultiplier tubes. The counting system consists of a Multi-Channel Scaler card. The photon counts are integrated for 5000 (12,500 since 2007) laser shots which correspond to an integration time of 250 s. The raw data comprise photon counts accumulated in the bins of time resolution of 2 μs which corresponds to a range resolution of 300 m. Using the expressions given by Roberts and Gimmestad (2002), the altitudes corresponding to the overlap start region and the full overlap region between laser beam and telescope field of view are found to be 3.18 km and 4.04 km, respectively. In this calculation, the divergence of laser beam was taken as 0.1 mrad and the distance between the telescope and the laser beam as 2 m. The lidar was operated during nights that were free from low level clouds. This limits the observation duration during monsoon seasons, when the sky is covered with thick low level clouds. Lidar data from the year 1998 to 2013 are used in this study.

2.3. Radiosonde data

In order to understand the characteristics of TTL and their relation to cirrus clouds we have used radiosonde data. Hydrogen filled balloons with GPS equipped radiosonde (Väisälä RS-80, RS-92, Japan make Meisei RS-06G) were launched daily at 17:30 IST (IST=UT+05:30 h) from Gadanki since 19 April 2006. In the current study, data up to November 2013 are used. After excluding failed balloon launches, around 1300 profiles of temperature, pressure, relative humidity and horizontal wind are obtained in