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Semitransparent cirrus clouds in the tropical tropopause layer during two contrasting seasons

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ABSTRACT

Association between semitransparent cirrus (STC) and tropospheric dynamics during the two contrasting seasons (Summer-monsoon and Winter) is studied using lidar and MST radar observations at Gadanki (13.5°N, 79.2°E) along with data from Geo-stationary satellite (KALPANA-1). The tropical tropopause layer (TTL) is found to be very conducive for the formation of STC. For those thicker STCs forming within TTL, the cloud top remains mostly steady with the top of the TTL, while the cloud base varies significantly in accordance with the altitude extent of tropospheric convective outflow. Based on depolarization characteristics of STCs (from lidar) along with regional distribution of tropospheric clouds derived from satellite data, altitude profile of horizontal wind, wind field at 150 hPa and air mass back trajectories, it can be reasonably inferred that, while the multi-layered and highly structured STCs during the monsoon period originate mostly from the deep convections, the sub-visual/ultra thin STCs during winter could mostly be of *in situ* origin.

1. Introduction

In the tropics, the region between the top of the tropospheric convective outflow (detrainment layer) and the altitude at which temperature reaches a minimum (cold point tropopause) is usually referred to (Fueglistaler et al., 2009) as the tropical tropopause layer (TTL). This is a transition region where the stratospheric radiative heating takes over the convective cooling from below. In the lower part of the TTL, even though the convective process dominates, the influence of radiative heating will not be insignificant. The effect of convection steadily decreases with increase in altitude and the radiative process gradually takes over. However, above the cold point effect of tropospheric convection is generally insignificant except for the "convective overshoots" associated with strong convective events. Based on the physical processes of interest, four different types of tropopause are defined over the tropics delineating the significance of each (Satheesan and Krishna Murthy, 2005). They are respectively the cold point tropopause, lapse rate tropopause as defined by WMO, level of top of all major convective outflows and level of minimum potential temperature lapse rate. In this context, it would be worth to note that all these levels of tropopause lie within the above defined tropopause layer.

This transition layer, which is home to different types of cirrus clouds, plays a key role in the vertical transport of water vapour and other chemical constituents into the stratosphere. As the tropical cirrus occurs at a higher altitude compared to those in middle and high latitudes, the ambient temperature is usually very small and in a few cases it decreases below 191 K. Because of this, cirrus clouds forming in the TTL region attract considerable interest. These clouds are believed to be a significant contributor to atmospheric greenhouse effect (McFarquhar et al., 2000; Haladay and Stephens, 2009) as well as hypothesized to play a major role in the dehydration of the lower stratosphere (Jensen et al., 1996; Luo et al., 2003) and thus becomes an important factor governing global climate, through their positive feedback.

Properties of tropical cirrus forming within the TTL could be strongly coupled with the convective activity in the troposphere. Shear production and buoyancy effects are also believed to play a dominant role in upper tropospheric turbulence associated with cirrus clouds (Smith and Jonas, 1996). In the near past, significant efforts are being pursued to study the properties of the tropical cirrus using lidar from Gadanki (Parameswaran et al., 2003; Sunilkumar and Parameswaran, 2005) mainly to understand their general features and frequency of occurrence in different periods of the year. These studies also revealed a close association between the altitude structure of turbulent kinetic energy and cirrus formation (Parameswaran et al., 2003). The present study is

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mainly concentrated on the properties of cirrus cloud forming within the TTL region and the plausible mechanism responsible for the generation of these clouds in two contrasting periods, monsoon and winter of the year.

2. Experiment and data

The MST radar is operated in vertical beam mode continuously for three days in each month during the period August 2004–January 2005, mainly to study the diurnal evolution of TTL in different periods of the year. Altitude profile of backscattered signal from MST radar with an altitude resolution of 150 m in vertical, at every 45 s for a duration of ~2 h are Fourier analyzed to derive the Doppler spectra. The first moment of the Doppler spectra provides the mean Doppler frequency from which the vertical wind velocity (w) is estimated. Time series of vertical wind data for every 2 h at different altitudes are used to derive the altitude profiles of temperature, horizontal divergence and turbulence parameters (Satheesan and Krishna Murthy, 2002, 2005).

The monostatic lidar equipped with Nd:YAG laser (Model: PL8020, Continuum, USA) emitting linearly polarized pulses at its second harmonic wavelength of 532 nm with 550 mJ pulse energy has laser pulse-width of 7 ns at a repetition rate of 20 Hz with a beam divergence of 0.45 m rad. The backscattered signal received using a 350 mm diameter telescope is separated into two orthogonal polarized components and acquired in photon counting mode with a basic altitude resolution of 300 m and time resolution of 250 s. This is used to estimate the backscatter ratio for the two orthogonal components (R_P and R_S, respectively) as well as the effective backscatter ratio (R) and the volume depolarization ratio (VDR) (Parameswaran et al., 2003). The cirrus cloud is identified from the altitude profile of lidar backscatter coefficient in the region up to 20 km, when the backscatter ratio in either of the two (cross-polarized) components exceeds a threshold value of 2, with a value of VDR exceeding 0.04. The applicability of this threshold condition is explained in detail in an earlier communication (Sunilkumar et al., 2003). The cloud optical depth is estimated from the lidar data by integrating the extinction coefficient from the cloud base to cloud top identified using the above criteria. The cloud optical depth is a measure of cloud strength (Sunilkumar et al., 2003), defined from the first moment of cloud backscatter ratio. Lidar is operated continuously for a period of 7–8 h during the night, when visibly clear (star lit) sky conditions prevailed, to study the properties of prevailing cirrus clouds. Role of upper tropospheric dynamical features associated with these cirri are examined from the MST radar data.

Regional distribution of tropospheric clouds over the Indian subcontinent and the surrounding oceanic regions derived from the brightness temperature observed in the water vapour (WV) and thermal infrared (TIR) channels of the very high resolution radiometer (VHRR) onboard the Indian geo-stationary satellite KALPANA-1 using the bi-spectral method (Roca et al., 2002) is used to study the spatial distribution of different types of clouds over the study region during the campaign period. The method of detecting different types of clouds including STC is discussed in the earlier publication (Rajeev et al., 2008). The amount of deep convective cloud and its geographical coverage provide the information on the spatial pattern of prevailing deep convections. This is used to infer the details regarding the source of semitransparent cirrus (STC) originating from convective outflows and that due to withering of convective clouds by strong wind shears. The origin of STC at a particular location at any time can then be traced back from air mass trajectories. In case if these trajectories do not encounter a convective system, it is quite reasonable to infer that the particular STC has not originated from a convective system and hence could be of *in situ* origin. Thus the satellite image along with the air back trajectories (from NCEP) is used to infer the genesis of the observed STCs during different phases of this campaign.

3. Convective outflows and the tropical tropopause layer

Rather than a well-defined layer at a particular altitude, the tropopause over the tropics is a transition region having finite width. This region extends from the top of the convectively dominated troposphere up to the base of the radiatively heated stratosphere. Depending on the physical process of interest, a particular altitude in this region is taken as the layer separating the troposphere and the stratosphere. In the following, we examine this aspect in detail before studying the properties of cirrus clouds in the upper troposphere.

The MST radar data recorded continuously for a period of 2 h are used to derive the altitude profile of temperature up to 22 km corresponding to this period, following the method described by Revathy et al., (1996, 1998). This method mainly involves identifying the Brunt–Väisälä frequency (N) from the temporal spectrum of the vertical wind (w). Using this altitude profile of N, the altitude profile of temperature is obtained through integration, using the surface temperature as the boundary value. From the altitude profile of temperature, the altitude at which the temperature reaches a minimum, defined as the cold point tropopause (CPT), is identified (as h_C). The altitude profile of vertical wind averaged for the same 2 h period is also used to derive the altitude profile of horizontal divergence following the method described by Satheesan and Krishna Murthy (2005). This method uses the continuity equation in which the local rate of change in density and the horizontal advection terms are neglected (Mehta et al., 2008). The horizontal divergence (D) can be expressed in terms of vertical wind as $D=(w/H)-(dw/dh)$. In this expression, positive values of D represent horizontal divergence and negative values the convergence. The scale height H is obtained using the temperature profile derived from the vertical wind for the same period. The altitude profiles of D are subjected to nine-point running mean filter mainly to filter out the small-scale fluctuations (if any) and generate a smooth profile, designated as the profile of $\langle D \rangle$. From this profile, the altitude of the major peak in divergence closest to but below the cold point tropopause is identified as the level of major convective outflow. The top of this outflow is designated as h_{DM} , the detrainment level of major convection cell. The horizontal divergence profile $\langle D \rangle$ generally exhibits more than one peak indicating the presence of convective detrainment at more than one level. The topmost altitude below which all the major convections get detrained is identified from the altitude profile of $\langle D \rangle$ as the top of that outflow closest to h_C where the value of divergence is $\geq$ 20% of its value at the major outflow level (h_{DM}) (Mehta et al., 2008) and designated it by h_{DC}. It is quite reasonable to assume that below this altitude all the major convections in the troposphere get detrained and hence indicate the level up to which convection dominates. This altitude is referred to as the convective tropopause. Note that h_{DC} showed a good correspondence with the attitude of minimum potential temperature gradient, which is also used for defining the tropopause in some cases (Mehta et al., 2008). Major features of this convective tropopause are explained in detail in the earlier publication (Mehta et al., 2008). If there is no such secondary peak in $\langle D \rangle$ profile between h_{DM} and h_C then h_{DM} itself is taken as the convective tropopause.