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Tropical tropopause layer cirrus and its relation to tropopause

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ABSTRACT

This study examines the spatial and temporal patterns of tropical tropopause layer (TTL) cirrus clouds (i.e., clouds with bases higher than 14.5 km) and their relationship to tropical tropopause including both cold point tropopause (CPT) and lapse rate tropopause (LRT). We use eight years (2006–2014) data from the Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) and Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) measurements. In addition to the CALIPSO cloud layer product, the clouds included in the current CALIPSO dataset as stratospheric features have been considered by separating clouds from aerosols, which are important in the TTL cloud analysis. It is also shown that the temporal variation of the stratospheric aerosols matches well with the volcanic eruption events. The TTL cloud fraction and the tropical tropopause temperature both have pronounced annual cycles and are strongly negatively correlated both temporally and spatially. The examination of the TTL cloud height relative to tropopause from collocated CALIPSO and COSMIC observations indicates that the tropopause plays a critical role in constraining the TTL cloud top height. We show that the probability density function of TTL cloud top height peaks just below the CPT while the occurrence of TTL clouds with cloud tops above the CPT could be largely explained by observed tropopause height uncertainty associated with the COSMIC vertical resolution.

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1. Introduction

It is generally recognized that air enters the stratosphere preferentially through upwelling in the tropics [1–3]. Since the transition is smooth between the convectively dominant Hadley circulation in the troposphere and the Brewer-Dobson circulation in the stratosphere, it is now well accepted that the transition from troposphere to stratosphere is a layer that extends several kilometers vertically rather than a material surface [4]. This layer is called the tropical tropopause layer (TTL). The base of the TTL is often defined as the level of zero net radiative heating rate, which is about 14–15 km [5–8] while the top of the TTL locates at about 17–19 km [6,7,9–12]. In this study, the TTL clouds are defined as clouds with bases higher than 14.5 km.

Although the TTL is the region where most air enters the stratosphere, the mechanism that controls air transport to stratosphere through the TTL is still not well understood. Convective overshooting is observed to lift air into stratosphere, but studies indicate that the mass fluxes associated with the convective overshooting are too small to be responsible for the main transport [13,14]. It is suggested that the large-scale slow ascent dominates mass transport across the TTL [5,9], but it is too slow to explain the observed tracer measurements [15–17]. Corti et al. [18] proposed that thin cirrus clouds widespreading in the TTL would enhance radiative heating rates and therefore facilitate the upwelling across the TTL. Therefore, the TTL clouds play an important role in climate not only through

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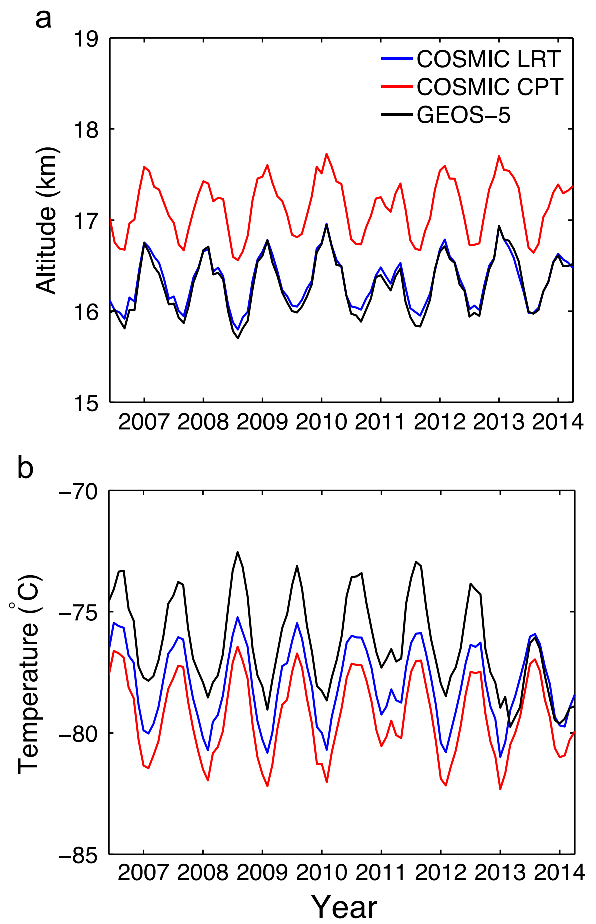

Fig. 1. Time series of monthly mean (a) tropopause heights and (b) tropopause temperatures for both lapse rate tropopause (LRT) and cold point tropopause (CPT) from COSMIC over 30°S–30°N. The tropopause height and temperature from the GMAO GEOS-5 used in CALIPSO data product are also shown. The tick mark for each year indicates 1 January.

its impact on the Earth's radiation budget [19,20], but also on the vertical transport that affects the water vapor and chemical concentration in the stratosphere [21–24].

Studies show that the temperature near the tropical tropopause has a dominant role to control the formation and maintenance of the TTL clouds [19,25,26]. In this study, we examine the temporal and spatial pattern of TTL clouds and their relationship with tropical tropopause temperature including both cold point tropopause (CPT) and World Meteorological Organization (WMO) lapse rate tropopause (LRT). We use the Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) cloud data and Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) temperature measurement. For the current CALIPSO Level 2 layer products (version 3), all layers with base altitude lying above the tropopause provided by the GMAO (Global Modeling and Assimilation Office) Goddard Earth Observing System Model, Version 5 (GEOS-5), are classified as so-called "stratospheric features", which have not been classified to individual features such as clouds and aerosols. Thus, we first aim to include the missing clouds by separating clouds from aerosols in the "stratospheric features" to better quantify the TTL clouds in this study.

Pan and Munchak [27] examined cloud top and tropopause relationships using cloud top observations from the CALIPSO cloud data and tropopause data from National Centers for Environmental Prediction Global Forecast System. They showed that the WMO LRT appears to be a significant constraint for the cloud top. While the vertical distribution of cloud tops in tropopause-relative coordinates shows a maximum at the LRT level, the significant occurrences of cloud top above the LRT are found in the tropics [27]. Recently, Munchak and Pan [28] examined the difference between the WMO LRT and CPT heights in the tropics using the COSMIC data and the impact on the cloud top-tropopause relationship with collocated CALIPSO and COSMIC observations. They found that the frequency of clouds above the tropopause is reduced if the CPT is used instead of LRT but the occurrence of clouds above the CPT is nevertheless significant. Different from the studies by Pan and Munchak [27] and Munchak and Pan [28], this study will focus on the TTL clouds instead of all clouds in the tropics. The clouds in the "stratospheric features", which might not be significant in the analysis of all clouds [27], can be important for TTL clouds analysis. Furthermore, the impact of tropopause height uncertainty due to vertical resolution of COSMIC temperature observation on the cloud top-tropopause relationship will be examined in this study.

This paper is organized as follows. Section 2 describes the datasets employed. Section 3 compares the COSMIC tropopause with that from the GEOS-5, the latter was used in the current CALIPSO data to define the "stratospheric features". The separation of clouds from aerosols in the "stratospheric features" is presented in Section 4. The spatial and temporal variations of TTL clouds along with tropopause temperatures are shown in Section 5. The relationship between cloud top and tropopause height and the impact of vertical resolution of COSMIC are discussed in Section 6. The summary and conclusions are given in Section 7.

2. Datasets

2.1. CALIPSO data

The CALIPSO satellite was launched in April 2006 into a sun-synchronous, 98.2° inclination polar orbit at an altitude of 705 km as part of the A-train constellation of satellites [29]. The primary instrument on-board CALIPSO is the Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP), a two wavelength (532 nm and 1064 nm) polarization sensitive lidar that provides vertical profiles of clouds and aerosols. CALIOP is able to detect clouds with optical depth of 0.01 or less with sufficient averaging, and clouds with optical depth as large as 5 before becoming completely attenuated. Cloud and aerosol layers are identified from the lidar backscatter profiles using a selective iterative boundary locator (SIBYL) algorithm [30]. CALIPSO