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Characteristics of cirrus clouds in the tropical lower stratosphere

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ABSTRACT

A unique type of cloud in the tropical lower stratosphere, which we call "stratospheric cirrus", is described in this study. Stratospheric cirrus clouds are generally detached from overshooting deep convection and are much smaller than subvisual cirrus often observed near the tropical tropopause. We analyzed two cases of stratospheric cirrus in the tropical and subtropical lower stratosphere captured by the space-borne lidar, Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP). Both cases occurred 2–3 hours after the most active phase of the nearby convective cloud clusters. Case 1 has a double-layer structure above the cold point height (CPH); the CPH and two cloud top heights are, respectively, 17.8, 18.9, and 19.9 km. Case 2 has a single cloud layer where CPH and the cloud top height are, respectively, 16.5 and 18.7 km. The mode radius and ice water content of the stratospheric cirrus clouds are estimated to be 4–10 μm and 0.2–0.8 mg/m^3 based on the radar-lidar method and consideration of the cloud particle terminal velocity. Comparisons with previous numerical model simulation studies suggest that the double-layer stratospheric cirrus clouds are likely from an overshooting plume, pushed up into the stratosphere in an overshoot when warm stratospheric air is inhomogeneously mixed with cold overshooting air. The single-layer stratospheric cirrus cloud is associated with some non-negligible wind shear, so it could be a jumping cirrus cloud, although we cannot rule out the possibility that it came from an overshooting plume because of the similarity in cloud characteristics and morphology between the two cases. Guided by the case studies, an automatic algorithm was developed to select stratospheric cirrus clouds for global survey and statistical analysis. A total of four years of CALIPSO and space-borne cloud radar (CloudSat) data were analyzed. Statistical analysis suggests that stratospheric cirrus clouds occur on the order of 3.0×10^3 times a year between 30 °S and 30 °N. Many of the stratospheric cirrus clouds are found in the pre-monsoon season in the South and Southeast Asia, where convection is deep and intense.

1. Introduction

Stratospheric water vapor is an important greenhouse agent that contributes to global warming (e.g., Solomon et al., 2010). In the tropics, it is transported from the troposphere to the stratosphere through the tropical tropopause layer (TTL) (Brewer, 1949; Fueglistaler et al., 2009). Understanding the regulation of water vapor in and above the TTL is therefore crucial.

Clouds are one of the most critical factors in the regulation of water vapor in the lower stratosphere. Clouds in the tropical lower stratosphere can be broadly divided into three types: a) cloud tops of overshooting deep convection (e.g., Luo et al., 2008; Iwasaki et al., 2010; Bedka et al., 2010), b) very thin cirrus clouds which are unusually wide (hundreds to thousands of km) and horizontally uniform, also known as subvisual cirrus (SVC; Sassen and Cho, 1992), and c) cirrus or anvil clouds which are neither overshoots nor SVCs; they differ from overshoots because they are generally detached from any overshooting tops, and they are distinct from SVC because of much smaller size. The third type is the main subject of this paper. We briefly introduce these clouds.

An overshoot is defined as a "dome-like protrusion above a cumulonimbus anvil, representing the intrusion of an updraft through its equilibrium layer" (American Meteorological Society, 2013). Overshoots are believed to change the amount of water vapor in the stratosphere

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but their net effect is not clear. For example, Danielsen (1993) analyzed airborne observations during the Stratosphere–Troposphere Exchange Project (STEP) in Darwin, Australia, and showed that overshooting air dehydrated the lower stratosphere because of larger overshooting cloud particles and the radiative cooling above the anvil clouds formed by the overshoot. Nielsen et al. (2007) found solid particles composed of ice 200 km away from deep convection in the tropical lower stratosphere and concluded some ice particles of overshooting clouds would be small enough to float for hours in the lower stratosphere. Iwasaki et al. (2010) analyzed A-Train synergy data collected by the space-borne lidar Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), the cloud radar CloudSat, and the imager Moderate Resolution Imaging Spectroradiometer (MODIS) and showed that overshooting caused hydration of the lower stratosphere. Homeyer et al. (2014) analyzed in-situ measurement and showed mixing ratio 1–2 km above tropopause around convective system was higher than background by 10 times or even more.

An SVC is characterized by its small optical thickness. Sassen and Cho (1992) introduced an empirical definition of the SVC as "optical thickness of less than about 0.03." One typical characteristic of an SVC is its unusually large width. Winker and Trepte (1998) summarized the morphology of SVCs based on space-borne lidar, LITE, reporting that the maximum and mean widths were, respectively, 2700 and 500 km. They also showed that SVCs were measured in both clear air and above severe convective cloud clusters. Boehm and Verlinde (2000) conducted ground-based lidar measurements for one month and proposed that SVCs were generated by a negative temperature anomaly induced by Kelvin waves. However, Comstock et al. (2002) analyzed ground-based lidar data including data analyzed by Boehm and Verlinde (2000) and demonstrated that negative temperature anomalies were not a clear source of SVC generation. Iwasaki et al. (2004) showed SVCs were not measured during positive temperature anomalies. Though the mechanism of SVC generation is not entirely clear, it is very likely generated by some large-scale processes in the TTL based on its unusually large width. An SVC could dehydrate the stratospheric water vapor because SVC occurrence and the water vapor mixing ratio in the lower stratosphere have a negative correlation (Wang et al., 1996).

A cirrus cloud above the cold point height (CPH) and anvil clouds, which we call "stratospheric cirrus cloud" in this paper after Fujita (1982), has fewer morphological characteristics. A stratospheric cirrus cloud could be, for example, a jumping cirrus cloud that jumps 1 km or more into the stratosphere from behind an overshooting top (Fujita, 1982; Wang, 2004; Hassim and Lane, 2010) or a plume-like cloud above an anvil cloud (Putsay et al., 2013). Putsay et al. (2013) suggested the plume-like cloud extends from an overshoot and hydrates the lower stratosphere because of the positive difference between brightness temperatures of 6.2 and 10.8 μm bands measured by the Meteosat (Schmetz et al., 1997), although the generation mechanism of the plume-like cloud is not known. Garrett et al. (2004) carried out airborne lidar and cloud radar measurements during the Cirrus Regional Study of Tropical Anvils and Cirrus Layers-Florida Area Cirrus Experiment (CRYSTAL-FACE) field program. They showed cirrus was generated above anvil clouds from top of overshoot. Because these clouds are observed in and around deep convection, the stratospheric cirrus clouds are likely generated by deep convection.

The three types of clouds in the tropical lower stratosphere are closely connected and work together to affect lower stratospheric water vapor. For example, overshoots could generate a stratospheric cirrus cloud, which may hydrate the lower stratosphere; higher relative humidity could, in turn, generate SVC. Among the three types, the stratospheric cirrus cloud is the least well understood partly because observation of stratospheric cirrus by using ground-based instruments is difficult due to strong attenuation of visible and infrared light in convective clouds and its cloud particles are too small to detect even by cloud radar, and partly because there is no clear definition of stratospheric cirrus in literature for easy identification using space-borne measurements. However, because stratospheric cirrus is likely generated by diabatic processes accompanying overshooting (Wang, 2013), understanding stratospheric cirrus is crucial for understanding stratosphere-troposphere exchange.

In this study, we focus on characterizing cloud microphysics and global distribution of stratospheric cirrus. Cloud microphysics such as effective radius and ice water content are important parameters to determine water budget and lifetime of stratospheric cirrus. Global distribution, on the other hand, may suggest generation mechanisms for stratospheric cirrus (Section 5). We carry out these studies using multiple years of observations from the A-Train constellation which consists of several synergistic satellites flying in close formation along the same sun synchronous orbit (Stephens et al., 2002).

This paper first reports on two stratospheric cirrus case studies in which CALIOP and CloudSat measurements of convective cloud clusters were made a few hours after their most active phases. Section 2 introduces satellite and other data used. Section 3 presents the two stratospheric cirrus cloud case studies. The particle size distributions of the stratospheric cirrus clouds are discussed in Section 4. In Section 5, an empirical algorithm is developed for global survey of stratospheric cirrus; statistical analysis of the occurrence frequency of stratospheric cirrus clouds is conducted based on four years data (2007-2010). Finally, we discuss possible generation mechanisms for stratospheric cirrus clouds in Section 6.

2. Data

The CALIOP, Imaging Infrared Radiometer (IIR), and CloudSat Cloud Profiling Radar (CPR) are part of the A-Train constellation. CALIOP, IIR, and CPR are, respectively, space-borne lidar, nadir-looking infrared radiometer, and 94-GHz cloud radar. The difference in the observational time of these sensors is only about 15 seconds. CALIOP data sets CAL_LID_L1 and CAL_IIR_L1 were used to characterize, respectively, vertical profiles of CALIOP backscattering coefficients and horizontal distributions of IIR brightness temperature along the orbit. Both are installed on the Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite. CloudSat data sets, 2B-GEOPROF and ECMWF-AUX, were used to obtain the vertical profiles of CloudSat radar reflectivity and temperature along the orbit. ECMWF-AUX is interpolated based on ECMWF operational analyses. We interpolated CALIOP and CloudSat data to fit every 0.01° in latitude (approx. 1 km) and 60 m in altitude. The horizontal resolution of IIR is 1 km.

The data from the Multi-functional Transport Satellite (MTSAT), were downloaded from ftp://mtsat-1r.cr.chiba-u.ac.jp and were used to investigate the temporal variation of horizontal distributions of brightness temperatures of the IR band, T_b. MTSAT is the Japanese geostationary satellite centered on 140°. The horizontal and temporal resolutions of the MTSAT IR channel are respectively 4 km and 30 min. We need to correct the parallax effect when using MTSAT data. Fig. 1 shows a schematic diagram of the parallax effect. MTSAT measures T_b of deep convection at A. However, that T_b is recorded at B in MTSAT data because latitude and longitude of MTSAT data are registered on the surface of the earth. For simplicity, we assumed all cloud top heights were 18 km to correct the T_b parallax effect. The parallax shift is 20–30 km in our case studies in Section 3.

Data from the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC), wetPrf, were used to quantify temporal and horizontal distributions of vertical profiles of temperature. COSMIC comprises six satellites and uses received GPS radio waves to retrieve atmospheric temperature profiles (Anthes et al., 2008).

The data of radiosonde were downloaded from the web site http://weather.uwyo.edu/upperair/sounding.html. ERA-Interim datasets were downloaded from http://apps.ecmwf.int/datasets/data/interim_full_