Atmospheric Research 161–162 (2015) 14–24

Contents lists available at ScienceDirect

Atmospheric Research

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

Role of deep convection on the tropical tropopause characteristics at sub-daily scales over the South India monsoon region

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ARTICLE INFO

Article history:
Received 26 June 2014
Received in revised form 12 March 2015
Accepted 17 March 2015
Available online 24 March 2015

Keywords:
Convection
Tropical tropopause parameters
Radiosonde
TTL

ABSTRACT

The role of deep convection on the tropical tropopause parameters at sub-daily scales using radiosonde observations at two locations in South-India affected by monsoon has been investigated. Special experiments were conducted under the Tropical Tropopause Dynamics (TTD) campaigns from two stations, (Gadanki (13.5°N, 79.2°E) and Trivandrum (8.5°N, 76.9°E) as a part of CAWSES India Phase-II programme during December 2010 to September 2013. In addition, data from regular radiosonde launches available from April 2006 to September 2013 are also utilized in the present study. Using satellite based infrared brightness temperature data, convection is classified into six categories based on the life cycle of the convection prevailing 3 h before and after the balloon reaching the tropical tropopause. Cold-point and lapse rate tropopause altitudes (CPH, LRH) and temperatures (CPT, LRT), convective outflow level (COH) and tropical tropopause layer (TTL) thickness extracted from individual soundings are grouped into six convection categories. Large amount of water vapour with diabatic cooling prevailed near the CPH during active convection leading to STE processes. At the same time, decrease in TTL thickness is observed not only because of pushing up of the COH but also due to decrease of CPH. On an annual basis a decrease (increase) in CPH and LRH (CPT and LRT) is noticed during active convection. This feature is more significant at Gadanki compared to Trivandrum. During the monsoon and pre-monsoon periods when the convection is rather widespread, CPH (CPT) shows a decrease (increase) at Gadanki while it increases (decreases) over Trivandrum. Large seasonal variation is noticed in the tropopause parameters even when they are segregated into different convective categories mainly due to intensity of the convection being different. During active convection, diabatic and adiabatic processes seem to be dominant at Gadanki and Trivandrum, respectively.

1. Introduction

Tropopause, which is considered to be the interface between regions of convective and radiative equilibrium, plays an important role in stratosphere–troposphere exchange (STE) processes (Holton et al., 1995). The magnitude of the coldest temperature around tropical tropopause and the sharpness of its gradient around this region determine the entry of water vapor into the lower stratosphere (Robinson, 1980; Mote et al., 1996). The tropopause in the tropics is not a sharp interface but an extended layer having the properties of both troposphere and stratosphere. This layer which is known as the tropical tropopause layer (TTL) extends over a few kilometres in thicknesses (Fueglistaler et al., 2009; Randel and Jensen, 2013). The boundaries of the TTL are, however, governed by radiative, convective and thermodynamic constraints. It is also considered as a layer between the level of convective outflow and cold point tropopause (Gettelman and Forster, 2002). The TTL is the region through which the exchange of minor constituents like water vapour and ozone takes place between the troposphere and stratosphere thereby affecting the global climate (Fueglistaler et al., 2009), in general. The variation in the altitude and temperature of the tropopause itself is considered to be a sensitive indicator of climate change (Santer et al., 2003).

Several processes like large scale circulation, small scale waves and convective activities influence the transport between the troposphere and stratosphere (Holton et al., 1995; Reid and Gage, 1996; Randel and Jensen, 2013). Deep convection which is quite frequent is considered to be a significant phenomenon responsible for the vertical transport of trace constituents in the tropics (Sherwood and Dessler, 2003). In general deep convection in the troposphere causes cooling in the TTL region (Kim and Dessler, 2004). However, it is not clear whether this cooling is due to convective detrainment and turbulent mixing (Sherwood et al., 2003) or due to radiative cooling caused by reduction of long wave radiation (Webster and Stephens, 1980). Among these, convective detrainment and the effect of overshooting convection on the heat balance of the TTL (Danielsen, 1993; Sherwood and Dessler, 2003; Randel and Jensen, 2013) remain rather unexplored. Several attempts have been made earlier to delineate the effects of tropical deep

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http://dx.doi.org/10.1016/j.atmosres.2015.03.012
0169-8095/

convection in modulating the TTL and the tropopause on day-to-day, monthly, seasonal, annual and inter-annual scales (Reid and Gage, 1996; Krishna Murthy et al., 1986; Kim and Dessler, 2004; Venkat Ratnam et al., 2005; Chae et al., 2010; Mehta et al., 2010; Paulik and Birner, 2012; Kumar et al., 2014; Parameswaran et al., 2003). However, the studies on tropopause at short time scales (day and less than a day) in relation to convection over land are sparse. Aircraft experiments to investigate the STE processes showed the ability of deep convection in the transport of air between the troposphere and stratosphere over the warm western pool region (Russell et al., 1993). A few studies were also carried out on the short-term variability of the tropopause (Johnson, 1986) and effect of convection (Sherwood et al., 2003). Mehta et al. (2008, 2010) has investigated the tropopause variation at sub-daily scales over the Indian region and found that the tropopause descends during the deep convection. They also indicated the need for a systematic examination of the tropopause during different convective conditions such as deep, shallow and no convection. However, no systematic attempts were made earlier to investigate its role at sub-daily scales over the Indian region (except a few studies like Mehta et al., 2008) despite the Indian region being one of the potential source regions for much of the air entering into the lower stratosphere (Highwood and Hoskins, 1998). Several other complex processes are also active through the unique weather conditions associated with the Indian Summer Monsoon dynamics (e.g., Vernier et al., 2009; Nishi et al., 2010; Jain et al., 2011; Panwar et al., 2012). Recent studies (Jain et al., 2013) have shown that convection over the Asian region is very deep and covers a larger geographical area as compared to the African and American summer monsoon regions. In order to understand the features of convection and its effects on the tropopause and TTL in this region, a special campaign namely Tropical Tropopause Dynamics (TTD) experiment (Venkat Ratnam et al., 2014a) that includes 3 h radiosonde launchings from two stations, namely, Gadanki (13.5°N, 79.2°E) and Trivandrum (8.5°N, 76.9°E) in the Indian region was designed and implemented as a part of the CAWSES-India, Phase II from December 2010. In the present study, an attempt has been made to examine the role of tropical deep convection in modulating the tropopause parameters on sub-daily scales over the South-Indian monsoon region.

2. Database

2.1. GPS radiosonde observations

To investigate the effects of tropical convection on the tropical tropopause characteristics, data from high resolution radiosondes (Väisälä RS-80 (April 2006 to March 2007), RS-92 (July to August 2006) and Meisei RD-06G (May 2007 to September 2013)) launched daily around 1730 IST (IST = UT + 0530 h) from Apr. 2006 to Sep. 2013 over Gadanki (13.45°N, 79.2°E), a tropical station lying in the southern peninsular region of India, is used. Note that there is no difference in the accuracies of the radiosonde instruments of different makes. However, there is a difference in the altitude resolutions. For Väisälä RS-80 it is 25–30 m (sampled at 5-s intervals) whereas for the other two radiosondes it is 10 m (sampled at 2-s intervals). So the entire data set is gridded at 100 m to bring the data to a uniform altitude interval and also to remove any outliers arising from random motions of the balloon. Quality checks are then applied to remove any further outliers arising due to various reasons to ensure high quality in the data. For details of these radiosondes and quality checks applied readers are referred to Mehta et al. (2011) and Venkat Ratnam et al. (2014b).

In order to investigate the variation of the tropical tropopause at sub-daily scales, radiosondes were launched every 3 h at 1130, 1430, 1730, 2030, 2330, 0230, 0530 and 0830 IST for three consecutive days in each month since December 2010 during special campaigns called Tropical Tropopause Dynamics (TTD) (Venkat Ratnam et al., 2014a) in addition to the regular daily evening launchings. Radiosondes were also launched from Trivandrum (8.5°N, 77°E), which is located at the southern tip of peninsular India, at the same timings since December 2010. Details along with the dates of these launchings can be had from Venkat Ratnam et al. (2014a). The data used for the present study includes 2591 (713) profiles of temperature (T), relative humidity (RH), zonal (U) and meridional (V) wind velocities obtained during April 2006 to September 2013 (December 2010 to September 2013) from Gadanki and around 646 profiles from Trivandrum from December 2010 to September 2013.

2.2. Infrared brightness temperature (IRBT) observations

It is well established that the IRBT, which is considered to be the equivalent blackbody temperature of the cloud top, can be used as a proxy for the convection. The IRBT observations are obtained from the Multifunctional transport Satellite (MTSAT-1R) which was provided by the Japan Meteorological Agency (JMA). This data, which is in the form of an array having a resolution of $0.1° \times 0.1°$ for latitude and longitude grids between 11°N to 15°N and 78°E to 81°E, available at 1 h intervals, covering 200 km of the launching site of Gadanki during April 2006 to September 2013, is utilised for this study. We also made use of the IRBT observations available for every half an hour with better resolution ($0.03° \times 0.03°$) obtained from the Climate Prediction Centre/NCEP/NWS covering both Gadanki and Trivandrum locations for TTD campaigns. Note that this data is a merged global product obtained from all available geostationary satellites (GOES-8/10 METEOSAT-7/5 & GMS) after correcting it for their viewing angles.

3. Background meteorological and atmospheric conditions over Gadanki and Trivandrum

It is desirable in this context to note the background atmospheric conditions prevailing at both the stations, Gadanki and Trivandrum, particularly in the vicinity of the tropopause. Over the Indian subcontinent, meso-scale phenomena, which include convective activity, dominate throughout the year. Based on background weather conditions India Meteorological Department (IMD) (http://www.imd.gov.in/) has divided the year into four seasons, namely winter (December–February), summer/pre-monsoon (March–May), monsoon/progressing South West (SW) monsoon (June–September), and post-monsoon/retreating SW monsoon/North East (NE) monsoon (October–November). The onset of the SW monsoon occurs in the first week of June (over Trivandrum), and its withdrawal starts in the middle of September (from the central India). Thereafter, NE monsoon prevails during October to November over south-eastern part of India, until the monsoon front withdraws fully from the Indian subcontinent.

The climatological monthly mean contours of temperature (T), relative humidity (RH), zonal wind (U) and meridional wind (V) observed over Gadanki averaged during April 2006 to Sep. 2013 (from 1730 IST regular launchings) are shown in Fig. 1(a)–(d), respectively. The climatological monthly means of cold-point tropopause altitude (CPH) and lapse rate tropopause altitude (LRH) along with the convective outflow level (COH) (the definitions of these are given in Sub-section 4.1) are also included in these figures. In general, the seasonal variation of temperature below 14 km (Fig. 1a) is very small compared to that near the tropopause. Higher (lower) altitudes and colder (warmer) temperatures can be noticed for the tropopause during winter (summer) months. The CPH shows strong seasonal variation with its altitude being highest during the winter season (17.7 km) and lowest during the summer monsoon season (16.5 km). The variations of the CPT show an opposite variation with highest temperature of 194 K during the pre-monsoon season and lowest temperature of 190 K during the winter season. The CPH and CPT on individual days vary from 18.5 km to 16.2 km and 195 K to 188 K, respectively. These features are consistent with those reported earlier (Mehta et al., 2010; Sunilkumar et al., 2013). Large variation in RH from winter to monsoon seasons can be noticed from Fig. 1(b). During winter, RH is very low (about 50%) which is