Journal of Atmospheric and Solar-Terrestrial Physics 121 (2014) 240–247

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

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

Detection of tropopause altitude using Indian MST radar data and comparison with simultaneous radiosonde observations

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A R T I C L E I N F O

Article history:
Received 10 February 2014
Received in revised form
3 September 2014
Accepted 10 September 2014
Available online 16 September 2014

Keywords:
Tropical tropopause
MST radar
Radiosonde
Long-term variability

A B S T R A C T

The structure and variability of tropical tropopause over Gadanki (13.5°N, 79.2°E) are delineated using data obtained from Indian MST radar operated in the vertical mode as a part of intense Tropical Tropopause Dynamics (TTD) campaigns conducted under the CAWSES India Phase II (Theme 3) program. Radar measurements for 72 h in each month from December 2010 to September 2013 have been considered. The identified tropopause altitude with radar (RTH) is compared with the cold point (CPH) and lapse rate tropopause altitudes (LRH) obtained from simultaneous radiosonde data at three hourly intervals during these campaigns. Most of the time, a very good agreement between the RTH and CPH and/or LRH from radiosonde measurements is observed. The mean difference between RTH and CPH and RTH and LRH is found to be 0.1 ± 1 km and 0.5 ± 1 km, respectively. The smaller differences between RTH and CPH noticed in the present work when compared to other mid- and polar latitudes might be due to the well defined tropopause structure in the tropical latitudes. As the radar provides reliable data on the tropopause, its long-term variability is investigated using the data from 2007 to 2012 available from the MST radar.

1. Introduction

The tropopause, which is the boundary between troposphere and stratosphere, plays a crucial role in the exchange of the mass, water vapor and other chemical species between the two atmospheric regions (Holton et al., 1995). These exchanges, broadly termed as Stratosphere–Troposphere Exchange (STE) processes, are mainly governed by the properties of this interface region. In this scenario, it is very important to understand the physical processes occurring around the tropopause region. The tropopause itself varies at different time scales, from sub-daily scales to day-to-day, monthly, seasonal, annual, inter-annual and to the solar cycle. Note that an increase in the tropopause altitude due to both natural and anthropogenic sources has been reported (Santer et al., 2003). Recent studies have shown that the tropical tropopause is not just a material surface but more of a transition layer named as the ‘tropical tropopause layer (TTL)’ which extends from the top of the turbulently mixed troposphere to the relatively stable stratified stratosphere (Gettelman and Birner, 2007; Fueglistaler et al., 2009). The top of the TTL is marked by the cold point tropopause altitude (CPH) and the base by the level of the top of all the major convective outflows, named as convective tropopause (COT).

In general, radiosonde observations carried out globally twice per day, are used to identify the tropopause on a global scale. Using temperature profile obtained from radiosonde, the tropopause is defined in different ways (Highwood and Hoskins, 1998), and the most commonly used one in the tropics is the cold point tropopause. The CPH is defined as the altitude of the temperature minimum that necessarily exists between the troposphere (where temperature decreases with altitude) and the stratosphere (where temperature increases with altitude). Another definition of the tropopause is the lapse rate tropopause altitude (LRH) defined by World Meteorological Organization World Meteorological Organization (WMO) (1957) as, ‘the lowest level at which the lapse rate decreases to 2 K/km or less provided that the average lapse rate between this level and all higher levels within 2 km does not exceed 2 K/km.’ As the radiosondes are generally launched twice a day world-wide, the data are useful mainly to investigate the tropopause variability from day-to-day to monthly,

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http://dx.doi.org/10.1016/j.jastp.2014.09.008

seasonal, annual, inter-annual and long-term trends (e.g., Reid and Gage, 1985; Krishnamurthy et al., 1986; Highwood and Hoskins, 1998; Shimizu and Tsuda, 2000; Randel et al., 2000; Seidel et al., 2001; Santer et al., 2003). Using radiosonde data from special campaigns with more than two launches per day, some case studies have been reported on its sub-daily variability at a few stations (e.g., Sherwood et al., 2003; Mehta et al., 2008). Several studies have been carried out to investigate the role of tides (Venkat Ratnam et al., 2014a, in this issue) and Kelvin waves (Tsuda et al., 2006) on the tropical tropopause using radiosonde observations from such special campaigns. Though modern satellites are able to provide observations with reasonably good spatial coverage, temporal and vertical resolutions remain a limitation. Global Position System (GPS) Radio Occultation (RO) measurements have provided new insight into the tropopause variability globally with their high vertical resolution and high accuracy measurements. These observations are well utilized to investigate day-to-day variability to long-term trends (Venkat Ratnam et al., 2005; Schmidt et al., 2010; Wang et al., 2013). However, temporal resolution is rather poor over a given grid/location and thus impossible to investigate sub-daily scale variability at a particular location. Therefore, short time scale variability of tropopause is not well established due to lack of proper instruments.

As MST radar returns depend on the refractive index fluctuations which in turn depends on temperature and water vapor gradients in the troposphere, they can be effectively utilized to identify and study the tropopause. For the first time, Gage and Green (1979) detected the tropopause from radar measurements and there exist a few studies using these radars across the world dealing with the tropopause (Alexander et al., 2013 and references therein). Note that MST radars are capable of continuous atmospheric monitoring (Gage and Green, 1982) with a much high temporal resolution than the radiosonde though the radar network is very small when compared to the radiosonde network. Different algorithms have been proposed to detect the tropopause altitude from the radar measurements such as, from the radar echo power (Tsuda et al., 1988; Nastrom et al., 1989; May et al., 1991), including the peak echo power (Vaughan et al., 1995; Yamamoto et al., 2003; Hall, 2013), the peak in the echo power gradient (Vaughan et al., 1995; Hooper and Arvelius, 2000; Alexander et al., 2013), the absolute value of echo power (Gage and Green, 1982) and stable layers (Jaya Rao et al., 1994). Using Indian MST radar located at Gadanki (13.5°N, 79.2°E), a few studies (Jaya Rao et al., 1994; Das et al., 2008) were carried out for detecting tropopause altitude and its sub-daily scale variability. However, detailed comparisons with established techniques like radiosonde in different seasons and its long-term variability remained yet to be carried out.

In the present study, we mainly focus on validation of the radar detected tropopause altitude with high vertical and temporal resolution radiosonde observations. For this study, we have conducted special campaigns called Tropical Tropopause Dynamics (TTD) (Venkat Ratnam et al., 2014b, in this issue). In these campaigns, the radar was operated for 72 h continuously in each month under the CAWSES India Phase-II program (Theme 3) over Gadanki. Radar detected tropopause altitude (hereafter called as RTH) is compared with the simultaneous radiosonde identified tropopause altitude obtained at 3 h intervals during these campaigns. The details of the data used and typical examples are mentioned in Sections 2 and 3, respectively. The analysis procedure adopted for detecting the tropopause altitude using MST radar observations is mentioned in Section 4, inter-comparison between RTH and radiosonde identified CPH and LRH is presented in Section 5 and on long-term variability in Section 6. Finally, summary and conclusions drawn from the present study are presented in Section 7.

2. Database

2.1. MST radar observations

The Indian MST radar located at Gadanki is a high power coherent backscatter VHF radar operating at 53 MHz with an average power aperture product of $\sim 7\times10^{8}$ W m^{2} and a peak power of 2.5 MW. The detail description of MST radar is given in Rao et al. (1995). This radar is operated for 72 h in two modes in each month since December 2010 with the specifications mentioned in Table 1. Details of these campaigns are presented in Venkat Ratnam et al. (2014b, in this issue). In the first mode, radar is operated for half-an-hour using all the 6 beams (E, W, Zy, Zx, N, S) for getting background wind structure. This is followed by second mode for continuous 6 h operation in only one vertical beam i.e., Zy. These two modes follow with a break for half-an-hour. This cycle is repeated for 72 h in each month. This period of 72 h is selected randomly depending on the radar time availability. The vertical resolution of this data is 150 m and temporal resolution is 35 s. Data from 29 such campaigns conducted during December 2010 to September 2013 are used in this study to detect the tropopause altitude from MST radar and compared with simultaneous radiosonde observations. Details of these campaigns are summarized in Table 2 of Venkat Ratnam et al. (2014b, in this issue).

Additionally, the vertical beam data from the MST radar operated for about half-an-hour to 45 min around 12 UTC (IST=UTC+0530 h) in the common mode since January 2007 has also been utilized here to study the long-term variability of the tropopause altitude. Though the radar is being operated with all the 6 beams for the common mode data acquisition, only the vertical beam data are considered in the present study. Vertical resolution of this data remains the same but the temporal resolution of this data is ~3.33 min as we selected only the vertical beams. Quality checks are applied to remove outliers, if any, following procedure mentioned in Mehta et al. (2011).

2.2. GPS radiosonde observations

High vertical resolution and high accuracy radiosonde flights are carried out at Gadanki using Meisei (RD06G) GPS radiosonde (Venkat Ratnam et al., 2014c) at 3 h intervals during the above mentioned TTD campaigns for three consecutive days in each month. The details of such launches are listed in Table 2 of Venkat Ratnam et al. (2014b, in this issue). From the radiosonde, data of zonal wind (U), meridional wind (V), temperature (T), and relative humidity (RH) were collected from ground level up to 32–35 km, with an altitude resolution of 10 m (2-s interval). This data is later gridded to 150 m to remove outliers, if any, arising from the random motion of the balloon and also to match with radar observations. Quality checks are again applied to remove outliers, if any, following procedure mentioned in Mehta et al. (2011). The

Table 1
Specification of MST radar operated for the present study.

Parameter	Specification
Frequency	53 MHz
No. of range bins	170
No. of FFT points	512
No. of coherent integrations	64
Inter-Pulse Period (IPP)	1000
No. of incoherent integration	1
Beam directions	All 6 beams (E, W, Zy, Zx, N and S) for half-an-hour and Zy alone for 6 h
Range resolution	150 m