

RESEARCH ARTICLE

Indian summer monsoon onset signatures on the tropical tropopause layer

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Over the Indian region, changes in the tropopause parameters during pre-monsoon to monsoon seasons have been reported. However, no study exists to date dealing with the Indian summer monsoon (ISM) onset signatures on the tropopause parameters. In the present study, the climatological structure of the tropical tropopause layer during the onset phase of ISM is delineated by using long-term (2006–2017) radiosonde observations over Gadanki (13.5°N , 79.2°E). A prominent transition in the tropopause parameters from pre-monsoon to monsoon is noticed and the transition is initiated from the day of ISM onset. Continuous decrease (increase) of tropopause altitude (temperature) is perceived after the ISM onset. The ozonesonde observations clearly show the strong enhancement in the ozone mixing ratio in the lower stratosphere ($\sim 16\text{--}20$ km) after the ISM onset. This clearly demonstrates the instantaneous warming of the tropopause region after the ISM onset in addition to the latent heat release due to the precipitation. Transitions from pre-monsoon to monsoon in the tropopause parameters are influenced strongly by onset of ISM which was attributed as seasonal changes earlier. These results provide strong evidence on the ISM onset signatures on the tropical tropopause parameters.

KEY WORDS

Indian summer monsoon, onset, STE process, tropopause layer

1 | INTRODUCTION

Indian summer monsoon (ISM), the seasonal reversal of the wind occurring in May–June, brings a huge amount of moisture from the Arabian Sea to the Indian subcontinent through south westerlies (Basha and Venkat Ratnam, 2013). One of the important and characteristic features of the ISM is its sudden onset which occurs over southern tip of India generally known as monsoon onset over Kerala (MOK). It is characterized by sudden and abrupt changes in the circulation and rainfall intensity. However, at the surface the ISM onset is first noticed by variability in the rainfall and a number of dynamical and thermodynamic precursors (Ananthakrishnan and Soman, 1988). In general, India Meteorological Department (IMD) declares the ISM onset dates in each year for the operational purpose. More details about the ISM onset

declared by the IMD can be found in Pai and Rajeevan (2009). The mean climatological date of the ISM onset is around June 1 with an inter-annual standard deviation of ~ 7 days (Pai and Rajeevan, 2009). Change in the wind direction from easterly to westerly, strengthening of low level jet (LLJ), tropical easterly jet (TEJ) speed crossing 30 m/s (Jagannadha Rao *et al.*, 2007), northwards moving of Intertropical Convergence Zone (ITCZ), increasing of convection activity (Sikka and Gadgil, 1980) and enhancement in the upper tropospheric humidity (Fasullo and Webster, 2003) during the transition period will change the thermal structure of the upper troposphere and lower stratosphere (UTLS).

In recent years, the tropical tropopause is getting more attention in the atmospheric research as the tropopause variability itself is considered as sensitive indicator for climate change (Santer *et al.*, 2003; Sausen and Santer, 2003; Son

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et al., 2009). The tropical tropopause, usually referred to as the boundary between the troposphere and the stratosphere, plays a significant role in the exchange of mass, momentum and minor species like ozone and water vapor between the two regions (Highwood and Hoskins, 1998; Gettelman and Forster, 2002; Fueglistaler *et al.*, 2009). The tropopause can be defined in many ways and the commonly used one in the Tropics is cold point tropopause (CPH; Highwood and Hoskins, 1998). It is defined as the altitude of the coldest point in the temperature profile that exists between troposphere and stratosphere. Another definition is “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” called as lapse rate tropopause (LRH; World Meteorological Organization (WMO), 1957). The LRH definition is valid in the Tropics and the extratropics while the CPH is valid only in the Tropics. The CPH is believed to be more meaningful especially for water vapor transport than the conventional LRH (Highwood and Hoskins, 1998). The level of maximum convective outflow above which the lapse rate departs from its moist adiabatic value is defined as convective outflow level (COH). A minimum in the potential temperature gradient profile is identified as COH (Gettelman and Foster, 2002). The cold point tropopause temperature (CPT), lapse rate tropopause temperature (LRT) and convective outflow level temperature (COT) are the corresponding temperatures of CPH, LRH and COH, respectively. In recent years the tropopause over the Tropics is considered as a transition layer called as a tropical tropopause layer (TTL; Highwood and Hoskins, 1998; Fueglistaler *et al.*, 2009). The top of the TTL is marked by the CPH and the base by the COH. The altitude difference between CPH and COH is called as the TTL thickness.

The tropopause itself varies temporally as well as spatially and its variability over Gadanki has been well reported (Mehta *et al.*, 2010; RavindraBabu *et al.*, 2014; Venkat Ratnam *et al.*, 2014a). Recently, Yuchchen and Canziani (2017) reported the differences between lapse rate tropopauses (LRTs) and LRT-like tropopauses calculated from mandatory levels (LRTMs) by using 37 upper air stations data over India (1973–2015). Sunilkumar *et al.* (2017) reported the TTL structure based on the static stability criteria over Indian region. They suggested in such a way that the TTL is considered as a composite of three sub layers such as bottom layer (BL), middle layer (ML) and an upper layer (UL) embedded between the potential temperatures ~350–360, ~360–380 and 380–420 K, respectively. It is stated that the tropopause is minimum in monsoon and higher in winter seasons (Mehta *et al.*, 2010). Same time TTL thickness is low in monsoon and it is strongly correlated with convective activity (low OLR) on seasonal scales (Mehta *et al.*, 2010).

It is important to study and understand the variability of tropopause during the onset phase of the ISM. Though the seasonal variations are well documented in the literature, to the best of our knowledge no systematic study exists to date which deals with the changes in the tropopause parameters during the onset of ISM. Recently, Mondal *et al.* (2017) reported on the inter-annual variability in ISM onset over Gangetic West Bengal (22.5°–25°N; 85°–90°E) with respect to dynamical variability around the tropopause region. However, they reported on the temperature gradient (Tg) between tropopause level (100 and 70 hPa) and mid-troposphere level (500–200 hPa) and found that decreasing (increasing) trend in the temperature gradient at the tropopause level (mid-troposphere level) over GWB. Hence, in this study, we made an attempt to understand the variability of tropical tropopause parameters with respect to the onset of ISM. The main objectives of the present study is to investigate the plausible relationship between ISM onset and tropical tropopause parameters such as cold-point tropopause altitude/temperature (CPT), lapse-rate tropopause altitude/temperature (LRT), convective outflow level altitude (COH) and TTL thickness.

2 | DATABASE

Daily radiosonde data collected at 1730 IST (1200 UTC) during the months of May and June in each year from 2006 to 2017 over Gadanki (13.5°N, 79.2°E) are used in the present communication. We have checked the available total launches for each day from May 1 to June 30 during the abovementioned period and the total launches are plotted in Figure 1e. We have good number of launches (~8/day) for each day during the data period. The accuracy of Meisei radiosonde measured temperature (T) and relative humidity (RH) are 0.5 K, 5%, respectively. More details of the different radiosonde sensors and their accuracy can be found in Venkat Ratnam *et al.* (2014b). For ozone changes during the ISM onset period, we have utilized electrochemical cell (ECC) ozonesonde observations from 2012 to 2017, particularly in the months of May and June over Gadanki. We have also used Microwave Limb sounder (MLS) ozone and water vapor observations during same period in the present study.

In general, India Meteorological Department (IMD) declares officially ISM onset dates every year over the southern tip of the Indian peninsula which is also called as monsoon onset over Kerala (MOK). Climatological onset obtained from IMD is shown in Figure S1, Supporting Information. The onset dates which are obtained from the IMD monsoon reports during 2006–2017 are as follows: May 26, 2006; May 18, 2007; May 31, 2008; May 23, 2009; May 31, 2010; May 29, 2011; June 5, 2012; June 1, 2013; June 6, 2014; June 5, 2015; June 8, 2016 and May 30, 2017. The ISM onset shows strong inter-annual variations. It is clear that there are some normal onset years as well as early/late

onset years. Apart from this data set, we have also used NOAA interpolated outgoing longwave radiation (OLR) data from 2006 to 2013 which is used as a proxy for convection.

3 | RESULTS AND DISCUSSIONS

3.1 | Climatological thermo-dynamical parameters during ISM onset

During ISM onset, significant increase in the daily rainfall, enhancement of vertical moisture transport and an increase in the kinetic energy take place (Mohanty *et al.*, 1983). After the MOK, the moisture content in the air increases which results in growth of deep cumulus convection. The LLJ in the lower troposphere and TEJ in the upper troposphere strengthen owing to the increase in latent heat release associated with the ISM onset over the southern tip of India (Ramesh *et al.*, 1996). The abruptness of the ISM onset is

due to explosive growth of organized deep convection. The latent heat will be released in to the atmosphere due to the deep convection triggering by the ISM onset over Kerala, which causes generation of atmosphere waves such as gravity waves, Kelvin waves, etc. These generated atmosphere waves can travel horizontally as well as vertically. Dhaka *et al.* (2007) clearly showed the modulation of CPH due to the atmospheric waves over equatorial region. It is natural to expect the changes in the TTL over Gadanki during the onset day or with delay of few days due to this deep convection triggered during the ISM onset. Based on this hypothesis, the present study focused on the TTL variability with respect to the ISM onset. The composite analysis of the TTL with respect to ISM onset is very useful for understanding the common features of the TTL during the onset.

Figure 1 shows a composite of height time cross section of radiosonde measured temperature (T), relative humidity (RH), zonal wind (U) and meridional wind (V) averaged over 12 years (2006–2017) of daily radiosonde observations between May 1 and June 30. May and June

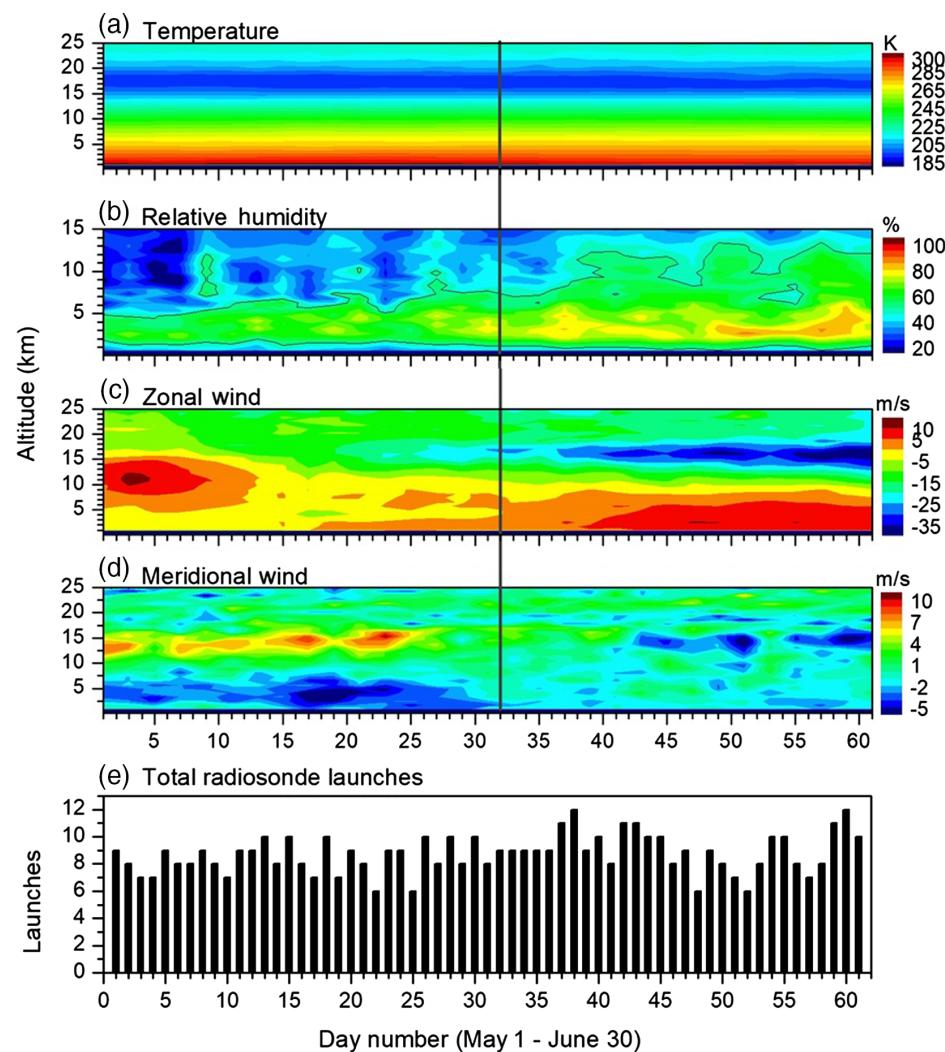


FIGURE 1 Climatological mean (2006–2017) contours of (a) temperature, (b) relative humidity, (c) zonal wind (d) meridional wind during May 1 to June 30 over Gadanki. Vertical line shows the climatological onset day over Kerala based on IMD reports. (e) Number of available radiosonde profiles on each day the same period

months represent the two different seasons and most of the time the onset of ISM will occurs last week of the May or first week of the June. Vertical black line shows the climatological onset day over Kerala (32nd day in Figure 1). Increase of the mid-troposphere humidity, strengthening of westerlies in the lower levels and exceeding of the zonal wind speed ~ 30 m/s in the upper troposphere can be noticed from Figure 1. Temperature does not show much variation and appears more or less identical (Figure 1a). However, the thickness of the minimum temperature between 15 and 20 km altitudes (blue color area) is gradually reducing as ISM progresses. In case of RH, significant distinct features are observed (Figure 1b). For the period May 1 to June 6 (1st–37th day in the figure), atmosphere is significantly drier above 6 km compared to the period after June 6. Higher RH values in the middle and upper troposphere (~ 10 –14 km) after June 6 indicating that the moisture transport due to the convection is reaching higher levels. This might be due to the transport of atmospheric moisture from Arabian Sea by strong southwesterlies during the monsoon. Over Indian region during monsoon period the convective clouds reaches ~ 7 km and these clouds can influence the moisture content in the upper troposphere (Jain *et al.*, 2015). The enhancement of mid-troposphere moisture after the onset of ISM is well known characteristics of ISM. It is clear that southwesterly in the lower levels and tropical easterlies in the upper levels become dominant after June 6 (Figure 1c). The zonal wind at upper levels crossed ~ 30 m/s on June 2 (33rd day in Figure 1) but the strengthening of this zonal

wind started from June 6 onwards. As earlier reported by Jagannadha Rao *et al.* (2007), the LLJ wind speed exceeds 8 m/s during the onset of ISM. The LLJ wind speed crossed 8 m/s on June 7 (38th day in Figure 1). Northwards wind in the upper troposphere and southwards wind in the lower troposphere is observed in the meridional wind during the month of May while during the month of June more or less southwards wind is observed. The observed climatological thermo-dynamical features and their changes are well captured the transition during ISM.

To see the changes between before and after the ISM onset more carefully, the composite analysis is made with respect to the onset day (set as zero). We have subtracted the mean onset profiles of T , RH, U and V from the corresponding individual daily profiles. The obtained anomaly in the T , RH, U and V are shown in Figure 2. Quite opposite features are noticed in the T anomaly during, before and after the onset. Before the onset, the T shows positive anomalies (~ 2 K) in the lower troposphere (\sim below 5 km) while negative anomalies are noticed between 8 and 13 km altitudes. Strong negative anomalies (>2 K) are noticed in the lower stratosphere (18–20 km) before the onset. Quite opposite features are noticed in the T anomalies just after the onset period. After the onset, the T anomaly shows the negative anomalies in the lower troposphere (below 5 km). However, strong positive anomalies are observed in the lower stratosphere (LT). However, some positive anomalies with less magnitude are noticed between 5 and 6 km altitudes and in the UTLS region (15–20 km) just 2 or 3 days after the onset.

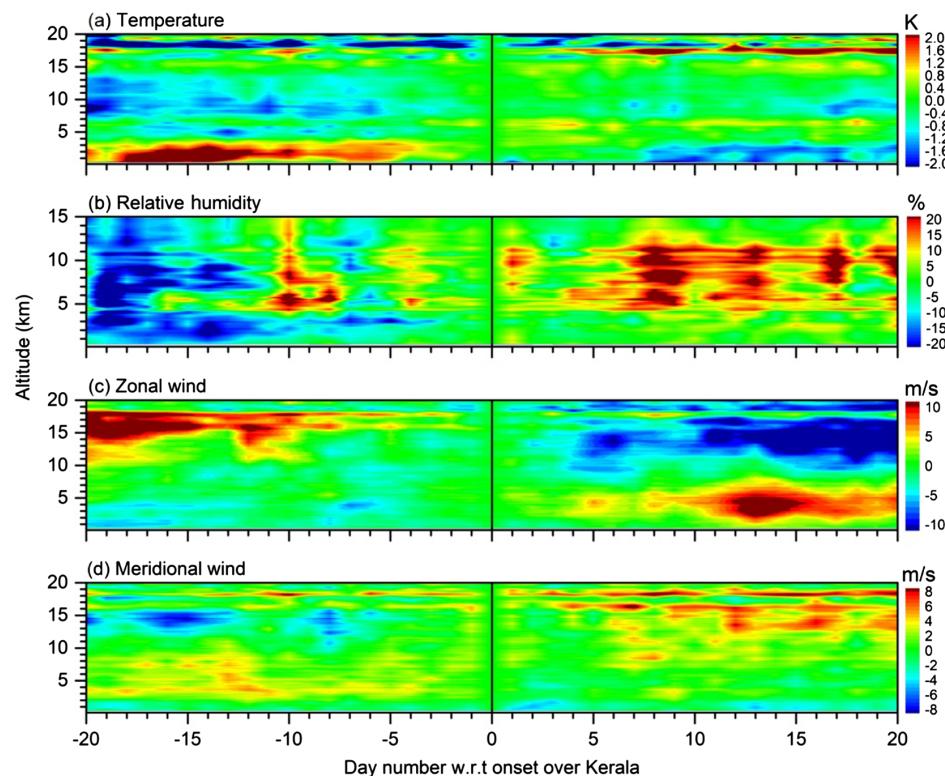


FIGURE 2 Climatological mean anomalies in (a) temperature, (b) relative humidity, (c) zonal wind and (d) meridional wind observed over Gadanki with respect to onset day over Kerala (onset day over Kerala as zero)

It is interesting to see that the changes in the T anomalies in the LT are more or less same up to 6 days from the day of onset. After 7 days from the onset, the T anomalies shows the strong positive anomalies in the UTLS region and more prominent in the lower stratosphere. Negative anomalies are observed in the LT. Interestingly, between 5 and 6 km altitudes, continues positive anomalies are observed. However, the magnitude of the T anomaly is less compare to the T anomaly observed in the lower stratosphere. This feature is clearly indicating the latent heat release due to the monsoon clouds. From the T anomalies, it is clear that the warming of the lower stratosphere over Gadanki is staring from 5 to 7 days after the MOK. This may be due to the either latent heat release due to precipitation or chemical species (ozone or water vapor) changes in the UTSL region. This aspect will be discussed in following sections. Gradual enhancement in the RH anomaly in the mid-troposphere is observed after the onset. This enhancement is started from the fifth day onwards and reaches higher altitudes after the seventh or eighth day then it sustained for next 10–15 days. Winds also shows same features as observed in T and RH, that is, strengthening of the LLJ and TEJ winds is clearly observed after the onset and this strengthening is more from the fifth day onwards. Thus, the observed anomalies clearly indicate that the transition of ISM over Gadanki will take around 5–7 days after the MOK.

Using the long-term radiosonde and OLR data, we have calculated different TTL parameters and OLR values during pre-monsoon and monsoon seasons over Gadanki. The calculated tropopause parameters during pre-monsoon (monsoon) are shown in Table 1. Drastic change in the tropopause parameters, that is, lowering of tropopause altitude, rising of the convective outflow level, lowering of TTL thickness and enhancement of convective activity from the pre-monsoon to monsoon season is clearly noticed from the above statistics. Though seasonal variations are well documented in the literature, changes in the TTL parameters associated with the onset of ISM have not been investigated yet.

3.2 | Climatological mean tropopause parameters with respect to ISM onset

The tropopause parameters are estimated using the daily radiosonde data obtained at 1730 IST during May 1 to June 30 of each year from Gadanki during 2006–2017. The composite analysis is made with respect to the date of MOK (set as zero). First, we have calculated the tropopause parameters from the daily available temperature profiles for the complete period. The obtained tropopause parameters are separated based on the MOK day for each individual year. Then we set the MOK day as zero and checked the variations in the tropopause parameters before (minus days) and after (plus days) the onset day. Finally using the composite analysis we have averaged 12 years of tropopause parameters.

TABLE 1 The 12-year mean calculated tropopause parameters from the daily radiosonde observations along with outgoing longwave radiation (OLR) during the pre-monsoon and monsoon seasons over Gadanki

Parameter	Pre-monsoon	Monsoon
CPH	17.5 ± 0.5	16.8 ± 0.5
CPT	189.9 ± 1.7	191.3 ± 2
LRH	17 ± 0.5	16.5 ± 0.5
LRT	190.5 ± 2.2	191.6 ± 2.2
COH	12.4 ± 1.4	12.9 ± 1.6
TTL thickness	5.1 ± 1.6	3.8 ± 1.6
OLR	241.5 ± 3.9	215.2 ± 3.3

Figure 3a,c shows the climatological mean values of CPH, LRH and COH along with corresponding temperatures (CPT, LRT and COT) with respect to the date of MOK. It is clear that the CPH and LRH shows significant decreasing trend after the ISM onset while the CPT and LRT shows the increasing pattern. Compared to CPH/CPT, LRH/LRT show more significant changes after the ISM onset. It is well known that the onset of ISM brings moist air from oceans resulting enhancement of moisture in the atmosphere, formation of clouds, less solar radiation and gradual decrease in the surface temperature. These changes during the onset can change the temperature lapse rate drastically in the lower troposphere. This may be the cause for observing more significant changes in the LRH/LRT than the CPH/CPT during the immediate onset of ISM. Generally the tropopause altitude and temperatures are in opposite phase (altitude decreases/temperature increases) indicating adiabatic processes. But after the onset (up to ~10 days), the phase of the tropopause altitude and temperatures remains the same. The processes which involve this could be due to one of the following: (a) convection, (b) exchange processes between troposphere (mainly water vapor) and stratosphere (mainly ozone), (c) horizontal advection from surroundings and (d) modulation by equatorial planetary waves or a combination of these (Mehta *et al.*, 2010). Later they retain the significant opposite phase with gradual decrease of altitude (CPH/LRH) and gradual increase of temperature (CPT/LRT). Interestingly, minimum in TTL thickness (Figure 3d) coincides well with the maximum in COH as well as low OLR after 3 days of the MOK. Strong convection (lower OLR) leads to higher COH (and lower the TTL thickness) and this aspect is clearly observed during the onset unlike earlier reported by Mehta *et al.* (2008) in which it was attributed to the seasonal change.

To examine further the relationship between ISM onset and tropopause parameters, we have taken the tropopause parameters on the MOK date as the base value and then we subtracted the daily tropopause parameters from the onset day tropopause parameters for getting the anomalies. The climatological mean of CPH (CPT), LRH (LRT), COH (COT) and TTL thickness on the date of MOK are 17.4 ± 0.03 km (189.7 ± 0.3 K), 17.2 ± 0.02 km

$(189.9 \pm 0.3$ K), 12.7 ± 0.1 km (220.2 ± 0.7 K) and 4.6 ± 0.1 km. Figure 4 shows the mean anomalies of different tropopause parameters with respect to the onset day tropopause parameters. After the onset of ISM up to 40 days from the ISM onset, a clear transition is observed in the tropopause parameters with 0.6–0.8 km increase in the tropopause altitude (CPH/LRH) and ~ 3 K decrease in the tropopause temperature (CPT/LRT). After the onset of ISM, gradual increase/decrease in the tropopause altitude anomalies (CPH/LRH)/tropopause temperature anomalies (CPT/LRT) are noticed which is same as observed in Figure 3. The negative anomalies are observed in CPH and CPT after the onset and both are close together for ~ 10 –15 days. However, the LRH and LRT clearly show the positive and negative anomalies immediate after the onset. From these results it is clear that, the lapse rate of the temperature profile shows immediate changes compared to the cold point in the temperature profile during the onset period. This is quite interesting feature and the present results clearly indicate that among all the tropopause parameters, the LRH/LRT

is better parameter to see the onset signatures in the tropopause parameters. The present results clearly show the ISM onset signatures on the TTL parameters.

3.3 | Water vapor and ozone variations

During transition from pre-monsoon to monsoon over India, the zonal wind changes its direction from easterly to westerly which brings large amount of moisture from Arabian Sea to the Indian subcontinent. Increase of RH represents moistening of the lower atmosphere. Moistening of the upper troposphere after the onset of ISM is already reported. ISM is one of the important sources for moisture transport from lower to upper troposphere (Basha *et al.*, 2013). In the present study, we also clearly observed moistening of the lower and upper troposphere after the onset from the radiosonde observed RH profiles (Figure 2b). However, the normal radiosonde measured water vapor is not valid in the TTL region due to the sensor accuracy. In the TTL region, the radiosonde measured WV is having $\pm 50\%$ uncertainty with respect to a reference-quality standard such as a

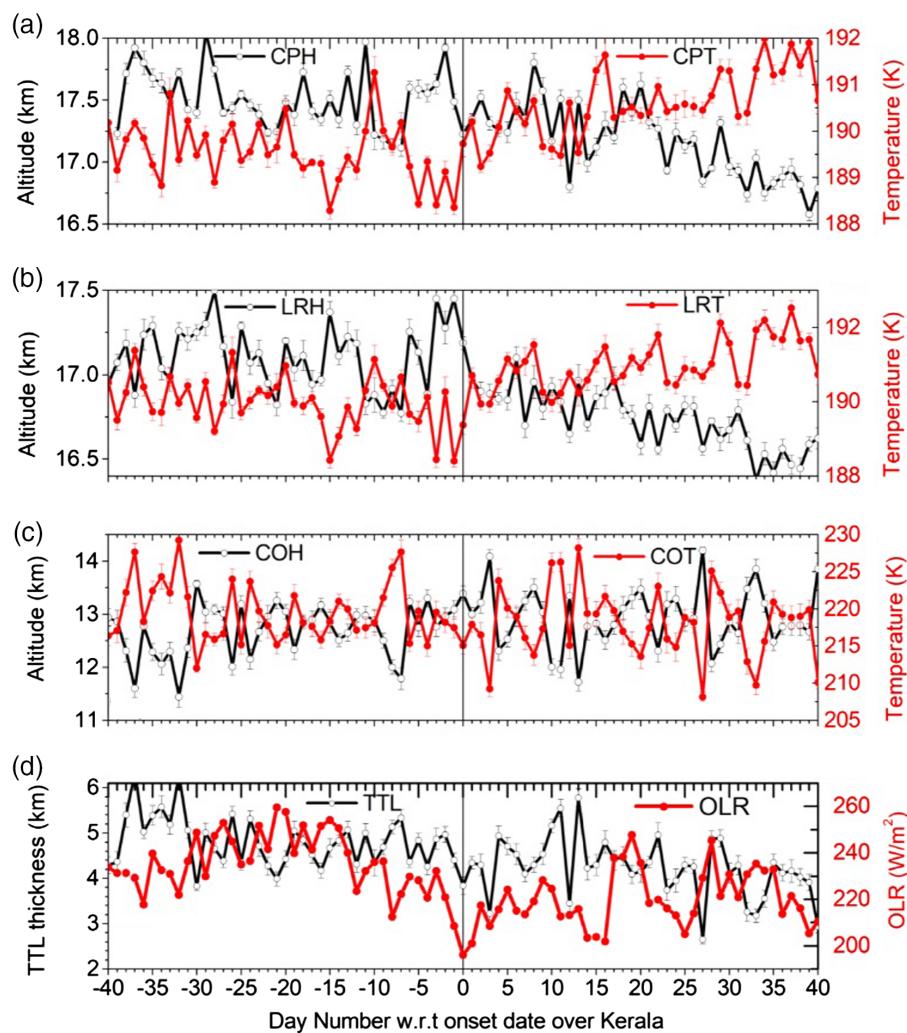


FIGURE 3 Climatological mean variability in the (a) cold point tropopause altitude (black) and corresponding temperature (red), (b) lapse rate tropopause altitude (black) and corresponding temperature (red), (c) convective outflow level altitude (black) and corresponding temperature (red) and (d) TTL thickness (black) and outgoing longwave radiation (red) observed over Gadanki with respect to monsoon onset over Kerala (onset day over Kerala as zero)

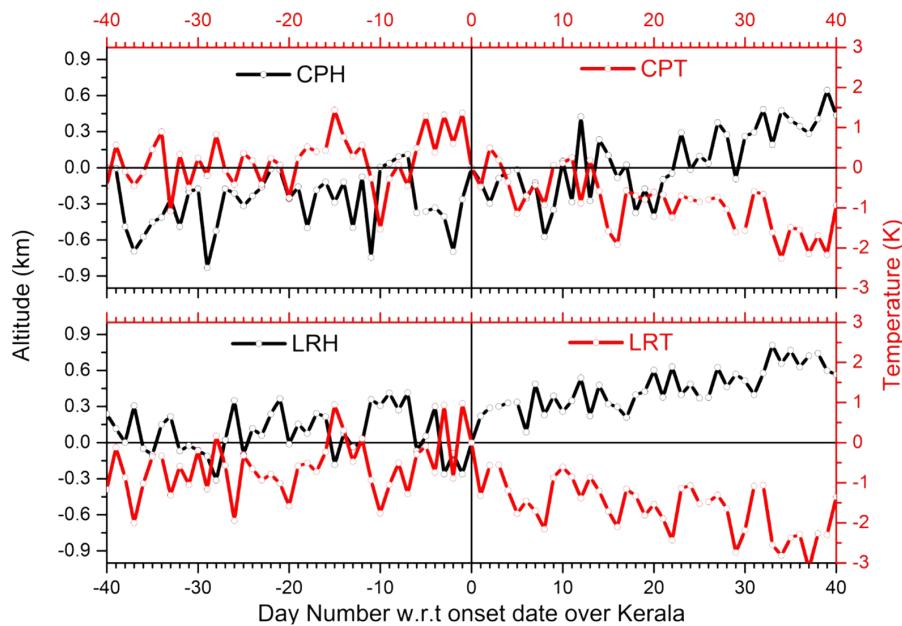


FIGURE 4 Climatological mean anomalies observed in the (a) cold point tropopause altitude (black) and corresponding temperature (red), (b) lapse rate tropopause altitude (black) and corresponding temperature (red) with respect to monsoon onset day (as zero) over Kerala

Cryogenic Frost-point Hygrometer (CFH) or a chilled mirror (CM) dew/frost-point hygrometer (Vomel *et al.*, 2003). Normal radiosonde relative humidity sensor will not work properly at the lowest temperatures (below -40°C). To avoid this, the daily MLS measurements from 2006 to 2017 during May and June months are used to see the changes in the water vapor in the TTL region. We have averaged MLS over passes over the grid ($10^{\circ}\text{--}16^{\circ}\text{N}$ and $76^{\circ}\text{--}82^{\circ}\text{E}$) and the results are plotted in Figure S2. WV gradually increases from the fifth day onwards after the onset and enhancement is significant at the 146 than 100 hPa. Interestingly, ozone also increases after the onset in the TTL region (100 and 82 hPa). Both WV and ozone increases from the fifth day onwards which is very well correlated with our radiosonde measured T and RH. Thus, enhancement in T can be partly due to this increase in ozone in addition to the latent heat release due to precipitation after the onset.

We further investigated the ozone changes during ISM transition period over Gadanki by using high resolution ozonesonde measurements. Changes in the ozone concentrations in the UTLS region will affect the temperature and dynamical structure of the UTLS region including TTL. Over Gadanki, we have minimum of two regular ozonesonde observations during 2012–2017 (Table 2). Total 23 ozonesonde launches are available in May and June. Out of 23, 4 launches are available during May 30 to June 1 which can be considered as onset day profiles, 10 launches are available during May 1 to May 25 (considered as before onset profiles) and 9 launches are available during June 8 to June 30 (considered as after onset profiles). To check the variability in the ozone before and after the onset, all the available profiles are averaged for getting mean profile for each category (before and after onset) and they are

subtracted from the mean onset profiles. The difference in T , RH and ozone are showed in Figure 5. The difference in the RH shows quite interesting features compared to the onset day. The negative values in the difference shows the RH is

TABLE 2 Ozonesonde launching details (launching date and time) along with balloon burst altitude, CPH and CPT observed in the months of May and June during 2012–2017 over Gadanki

Date	Launching time	Balloon burst height	CPH (km)	CPT ($^{\circ}\text{C}$)
May 2, 2012	0900	32.4	17.9	-86.9
May 16, 2012	0900	32.1	18.3	-84.3
May 30, 2012	0600	30.1	18.5	-78.9
Jun 14, 2012	0900	32.5	17.6	-88.9
Jun 27, 2012	0600	31.9	16.4	-81.8
May 6, 2013	0600	35.04	17.2	-91.4
May 22, 2013	0600	30.2	17.4	-85.7
Jun 8, 2013	0900	25.8	16.6	-84.8
Jun 18, 2013	0600	29.6	16.6	-82.5
May 30, 2014	0900	33.4	17.4	-82
Jun 5, 2014	0600	34.4	18.2	-85.9
Jun 18, 2014	0900	34.2	17	-82.4
May 8, 2015	0900	31.1	17.6	-84.5
May 25, 2015	0900	34.1	17.7	-85.8
Jun 24, 2015	0900	32.6	17.3	-82.7
May 4, 2016	0900	29.2	18.3	-85.1
May 19, 2016	0900	22.9	18.3	-86.7
Jun 1, 2016	0900	30.3	17.2	-83.7
Jun 16, 2016	0900	31.1	17.8	-80.8
May 3, 2017	0900	30.9	16.8	-83.5
May 17, 2017	0900	31.2	17.7	-86
May 31, 2017	0900	37.3	17.6	-85
Jun 14, 2017	0900	31.5	17.8	-85

more compared to the onset day. In the RH difference profile (onset-after), two minimum peaks are observed one around 5 km; another one around 9–10 km. The strong enhancement in the RH at 5 km altitude clearly shows the moisture transport due to the strong westerlies during the monsoon. Below 12 km, ozone decreased after the onset whereas before the onset it is more or less same as that of onset day though there is a decrease around 5 km altitude. However, between 16–20 km altitudes, ozone shows large enhancement after the onset and significantly less before the onset. In lower troposphere and middle troposphere, photochemical reactions are the main source for ozone, whereas in the upper troposphere transport from lower stratosphere also contributes. The strong enhancement in the ozone clearly indicates the warming of the UTLS region as noticed in the T anomaly in Figure 2a as well as Figure 5a. Thus, enhancement of ozone in the UTLS region and increase of mid and upper troposphere WV may have strong impact on the thermal structure of the UTLS region as well as TTL parameters.

4 | SUMMARY AND CONCLUSIONS

Indian summer monsoon (ISM) onset is one of the most dramatic phenomena happening over Indian subcontinent during end of May or beginning of June every year. In general, the climatological mean monsoon onset over Kerala (MOK) is on June 1 with standard deviation of 7 days. In the present study, we investigated the plausible relationship between ISM onset and the tropopause parameters such as CPH/CPT, LRH/LRT, COH and TTL thickness over a tropical station Gadanki by using high-resolution long-term (2006–2017) daily radiosonde observations. The main findings are summarized below:

1. The effect of ISM onset/arrival is observed on the tropopause parameters with decrease in the tropopause altitudes (CPH/LRH) and increase in the tropopause temperatures (CPT/LRT) and minimum in the TTL thickness.
2. There exists distinct patterns in all the tropopause parameters before and after the onset. Transitions from pre-monsoon to monsoon in the tropopause parameters are influenced strongly by onset of ISM which was attributed as seasonal change in the tropopause parameters earlier.

Significant increase in the ozone between 16 and 20 km and water vapor in mid and upper troposphere is noticed that contributed to the observed changes in UTLS thermal structure in addition to the latent heat release due to precipitation after the onset. Thus, the present study clearly demonstrated the observational evidence of arrival of ISM signals using tropopause parameters and water vapor and ozone. Among all the tropopause parameters, the LRH/LRT is found to depict the clear changes during pre-monsoon to monsoon transition. Further investigations are required to make this parameter also as an indicator for monsoon onset.

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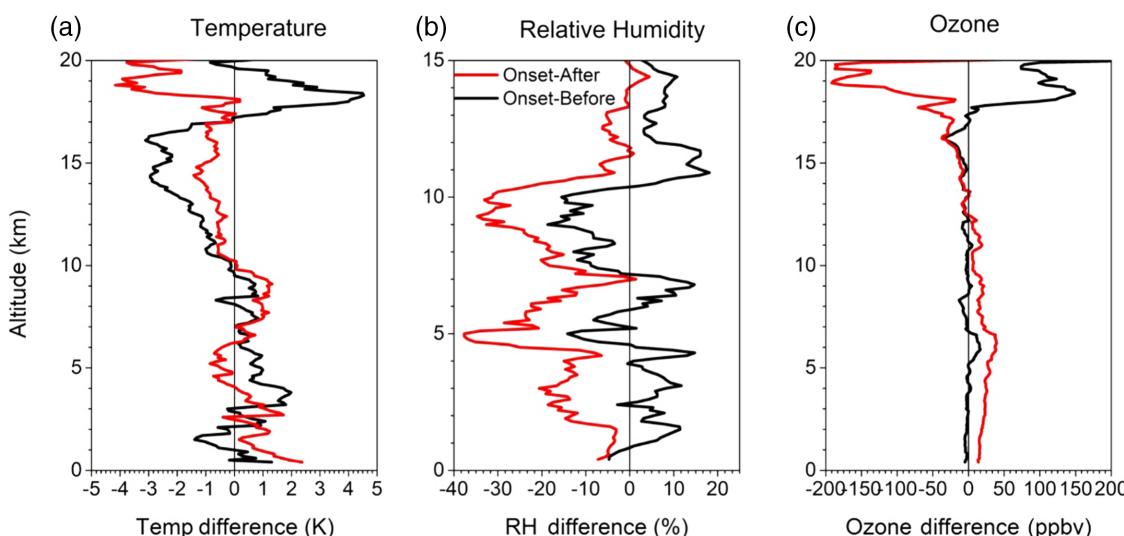


FIGURE 5 Mean difference between onset day and before onset days (black) and onset day and after onset days (red) observed in (a) temperature, (b) relative humidity and (c) ozone mixing ratio. The observed results are obtained from the available ozonesondes which are showed in Table 1

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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