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Effect of tropical cyclones on the tropical tropopause parameters observed using COSMIC GPS RO data

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Abstract

Tropical cyclones (TCs) are deep convective synoptic scale systems and play an important role in modifying the thermal structure, tropical tropopause parameters and hence stratosphere–troposphere exchange (STE) processes. In the present study, high vertical resolution and high accuracy measurements from COSMIC Global Positioning System (GPS) Radio Occultation (RO) measurements are used to investigate and quantify the effect of tropical cyclones that occurred over Bay of Bengal and Arabian Sea in last decade on the tropical tropopause parameters. The tropopause parameters include cold point tropopause altitude (CPH) and temperature (CPT), lapse rate tropopause altitude (LRH) and temperature (LRT) and the thickness of the tropical tropopause layer (TTL), that is defined as the layer between convective outflow level (COH) and CPH, obtained from GPS RO data. From all the TCs events, we generate the mean cyclone-centered composite structure for the tropopause parameters and removed from climatological mean obtained from averaging the GPS RO data from 2002–2013. Since the TCs include eye, eye walls and deep convective bands, we obtained the tropopause parameters based on radial distance from cyclone eye. In general, decrease in the CPH in the eye is noticed as expected. However, as the distance from cyclone eye increases by 3, 4, and 5° an enhancement in CPH (CPT), LRH (LRT) are observed. Lowering of CPH (0.6 km) and LRH (0.4 km) values with coldest CPT and LRT (2–3 K) within the 500 km radius from the TC centre is noticed. Higher (2 km) COH leading to the lowering of TTL thickness (2–3 km) is clearly observed. There exists multiple tropopause structures in the profiles of temperature obtained within 1° from centre of TC. These changes in the tropopause parameters are expected to influence the water vapour transport from troposphere to lower stratosphere and ozone from lower stratosphere to the upper troposphere and hence STE processes.

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1 Introduction

Tropical Cyclones (TCs) are one of the most dangerous natural and deep convective synoptic scale systems that occur throughout the tropical region globally. Every year, they cause considerable loss of life and damage to property. India has a long coastline, which is prone to very severe cyclone formations in the Arabian Sea (AS) and Bay of Bengal (BoB). Over the Indian region, these TCs occur during the pre-monsoon (April–May), early monsoon (June) and post monsoon (September–November) seasons. They persist for a few days to weeks and have large convective activity around the eye with a horizontal scale of hundreds of kilometres. During the developing stage of TCs, a large drop in its central pressure occurs and the most extreme vertical velocities are usually observed. TCs contain large amounts of water vapour, energy and momentum, and transport water vapour and energy to the upper troposphere and lower stratosphere (UTLS) region. This will change the thermal and chemical structure of UTLS. Hence, TCs play a very important role in affecting the thermal structure and dynamics of UTLS. The concentration of the water vapour transported to the stratosphere is controlled by the cold temperatures present at the tropopause. The life time and size of cyclones also might be affecting the tropopause parameters on the regional scales. There is a possibility that TCs lift and cool the tropopause more than other meso scale systems. It is well known that the intensity and frequency of TCs have increased in recent years (Emmanuel, 2005; Webster et al., 2005).

The tropopause, which is the boundary between troposphere and stratosphere, plays a crucial role in the exchange of mass, water vapour and other chemical species between the two atmospheric regions (Holton et al., 1995). Most of these exchanges take place around tropopause only and as such it is very important to study and understand the physical processes occurring around the tropopause region. The tropopause itself varies temporally and as well as spatially. Generally, radiosonde data have been used to study the tropopause parameters and their characteristics (e.g., Randel et al., 2000; Seidel et al., 2001). However radiosonde data is not available over oceans particularly

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during severe atmospheric conditions like TCs. Thus, obtaining the tropopause characteristics during TCs remained a daunting task. However, the availability of Global Positioning System (GPS) Radio Occultation (RO) measurements with high vertical resolution, high accuracy and all-weather capability made it possible to study the tropopause characteristics over globe including over oceans.

A few studies have been carried out relating the TCs and its link to the UTLS as well as tropopause parameters. Studies include the thermal and dynamical structure of UTLS during TC (Koteswaram, 1967), horizontal and vertical structure of temperature in the cyclone (Waco, 1970), temperature and ozone variations in a hurricane (Penn, 1965), troposphere–stratosphere transport and dehydration in cyclones (Danielsen, 1993), UTLS structure during TCs using AIRS and MLS measurements (Ray and Rosenlof, 2007) and estimating the TC cloud top height and vertical temperature structure using GPS RO measurements (Biondi et al., 2013). Recently Emmanuel et al. (2013) showed that the modulations of the cold point temperature influence the maximum potential intensity of tropical cyclones and tropical cyclone activity. However, the effect of deep convection associated with the TCs on the tropopause parameters is not yet fully understood.

The main objective of the present study is to investigate the spatial variation of tropopause parameters such as cold point tropopause altitude (CPH)/temperature (CPT), lapse rate tropopause altitude (LRH)/temperature (LRT), convective outflow level altitude (COH) and TTL thickness with respect to TC centre during entire TC period. Vertical structure of temperature and tropopause parameters within the 5° radius away from the cyclone centre during TC period is also presented. The water vapour variability in the vicinity of TC is also investigated. The details of the data used for the present study are mentioned in Sect. 2. Methodology for obtaining tropopause parameters during TC period is mentioned in Sect. 3. Results and discussion are presented in Sect. 4. Finally, summary and conclusions drawn from the present study are presented in Sect. 5.

2 Database

2.1 COSMIC GPS RO data

The temperature profiles obtained from the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) GPS RO over the BoB during the TC is utilised for the present study. COSMIC GPS RO is a constellation of six microsatellites equipped with GPS receivers (Anthes et al., 2008). These satellites are launched in early 2006 and started providing data from April 2006. During its initial phase, all the six satellites were not fully configured so as to get uniform distribution of occultations. Thus, data from 2007 to 2013 have been used for the present study. It provides 2000–2500 occultations for a day over entire globe. Details of temperature retrieval from bending angle and refractivity profile obtained from GPS RO sounding are presented elsewhere (Kursinski et al., 1997; Kuo et al., 2004; Anthes et al., 2008; Schreiner et al., 2010). For the present study we use level 2 dry temperature profiles to calculate the tropopause parameters during the TCs. In addition, we also used CHAllenging Minisatellite Payload (CHAMP) GPS RO data that are available between the years 2002 to 2006. This complete data (2002 to 2013) is used to generate the background climatology of tropical tropopause parameters over North Indian Ocean. The vertical resolution of the temperature is 200 m. Note that this data is validated with variety of techniques including GPS radiosonde and found very good match particularly in the UTLS region (Rao et al., 2009).

2.2 TCs best tracks

We have taken the TC track information (TCs best tracks) data from the India Meteorological Department (IMD) for the period 2007 to 2013. Though GPS RO data is available between 2002 and 2006 from CHAMP GPS RO, we have not utilised it for estimating the tropopause parameters during TC as the number of occultations from this single satellite are too sparse (maximum 250–300 occultations over entire globe).

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TCs track information includes TC name, dates, centre latitude and longitude, cyclone intensity (CI) (T-number) and MSL pressure of the TC at every 3 h intervals during the formation of the TC. During this period (2007 to 2013), around 44 TCs have formed over North Indian Ocean. For the present study, we consider only the TCs which are having life time of minimum 4 days and more while considering the intensity of the TCs. From these 44 TCs we selected 16 TCs based on life time of TCs to investigate the effect of TCs on the tropical tropopause parameters. The tracks of all the TCs used for the present study are shown in Fig. 1 and different colours indicate TCs occurred in different years. Note that only 2 TCs have formed over AS and rest all formed over BoB. Only one TC that formed over BoB have crossed the Indian land mass and have strengthen again when it reached AS. The details of TC such as name, grade, CI (T) number as designated by IMD, life time, central latitude and longitude (position) of the cyclone where lowest pressure and highest wind speed are observed with estimated pressure drop are shown in Table 1.

3 Analyses procedure

3.1 Estimation of different tropopause parameters

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 exists between the troposphere and stratosphere. Another one is LRH defined by 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."

In recent years, the study of the tropopause over tropics has led to the concept of a Tropical Tropopause Layer (TTL) (Highwood and Hoskins, 1998; Gettlemen and Birner, 2007; Fueglistaler et al., 2009), which is the transition region between the

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convective-radiative equilibrium of the troposphere and the stratosphere. In this transition region both stratospheric and tropospheric processes interact. The top of the TTL is marked by the CPH and the base by the level of the top of all the major convective outflows, named as convective tropopause altitude (COH) and the altitude difference between CPH and COH is the TTL thickness. A minimum in potential temperature gradients is identified as COH following Gettleman and Foster (2002). Note that it closely matches with the divergence profile obtained from Mesosphere Stratosphere Troposphere (MST) radar observations (Mehta et al., 2008). All these parameters (CPH, CPT, LRH, LRT, COH and TTL thickness) are estimated for each profile of GPS RO during the entire TC life time. In order to estimate the effect of TCs on the tropopause parameters, the background of all the tropopause parameters is obtained by averaging the data from 2002 to 2013 (climatology) with exclusion of the days of the TCs. These climatological values are grouped at $2.5^\circ \times 2.5^\circ$ grids.

3.2 Classification of the TCs

Effect of the TCs on the tropopause parameters mainly depends on the intensity of the cyclone. Based on the intensity (also called as T-number) of cyclone, IMD has defined various stages of the TC. It is named as low pressure when the maximum sustained wind speed at the sea surface is < 17 knots, Depression (D) (17–27 knots), Deep Depression (DD) (28–33 knots), Cyclonic Storm (CS) (34–47 knots), Severe Cyclonic Storm (SCS) (48–63 knots), Very Severe Cyclonic Storm (VSCS) (64–119 knots) and Super Cyclonic Storm (SuCS) (> 119 knots). As an example, the TC Nargis is chosen to show the different stages of TC and also its pressure and wind speed. The TC "Nargis" originated as a depression formed over southeast BoB at 03:00 UTC on 27 April 2008. From Table 1 it is clear that this cyclone comes under the category VSCS which has CI of 5. The observed IMD track of the VSCS Nargis is shown in Fig. 1 (green line). This system slightly moved north eastwards and intensified into a cyclone at 00:00 UTC of 28 April. It remained stationary for some time and further intensified into a SCS at 09:00 UTC of 28 April and into a VSCS grade, as classified by the IMD at

03:00 UTC of 29 April (Pattnaik and Rama Rao, 2008). Further it moved eastward and crossed the coast of Myanmar on 2 May at 06:00 UTC.

The IMD reported maximum wind speed and minimum SLP of the TC Nargis are shown in Fig. 2a. Note that highest wind speed (∼ 90 knots) and lowest pressure (∼ 960 hPa) are noticed on 2 May. The interpolated outgoing long-wave radiation (OLR), which is considered as proxy for tropical deep convection, obtained from NOAA satellite on 28 April 2008 is shown in Fig. 2b along with the track of the cyclone provided by IMD. Black circles are drawn to show the 500, 1000, 1500 and 2000 km radius from the TC center. Note that this cyclone was stationary on 28 April and the minimum OLR (maximum convection) which was as low as 90 $W m^{-2}$, lay over the region within 500 km and extended to south east and west side of cyclone track within 1000 km.

The COSMIC RO data obtained for each day during the cyclone period are separated based on IMD cyclone best track data and calculated the tropopause parameters for each individual temperature profile. Since IMD based TC track data is available at 3 h intervals, we considered the middle of the coordinates (latitude and longitude) of particular day of TC as the centre of TC for that day. Based on these centres we calculated the distance from the TC centre for each individual RO available on particular TC day at intervals of 500 up to 2000 km.

4 Results and discussion

4.1 Tropopause parameters observed during VSCS Nargis

The locations of all the COSMIC GPS RO observations on 28 April 2008 are shown (white circles) in Fig. 2b. There were about 40 occultations that occurred within 2000 km from the centre of the cyclone. All the tropopause parameters mentioned in Sect. 3.1 are estimated for each of these profiles and climatological values were substracted for estimating the effect of the TCs on the tropopause parameters. Typical example of cyclone-centred tropopause parameters obtained from the COSMIC GPS RO profiles

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during TC Nargis on 28 April 2008 is shown in Fig. 3. Though it is difficult to draw any conclusion from this figure as occultations are sparse, it is clear that CPH and LRH are slightly lower (∼ 17.25 km) within 500 km and higher (> 17.5 km) away. There is no substantial difference in the CPT and LRT within 500 km of TC in this example. However, COH is a little higher (∼ 14 km) within 500 km and slightly lower away from it and TTL thickness is small (< 4 km) within 500 km from the centre of TC Nargis. This suggests that the TC affects the tropopause parameters. Note that the variations observed away from 500 km, mainly over land, can be partly attributed to the latitudinal change itself which will be discussed further in the next sections.

4.2 Spatial variations of tropopause parameters from the centre of TC

In this sub-section, the spatial variations of tropopause parameters from the cyclone centre for different intensities of TC are presented. From the example of Nargis it is clear that we have less number of occultations for a single TC day and hence it is difficult to describe the tropopause characteristics away from the TC centre. For getting more data points for statistically significant results, we have separated COSMIC RO data based on TC intensity from all the 16 TCs. When we separated these based on TC intensity wise with respect to their distance from the TC centre there are 381, 727, 1124, 481 and 865 occultations for D, DD, CS, SCS and VSCS, respectively. From these profiles, we made a 250 km × 250 km grid of tropopause parameters based on TC centre for all TC intensities. After going through the detailed analysis, no significant difference in the tropopause parameters between D and DD, CS and SCS was noticed. So, we have combined the observations obtained during those periods, respectively. Since there is no significant difference in the tropopause parameters during D and DD we have not shown these here.

Figure 4 shows cyclone-centered composite of CPH, LRH, CPT, LRT, COH and TTL thickness for the cases of CS and SCS. From the figure it is clear that the south west side of the area up to 2000 km radius from the TC centre the CPH (Fig. 4a) and LRH (Fig. 4b) is lower than the north side of the TC centre. However, colder tropopause tem-

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peratures are clearly observed within 1000 km in case of CPT (Fig. 4c) and throughout 2000 km in the eastern side in case of LRT (Fig. 4d). A 10 K difference in the CPT and LRT can be noticed from the TC centre to the north side. Very interestingly COH is much higher over 1000 km and also towards south side from the TC centre with maximum altitude of around 15 km (Fig. 4e) leading to a smaller TTL thickness (Fig. 4f). Note that TTL thickness is less than 3 km within 500 km from the centre of TC and up to 1500 km in the southern side. These different variations in the tropopause parameters might be due to two reasons. One may be due to distribution of convection during developing stages of TCs such as depression and deep depression on the south side of the TC centre which moved north-west side. Another reason, at least in part, can be attributed to the latitudinal variation. However, we found very low values of CPH within the 500 km radius from the TC centre. Similar variations are observed when we separated the TC based on different intensities (figures not shown). Thus, in general, we observed lowering of CPH and LRH values with coldest CPT and LRT within the 500 km radius from the TC centre. Higher COH leading to lowering of TTL thickness is clearly observed. Higher COH within the 500 km from the TC centre suggests that maximum convective outflow reached higher altitude. At the same time lowering the CPH, leading to the small TTL thickness, within the TC centre is observed probably due to the subsidence. In order to quantify the effect of TCs on the tropopause parameters more clearly we have obtained anomalies by subtracting the tropopause parameters observed during TC from the background climatological tropopause parameters.

Figure 5 shows mean difference of cyclone-centered tropopause parameters from the background climatology observed in CPH, LRH, CPT, LRT, COH and TTL thickness. Note that this figure is the composite of the all the tropopause parameters irrespective of the TC intensity. Thus, some differences between Fig. 4 and Fig. 5 can be expected. In general, the CPH (LRH) is lowered by 0.6 km (0.4 km) in most of the areas within the 1000 km radius from the TC centre and CPT (and LRT) is colder by 3–4 K. Note that this decrease in the CPH is not uniform over 2000 km radius from the centre. Throughout the area 2000 km from centre the temperature is more or less colder or

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equal to the climatological value in both CPT/LRT. COH has increased up to 2 km within 500 km from the TC centre and at some areas up to 1000 km. TTL thickness is reduced by 2 km within 500 km from the TC centre and over some areas up to 1500 km. Note that this decrease in TTL thickness is not only because of pushing up of the COH but also decrease of CPH. It is worth quoting the recent findings of Biondi et al. (2015) where they reported a decrease in the temperatures of 3–4 K and reduction in the TTL thickness to 2–3 km over north Indian basin. Our findings exactly match with their reports for Indian region.

4.3 Spatial variations of water vapor from the centre of TC

Deep convection is expected to reach up to the tropopause altitude and sometimes above during the TCs leading to the penetration of water vapor to the lower stratosphere. At the same time chances of pushing down the ozone from the lower stratosphere leading to lower CPH (subsidence) is also expected leading to the STE processes. Though not completely relevant to the present study, it is worth to recall recent results by Škerlak et al. (2014), where it was shown quantitatively that maxima of STE are located over the storm (cyclone) track regions in the North Atlantic and North Pacific during all seasons (except summer) with an averaged mass flux of approximately 500 $kg\,km^{-2}\,s^{-1}$ from the stratosphere to the troposphere and approximately 300 $kg\,km^{-2}\,s^{-1}$ in the opposite direction. It will be interesting to investigate how these numbers compare for TC over Indian region. Since GPS RO also provides information on water vapor (Kishore et al., 2011), we have investigated further the effect of TCs on the vertical distribution of water vapor. Cyclone centered – composite of averaged RH observed during all the TCs irrespective of TC intensity in the layer 0–5, 5–10 and 10–15 km using COSMIC GPS RO wet-profiles is shown in Fig. 6a–c, respectively. Note that above these altitudes, water vapour is not sensitive in the GPS RO measurements. In general, larger RH values are noticed in the south-eastern side of the TCs in the lower layer (0–5 km) and throughout south side of the TC in the layer 5–10 km. Higher RH is noticed within 500 km from the TC centre. Interestingly, high RH values of 70 % or more are noticed on the eastern side of TC in the layer 10–15 km. Thus, it is clear that deep convection prevailing during the TC within 500 km from the centre of TC can penetrate to the lower stratosphere through the tropopause. The higher RH values observed in the layer 10–15 km may be due to the upper level anti-cyclonic circulation over the cyclones. Ray and Rosenlof (2007) reported higher water vapour mixing ratios to the east of the cyclone centers for TCs over Atlantic and Pacific Oceans and found averaged water vapour is enhanced by 30–50 ppmv or more within 500 km of the eye compared to the surrounding average water vapour mixing ratios. Our results match well with these. Note that Biondi et al. (2015) reported 30–50 % of the time overshooting of the convection during TCs strongly supporting our findings. At the same time, Midya et al. (2012) reported that over BoB and AS the total column ozone (TOC) decreases steadily before and during the formation of a TC, followed by a more or less increasing trend after dissipation of the cyclone. A very recent case study by Das et al. (2015) also confirms the intrusion of stratospheric air into the upper and middle troposphere during the passage of tropical cyclone Nilam. It will be interesting to see the variability of ozone during the same time for all the cyclones presented here to investigate the STE processes away from the TC center.

From the above, in general, it can be concluded that tropical tropopause is significantly affected by the TCs. The effect is more pronounced within 500 km from the centre of TC. Note that TCs have eye, eye wall, rain bands, convective cloud tops, strong updrafts and cirrus deck, all occurring in the range of 500 to 1000 km from the TC centre. From the above results, we expect a significant effect of the TCs on the tropopause parameters could be felt up to 500 km from the TC centre. We have further investigated the effect of TCs on the thermal structure of UTLS region and the results are presented in the next section.

4.4 Vertical thermal structure of UTLS within 500 km from TC centre

We considered the GPS RO with respect to the IMD best track data and took ±1 h time window of co-located RO profiles with respect to IMD best track time for every 3 h.

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Based on this we calculated the distance from the TC centre. We classified them with respect to distance from the centre as 1, 2, 3, 4, and 5° respectively. There were 90 GPS RO profiles occurring within 5° and when we separated them at 1° steps there were 7, 11, 20, 20 and 32 profiles, respectively. Figure 7 shows mean vertical structure of temperature with respect to distance with in 5° at steps of one degree radius from TC centre along with standard error. Enlarged portion in the Fig. 7 shows vertical structure of the temperature within the UTLS region from 16–18 km. Here we considered ±1 h time window of co-located RO profiles with respect to IMD cyclone best track data for getting thermal structure over TC period. Note that this is a better time window resolution than the earlier reported 3 h time window by Biondi et al. (2013) for describing the thermal structure during cyclone period. In general, no significant difference in the temperature structure within 5° from TC centre below 14 km is noticed. This is mainly due to the synoptic nature of convection within the 5° radius from the TC centre. Generally, in the troposphere below approximately 14 km the radiative cooling balances the latent heat release by convection. However, large variation in the mean temperature structure can be noticed above 14 km. This is mainly due to balancing between the radiative heating and the stratosphere-driven upwelling above 16 km. Strong updrafts around the eye wall and down drafts, subsidence near the eye, and formation of the cirrus clouds might change the temperature structure in the UTLS region strongly. It is interesting to notice lowering of tropopause altitudes with colder temperatures in the profiles obtained within 1°, followed at 3, 2 and 4°. It indicates that rain bands are of the size of roughly 1° (110 km). There exists a temperature difference of 5 K in the UTLS region in the profiles that occurred within 1° from the profiles that occurred away of 4°. These are statistically significant differences as the error bars do not mix with each other for the profile that occurred within 1° to rest of the profiles. Warmer temperatures are also visible in the lower stratosphere in the profiles that are obtained within 1° when compared to those occurred away. Multiple tropopause structures are clearly visible in the profiles that occurred within 1° from the TC. The cause for these multiple tropopauses might be either due to clouds (Biondi et al., 2013) or wave activity or cirrus or ozone (Mehta et al., 2011) which demands separate investigation.

We also calculated the tropopause parameters with respect to 1, 2, 3, 4, and 5° away from the TC centre respectively. Figure 8 shows the mean tropical tropopause parameters of CPH, CPT, LRH, LRT, COH and TTL thickness observed from the profiles that are available within the 5° radius from the TC centre. In general, CPH (CPT) increases (decreases) as we move away from the TC centre within 5° (except at 2° in case of CPH) (Fig. 8a). There exists a difference of 0.4 km (3 K) in the CPH (CPT) within 5° from centre of TC. Similar variability in the LRT is observed but not in LRH (Fig. 8b). An inverse relation between LRH and LRT is noticed but not in CPH and CPT. A nearly 2 km decrease in COH is clearly noticed (Fig. 8c) when we move away from the TC centre leading to the increase in the TTL thickness of 3 km (Fig. 8d). Note that lowering of CPH (may be due to the presence of subsidence and strong downdrafts) in the eye region and higher COH leading to lowering of TTL thickness within 1° from the TC centre is again noticed. Most of the overshooting convection may occur within the 2° and top of the convection may be lifting the tropopause higher. An additional 1 km of lowering of the TTL thickness within 1° when compared to 5° away from TC centre is mainly coming from lowering of CPH. Thus, decrease in TTL thickness is the combination of pushing up of COH and lower of CPH.

5 Summary and conclusions

In the present communication, we investigated and quantify the effects of tropical cyclones that occurred between 2007 and 2013 on the tropical tropopause parameters obtained from simultaneous high vertical resolution and high accuracy COSMIC GPS RO measurements. TCs are categorized based on their intensity as their effect on the thermal structure and thus tropopause parameters will be different for different intensities. Out of 44 cyclones that originated over BoB and AS, investigation is carried out on 16 cyclones which lasted for more than 4 days. The TC centre is fixed based on the

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best tracks data available from IMD at 3 h intervals. GPS RO overpasses that occurred within the radius of 2000 km from the centre of TC are separated. Tropical tropopause parameters are estimated for each individual profiles that occurred at various distances within 2000 km and are grouped for every 500 km radius from the centre of TC. They are further separated based on the intensity of the TC. In order to make quantitative estimates of the effect of TCs on the tropopause parameters, individual tropopause parameters obtained during TC are removed from the climatological mean tropopause parameters that are obtained by averaging the GPS RO measurements available from 2002 and 2013 (CHAMP + COSMIC). The effect of TCs on the vertical distribution of water vapor obtained from COSMIC GPS RO is also investigated. Again GPS RO overpasses that occurred within the radius of 500 km from the TC center within the ±1 h for every 3 h are separated for every 1, 2, 3, 4, and 5° from the center of the TC. Finally, detailed investigations are made to see the effect of TCs on the tropopause parameters within 5° from the centre of TC. The main findings of the present study are summarized in the following:

1. In general, the CPH (LRH) is lowered by 0.6 km (0.4 km) in most of the areas within the 1000 km radius from the TC centre and CPT (and LRT) is colder by 3–4 K. COH has increased up to 2 km and TTL thickness reduced by 2 km within 500 km from the TCs and at some areas up to 1000 km.

2. CPH (CPT) increases (decreases) as we move away from the TC centre within 5°. There exists a difference of 0.4 km (3 K) in the CPH (CPT) within 5° from centre of TC. Similar variability in the LRT is observed but not in LRH. An inverse relation between LRH and LRT is noticed but not in CPH and CPT. Nearly 2 km decrease in COH is clearly noticed when we move away from the TC centre leading to the total increase in the TTL thickness of 3 km within 5°.

3. The decrease in TTL thickness within 500 km from TC centre is not only because of pushing up of the COH but also decreasing of CPH.

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4. Higher RH is noticed within 500 km from the TC centre reaching as high as 15 km. Thus, it is clear that deep convection prevailing within 500 km from the centre of TC can penetrate to the lower stratosphere through the tropopause.

5. In general, no significant difference in the temperature structure within 5° from TC centre below 14 km is noticed. However, large variation in the mean temperature structure is noticed above 14 km. There exists a temperature difference of 5 K in the UTLS region in the profiles that occur within 1° from the profiles that occurred away of 4°.

6. Multiple tropopause structures are also visible in the profiles that occurred within 1° from the TC.

7. The colder tropopause temperatures are clearly observed within 1000 km in case of CPT and throughout 2000 km in the eastern side in case of LRT. In general, larger RH values are noticed in the south-eastern side of the TCs in the lower layer (0–5 km) but throughout south side of the TC in the layer 5–10 km. Higher RH values of 70 % or more are noticed on the eastern side of TC in the layer 10–15 km. Interestingly COH is much higher over 1000 km and also towards south side from the TC centre with maximum altitude of around 15 km leading to the lesser TTL thickness. TTL thickness is less than 3 within 500 km from the centre of TC and up to 1500 km in the southern side.

Thus, this study clearly demonstrated that the TCs can significantly affect the tropical tropopause and the effects are more pronounced within 500 km from the centre of TC. It will be interesting to see the ozone variability in the upper troposphere and water vapor in the lower stratosphere using satellite observations at the same time and hence STE processes during the TC which will be our future work. Further, in the present study we are unable to make quantitative estimates of the tropopause parameters variability during different stages (time series) of the cyclone due to sparse data of existing GPS RO observations. Once the data is available from the other similar payload (ROSA on-

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board Megha Tropiques) launched in 2011 in low inclination and forthcoming COSMIC-2, which will have six low earth orbit GPS receivers to be launched in low inclination in the first half of 2016, we can able to quantity the effects more effectively.

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Table 1. Cyclone name, grade, cyclone intensity number, period, centre latitude, centre longitude, estimated central pressure, estimated maximum sustained surface wind, estimated pressure drop at the centre of all the cyclones used in the present study provided by IMD.

Cyclone Name	Grade	CI. No	Period	Centre latitude	Centre longitude	Estimated Central Pressure (hPa)	Estimated Maximum Sustained Surface Wind (kt)	Estimated Pressure drop at the Centre (hPa)
03B	CS	2.5	21–26 Jun 2007	23.5	66	986 (25 Jun)	35	6
Gonu	SUCS	6.5	2–7 Jun 2007	20	64	920 (4 Jun)	127	80
SIDR	VSCS	6	11–16 Nov 2007	19.5	89	944 (15 Nov)	115	66
Nargis	VSCS	5	27–3 May 2008	16	94	962 (2 May)	90	40
Aila	SCS	–	23–26 May 2009	22	88	968 (25 May)	60	20
Jal	SCS	3.5	4–7 Nov 2010	11	84	988 (6 Nov)	60	18
Giri	VSCS	5.5	20–23 Oct 2010	19.8	93.5	950 (22 Oct)	105	52
PHET	VSCS	4.5	31 May–6 Jun 2010	18.5	60	964 (2 Jun)	85	36
Laila	SCS	3.5	17–21 May 2010	14.5	81	986 (19 May)	55	15
Thane	VSCS	4.5	25–30 Dec 2011	12	81	970 (29 Dec)	75	30
Nilam	CS	3	28 Oct–1 Nov 2012	11.5	81	990 (31 Oct)	45	10
Phailin	VSCS	6	8–14 Oct 2013	17.1	86.8	940 (11 Oct)	115	66
Madi	VSCS	4	6–12 Dec 2013	15.4	85.3	988 (10 Dec)	65	16
Helen	SCS	3.5	19–22 Nov 2013	16.1	82.7	990 (21 Nov)	55	17
Mahasen	CS	3	10–16 May 2013	18.5	88.5	990 (15 May)	45	10
Leher	VSCS	4	23–28 Nov 2013	13.2	87.5	980 (26 Nov)	75	26

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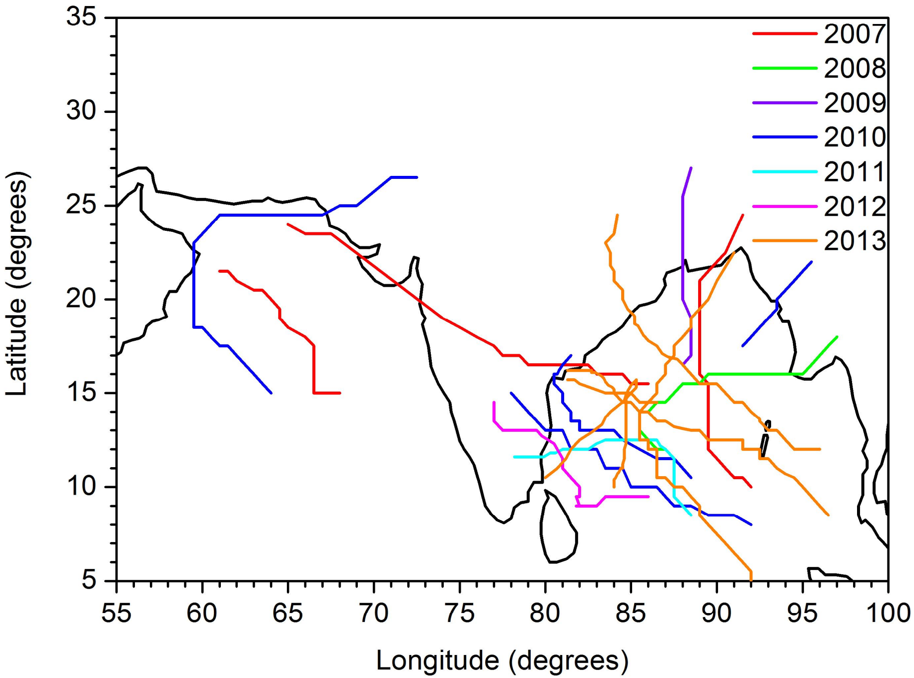

Figure 1. TC tracks with minimum TC life time 4 days and above used for the present study during 2007–2013 over North Indian Ocean. Different colors indicate TCs that occurred in different years.

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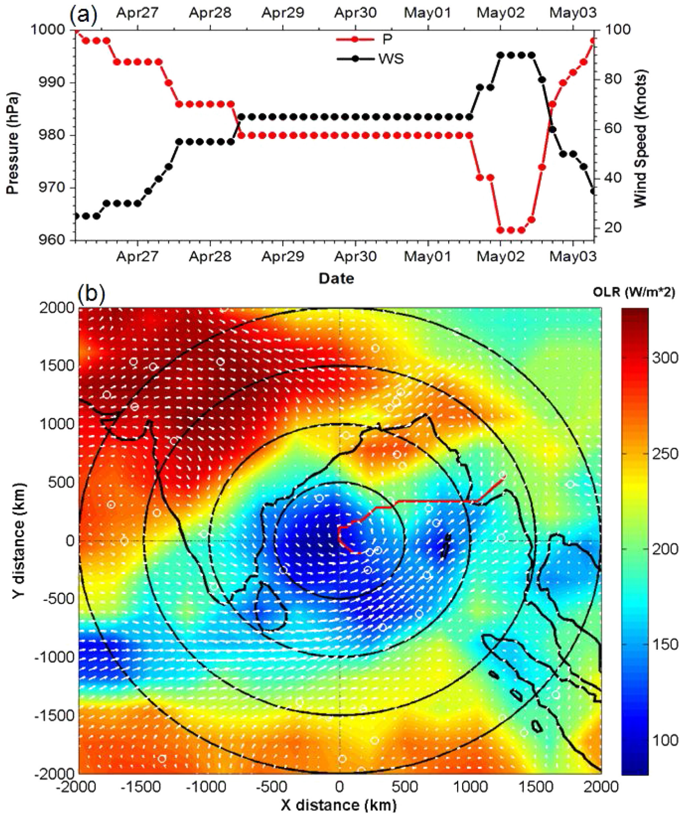

Figure 2. (a) IMD observed minimum sea level pressure (MSLP; red line) and maximum wind speed (black line) during TC Nargis. **(b)** TC centered – composite of NOAA OLR observed on 28 April 2008 along with IMD observed Nargis track (red colour line). White arrows show the wind vectors obtained from ERA-Interim on the same day. White circles show the COSMIC RO observed on the same day. Black circles are drawn to shown the 500, 1000, 1500 and 2000 km away from TC centers.

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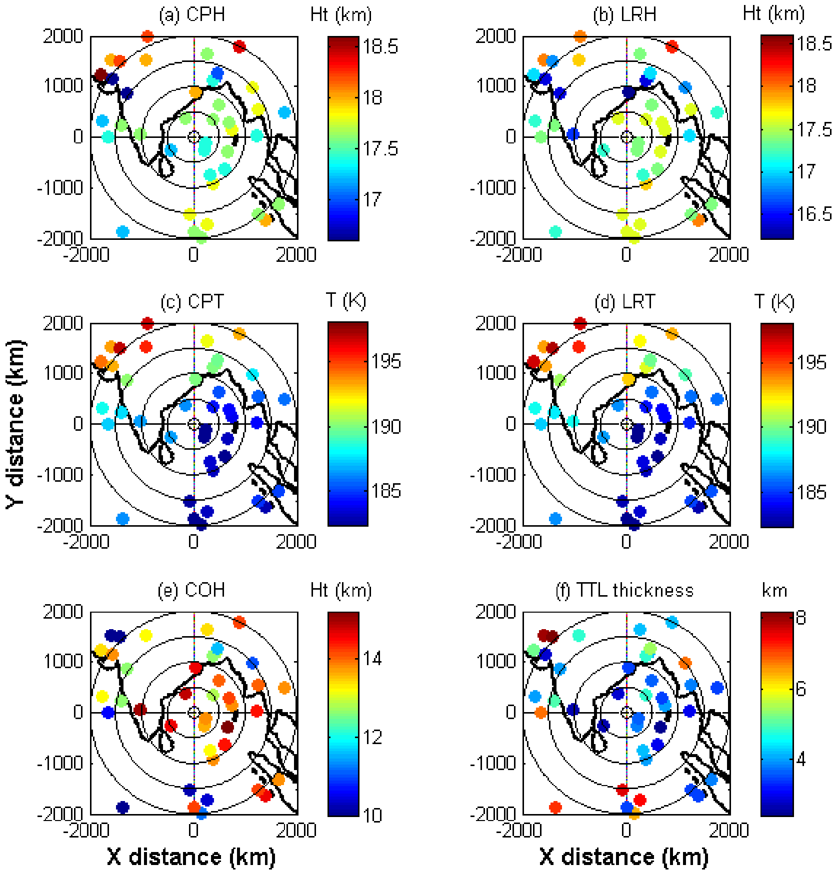

Figure 3. Spatial variation of **(a)** CPH, **(b)** LRH, **(c)** CPT, **(d)** LRT, **(e)** COH and **(f)** TTL thickness with respect to cyclone center Nargis observed on 28 April 2008 for the RO shown in Fig. 3b. Black circles are drawn to shown the 500, 1000, 1500 and 2000 km away from TC centers.

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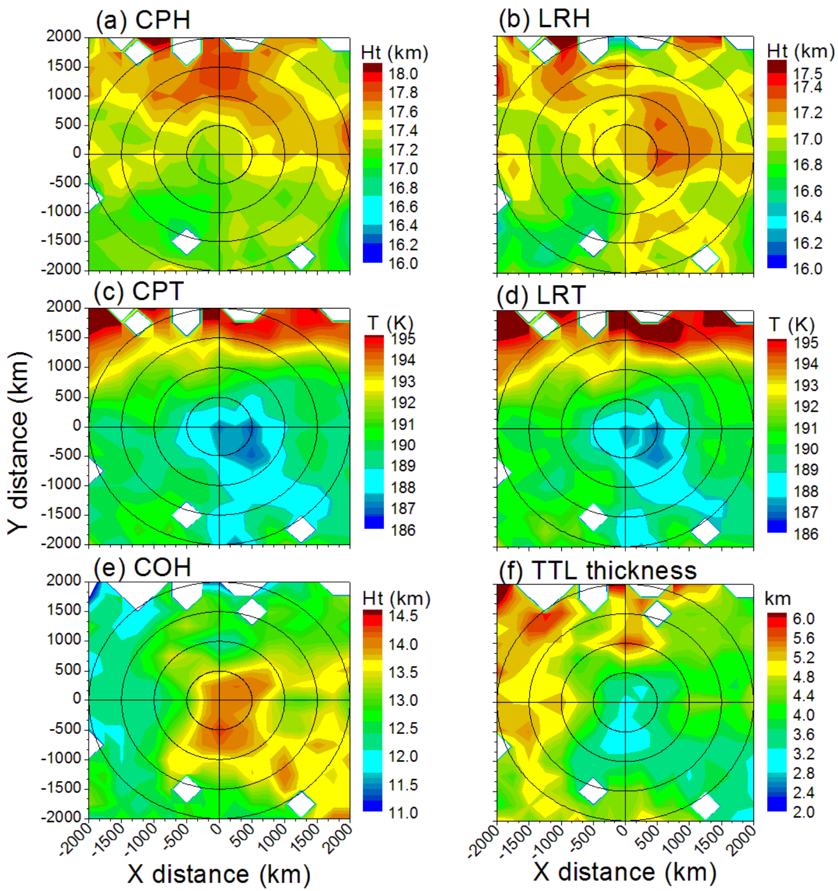

Figure 4. Cyclone centered – composite of **(a)** CPH, **(b)** LRH, **(c)** CPT, **(d)** LRT, **(e)** COH and **(f)** TTL thickness observed during the CS and SCS.

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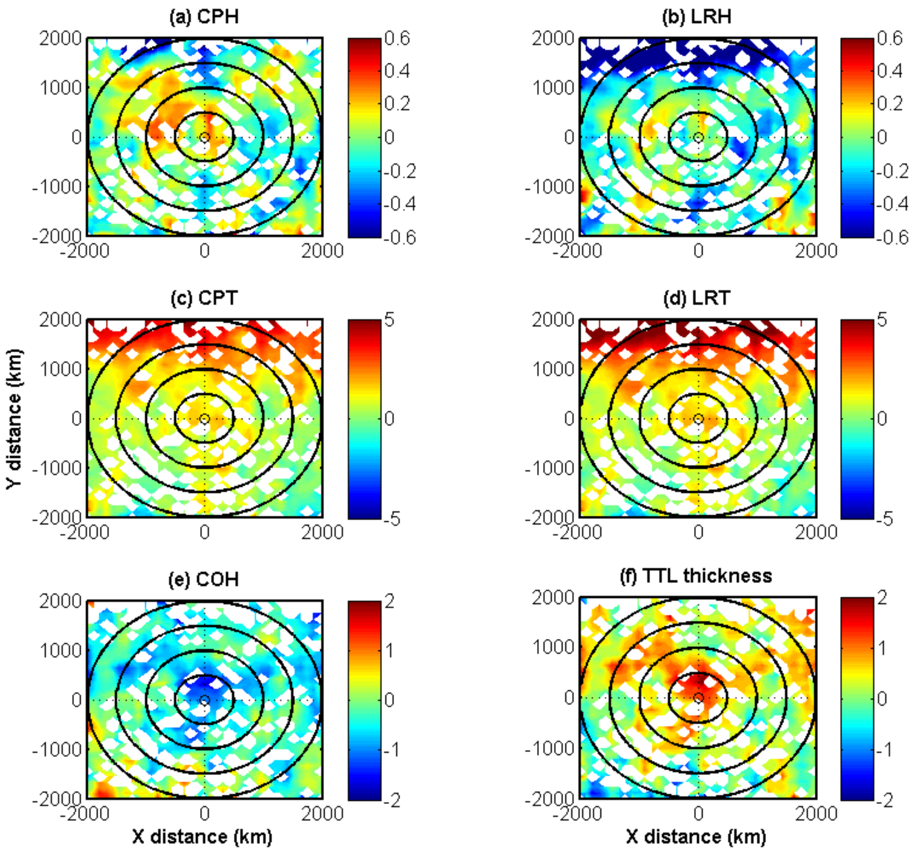

Figure 5. Same as Fig. 4 but for the mean difference in the tropopause parameters between climatological mean and individual tropopause parameters observed during TCs (irrespective of cyclone intensity).

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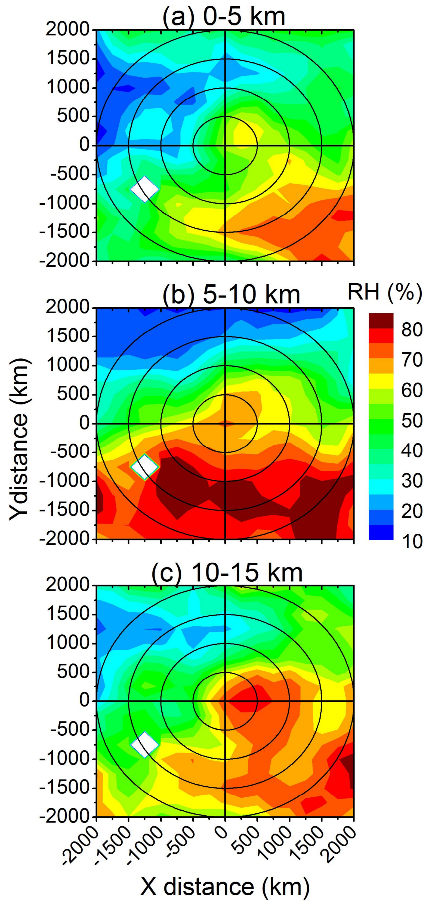

Figure 6. Cyclone centered – composite of averaged RH observed during TCs (irrespective of TC intensity) in the layer **(a)** 0–5 km, **(b)** 5–10 km and **(c)** 10–15 km using COSMIC GPS RO wet-profiles.

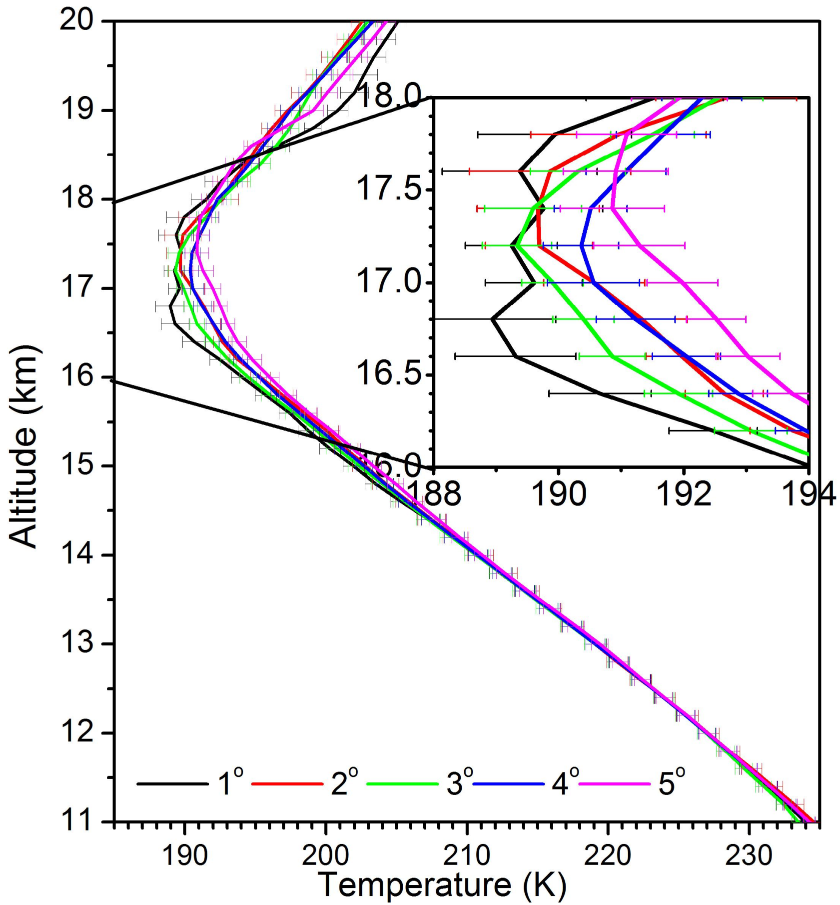

Figure 7. Mean temperature structure observed using GPS RO profiles that occurred within 1, 2, 3, 4, and 5° from the TC centre. Horizontal bars show the standard error. For clarity, the temperature structure observed between 16 and 18 km is shown in the box.

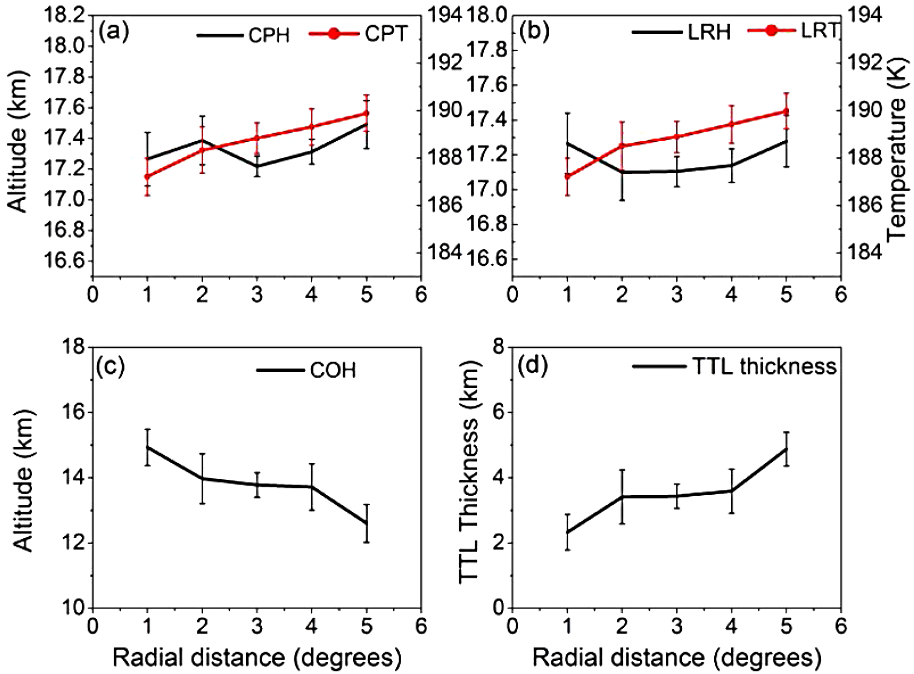

Figure 8. Variability in the tropopause parameters of **(a)** CPH and CPT, **(b)** LRH and LRT, **(c)** COH and **(d)** TTL thickness that observed within 5° from the centre of TC. Vertical bars show the standard error.

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