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## Tropopause characteristics over a southern subtropical site, Reunion Island (21°S, 55°E): Using radiosonde-ozonesonde data

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[1] In this paper, we present tropopause characteristics using in situ radiosonde-ozonesonde observations carried out over the past 13 years (September 1992 to February 2005) from a southern subtropical site, Reunion Island (21°S, 55°E). Three kinds of tropopause definitions, namely, cold-point tropopause (CPT), lapse rate tropopause (LRT), and ozone tropopause (OT), are characterized. The ozone tropopause for Reunion is appropriately defined as the height at which the vertical gradient of the ozone mixing ratio exceeds 55 ppbv/km and the ozone mixing ratio is over 75 ppbv. The overall height distribution of the three kinds of tropopause ranges in between 12.5 and 18.5 km. Of the three definitions, CPT follows higher heights of distribution, followed by LRT and then OT. The sharpness of tropopause height detection for LRT and OT has been examined, and it has been found that the detection frequency of a definite OT is larger than that for LRT. The results also showed no indefinite OT for a subtropical station in comparison to the results obtained for Northern Hemisphere midlatitude and high-latitude stations. After adopting a few modifications in the sharpness of ozone tropopause detection, the result remains the same, with a single indefinite case. The indefinite ozone tropopause case was identified when Reunion Island was located nearer to the divergence zone of wind as well as in the anticyclonic region of jet stream entrance. The LRT sharpness results are found to be in good agreement with the other published definition.

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### 1. Introduction

[2] The tropopause plays an important role in trace gas exchange and wave dynamics between the troposphere and lower stratosphere (e.g., stratosphere-troposphere exchange (STE), gravity wave dynamics or planetary/Rossby wave interactions, etc.). Further, the studies on tropopause characteristics are expected to provide a better understanding of stratospheric/tropospheric chemical constituents (mainly water vapor and ozone). Globally, temperature measurements from radiosonde data have been used to characterize tropopause and to study the temperature variability between the troposphere and lower stratosphere [Atticks and Robinson, 1983; Parker, 1985; Gaffen, 1993, 1996; Reid, 1994; Finger *et al.*, 1995; Parker and Cox, 1995; Parker *et al.*, 1997; Highwood and Hoskins, 1998; Seidel *et al.*, 2001].

[3] At present, five different definitions are accepted and widely used for identifying the tropopause, namely, the cold-point tropopause (CPT), the lapse rate tropopause (LRT), the ozone tropopause (OT), the isentropic potential vorticity (IPV) tropopause and the 100-hPa pressure level

(PLT). Selkirk [1993] and Highwood and Hoskins [1998] suggested that the cold-point tropopause height (the height where the temperature inversion takes place) plays an important role in stratosphere-troposphere exchange (STE). Later, Highwood and Hoskins [1998] used three different definitions to locate tropopause and characterized the significance of each definition. The World Meteorological Organization (WMO) defines the thermal tropopause as the lowest level where the lapse rate exceeds 2 K/km, provided that it remains above this threshold within this level and 2 km above, this definition has operational use but limited physical relevance, especially over equatorial latitude where there is a possible link between the convective processes and LRT [Highwood and Hoskins, 1998]. The IPV tropopause definition of the tropopause is useful for higher latitudes, but not close to the equator. The 100-hPa pressure surface has been considered for the tropopause as available directly from models, such as climate change models or simple radiative convective models. Over a subtropical site, Pan Chiao, (25°N; 121°E), Taiwan, Thulasiraman *et al.* [1999] presented the temperature structure for 0.5–30 km region and found that the CPT follows the annual variation with height around 16.5 km and temperature about 192.6 K. Shimizu and Tsuda [2000] also used the CPT definition to characterize the tropical tropopause at Bandung (6.9°S, 107.6°E) and found that the tropopause height is distributed between 16.6 and 17.4 km with a minimum temperature in the range from 188 K to

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191 K. Their results are also in agreement with *Reid and Gage* [1996] for Truk (7.47°N; 151.85°E). Recently, *Seidel et al.* [2001] used radiosonde data from 83 stations around the globe during the period from 1961 to 1990 and studied the tropopause climatological statistics. The study indicated an increase in height of about 20 m/decade, a decrease in pressure of about 0.5 hPa/decade, a cooling of about 0.5 K/decade, a small change in potential temperature, and a decrease in saturation volume mixing ratio of about 0.3 ppmv/decade.

[4] On the other hand, the tropopause sharpness depends on the method of detection and it quantifies the separation between troposphere and stratosphere [*Zängl and Hoinka*, 2001; *Birner et al.*, 2002; *Pan et al.*, 2004; *Zahn et al.*, 2004a, 2004b; *Schmidt et al.*, 2005]. Further, the failure or low accuracy of tropopause height detection is due to the background atmospheric conditions, such as STE, cyclonic events, Intertropical Convective Zone (ITCZ) passage and strong jet streams. Few results are published in connection with this, and many of them are focused on the lapse rate tropopause (or thermal tropopause) detection. *Kyro et al.* [1992] suggested that the ozone concentration and its gradient provide a more accurate and appropriate measure of tropopause height than the temperature lapse rate. However, the ozone tropopause identification is difficult when there are interleaved layers of low and high ozone concentrations in the upper tropospheric heights (as in the case of STE). *Bethan et al.* [1996] compared the ozone and thermal tropopause heights for the northern extratropical region and found that the ozone tropopause is just below the thermal tropopause. They reported that ozone tropopause could provide a more accurate position of tropopause height than thermal tropopause. *Zängl and Hoinka* [2001] used radiosonde and ERA Reanalysis data to characterize tropopause in the polar regions. They also provided details on the sharpness of the thermal tropopause defined by a change in the vertical temperature gradient across the tropopause and found high and low value in summer and winter, respectively. Using 10 years of radiosonde data for two midlatitude stations, *Birner et al.* [2002] illustrated a strong inversion at the lapse rate tropopause with a vertical extension of 2 km and a temperature increase of 4 K. Similarly, *Bethan et al.* [1996], *Pan et al.* [2004], and *Zahn et al.* [2004a] have also addressed the sharpness of tropopause using the relationship between stratospheric tracer ( $O_3$ ) and tropospheric tracer (CO) and they proposed a “chemical tropopause” definition based on sudden changes in correlation between  $O_3$  and CO concentrations. The result also documented that the uncertainty in chemical tropopause height determination was  $\sim 150$ – $200$  m. More recently, *Schmidt et al.* [2005] used Global Positioning System (GPS) radio occultation (RO) and studied lapse rate tropopause variations and their sharpness. They quantified the sharpness of tropopause with changes in the vertical temperature gradient across the tropopause and documented that the sharpness is high for the tropics and less for the polar regions.

[5] Tropopause height varies with latitude and is generally higher at the equator and decreasing toward the poles. It is also highly variable from day to day and from season to season [*Hoerling et al.*, 1993; *Hoinka et al.*, 1993]. Over the subtropics, very few studies are available for characterizing

the tropopause and the sharpness of its detection. In this paper, we present the detailed characteristics of the tropopause and their sharpness of detection using 13 years of radiosonde-ozone data from a subtropical site, Reunion (21°S, 55°E). The paper is organized as follows: the next section provides a brief sketch on data used and the analysis pursued. Section 3 presents results obtained from 13 years of in situ radiosonde-ozone data. It includes the detection of ozone tropopause height and the sensitivity of detection, different tropopause characteristics and sharpness variation. Subsequently, the results are discussed and compared with the earlier reported results. The summary and conclusion are given in section 4.

## 2. Radiosonde-Ozone Data

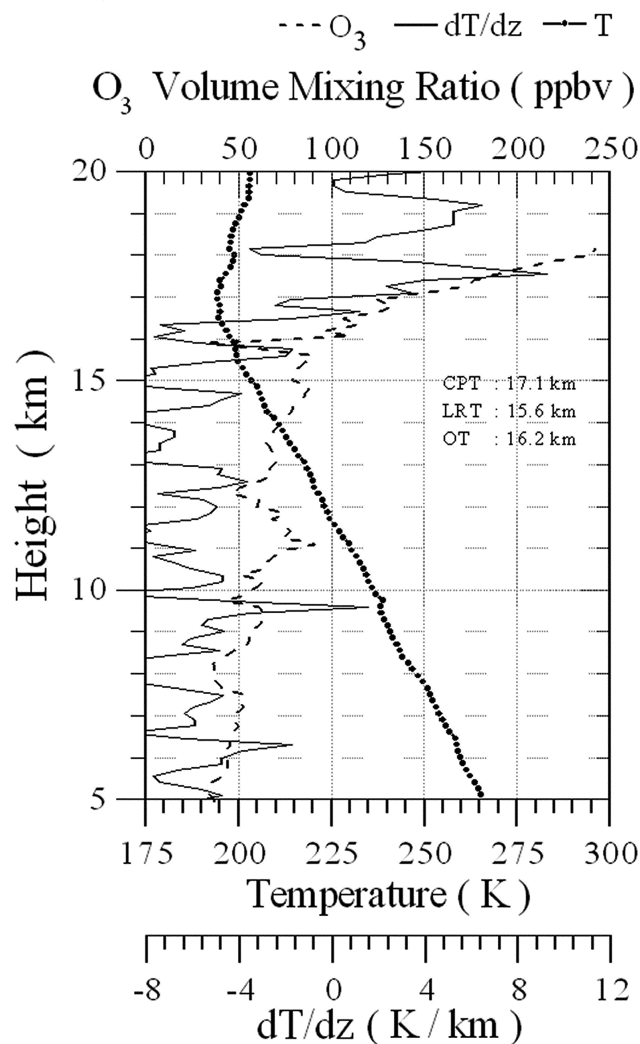
[6] We have used standard radiosonde-ozone data to study the tropopause characteristics. The radiosonde includes different atmospheric sensors that provide information on temperature, humidity and pressure. The radiosonde is of Vaisala RS 80 type with ascent rate of 5 m/s. The raw data correspond to a  $\sim 35$  m height resolution in the tropospheric height region and extend to  $\sim 90$  m in the tropopause region. Further details on the explanation and accuracy of ozone data measurements are available elsewhere [*Baldy et al.*, 1996; *Randriambelo et al.*, 2000]. Balloons were launched bimonthly from September 1992 to December 1999 and once a week since January 1999. The registered data at a fixed time interval are linearly interpolated to fit for 150 m vertical resolution in the height range of 0.5–30 km. The radiosonde is accompanied by an Electrochemical Concentration Cell (ECC) to provide height profile of ozone mixing ratio (in terms of partial pressure in nanobars). Then the ozone mixing ratio is converted to parts per billion volume (ppbv) and used for the present study. The data have been collected regularly in the framework of two different programs: the Southern Hemisphere Additional Ozonesonde (SHADOZ) and the Network for Detection of Atmospheric Composition and Change (NDACC, previously NDSC). More details on the SHADOZ program are available from *Thompson et al.* [2003a, 2003b] and for NDACC from *Kunyo and Solomon* [1990].

[7] The present study uses 293 radiosonde-ozone flights data collected for the period from September 1992 to February 2005. The available data distributions for each month are of  $\sim 25$ – $30$  flights. In case of tropopause characterization, the radiosonde-ozone flights that reached a height range of at least 20 km have been used. Out of 293 observations, 275 cases (94%) are considered for tropopause characteristics, irrespective of year and month.

### 2.1. Tropopause Definitions

[8] Following *Bethan et al.* [1996], *Reid and Gage* [1996], *Highwood and Hoskins* [1998], and *Seidel et al.* [2001], we have used the existing three kinds of tropopause definitions with minor modifications: (1) The lapse rate tropopause (LRT) is the lowest height at which the temperature gradient is greater than or equal to  $-2$  K/km, provided that the averaged temperature gradient between this level and all the higher levels within 2 km does not exceed  $-2$  K/km. (2) The cold-point tropopause (CPT) is the height

19 July 2000



**Figure 1.** Height profile of temperature, temperature gradient, and ozone obtained for 19 July 2000.

where the minimum temperature is found below 20 km. (3) The ozone tropopause (OT) is the height at which the vertical gradient of ozone mixing ratio exceeds 55 ppbv/km and ozone mixing ratio is over 75 ppbv (at and above this height).

[9] The above mentioned methods of identification of tropopause height are illustrated in Figure 1, which shows the height profiles of temperature and ozone as observed on 19 July 2000. It is noted that the actual measurements of temperature and ozone are obtained for the height region from ground to 30 km. By applying the above definitions to this profile, the tropopause heights are found to be at 16.2 km, 15.6 km and 17.1 km, which correspond to OT, LRT and CPT.

## 2.2. Sharpness Criteria

[10] The accuracy of detecting tropopause is sometimes questionable and needs to be examined. Few studies on tropopause detection found the existence of more than one tropopause and tropopause folding [e.g., *Selkirk*, 1993;

*Bethan et al.*, 1996; *Folkens et al.*, 1999; *Baray et al.*, 2000]. *Bethan et al.* [1996] reported on the sharpness of LRT and OT detection for midlatitude regions. There is no study on sharpness for tropical tropopause detection though the tropics are highly influenced by ITCZ, convections, cyclones, etc. Here, we examine the sharpness of detected LRT and OT. Initially, we have examined the *Bethan et al.* [1996] criteria for OT and LRT definition by adopting the sharpness height  $h$  as definite when  $h \leq 0.6$  km, intermediate when  $1.2 \text{ km} \geq h > 0.6$  km and indefinite when  $h > 1.2$  km. The results obtained are tabulated in Table 1. This leads to a large number of indefinite LRT cases and very few definite LRT cases, whereas most OT are reported as definite with a few indefinite cases. This distribution is likely to result from a lower interval of sharpness height region (0.6 km) used and a lower height resolution of data than given by *Bethan et al.* [1996]. To optimize  $h$  for our data sets, we have used various permutation level of  $h$  for classifying the tropopause sharpness and optimized by finding the lower frequency of occurrence of indefinite tropopause for both LRT and OT. We proceeded in step of 0.3 km, i.e.,  $h$  with an interval of 0.9 km, 1.2 km and 1.5 km. When we used the sharpness interval ( $h$ ) of 0.9 km, we found almost the similar result as before (i.e., more number of indefinite LRT cases). Whereas when 1.2 km sharpness height interval was utilized, we found that the LRT show more intermediate cases than indefinite. At the same time, we have not found any significant difference in OT distribution between  $h$  as 0.9 km, 1.2 km and 1.5 km. Thereby we modified the *Bethan et al.* [1996] criteria with  $h$  interval as 1.2 km, which uniformly fit for the LRT and OT definitions. The criteria used are as follows: (1) For the lapse rate tropopause, the sharpness of LRT has been classified into three categories: definite, ( $h \leq 1.2$  km), intermediate, ( $2.4 \text{ km} \geq h > 1.2$  km) and Indefinite, ( $h > 2.4$  km). Here,  $h$  stands for the height region from the lapse rate tropopause height to the height where the temperature gradient is less than  $-5$  K/km (upper troposphere lapse rate). (2) For the ozone tropopause, the sharpness is defined as above, with  $h$  given by the distance from the ozone tropopause to the level where the ozone mixing ratio falls to within 5 ppbv of the mean free tropospheric ozone value. The free troposphere is defined as the region between 3 km and OT.

## 3. Results and Discussion

### 3.1. Sensitivity of Ozone Tropopause Definition

[11] The ozone tropopause definition is not widely used and the threshold adopted by *Bethan et al.* [1996] (i.e., OT as the height at which the vertical gradient of ozone mixing ratio exceeds 60 ppbv/km and ozone mixing ratio is over 80 ppbv) might be applicable for the northern extratropics. Hence we performed a sensitivity study on the above

**Table 1.** Percentage of Detected LRT and OT Sharpness Following the *Bethan et al.* [1996] Criteria

Criteria	LRT, %	OT, %
Definite, $h \leq 0.6$	5.5	95.7
Intermediate, $1.2 \leq h > 0.6$	7.3	2.6
Indefinite, $h > 1.2$	87.2	1.7



**Table 2.** Sensitivity of the Ozone Tropopause Height Detection Using Different Thresholds

Criteria Parameters				
Referential Threshold		Modified Threshold		Tropopause Height Within $\pm 0.15$ km by Change in Criteria, %
O <sub>3</sub> , ppbv	dO <sub>3</sub> /dz, ppbv/km	O <sub>3</sub> , ppbv	dO <sub>3</sub> /dz, ppbv/km	
80	60	80	55	86.2
80	60	75	55	70.5
75	60	75	55	88.0
80	60	75	60	82.2
80	55	75	55	81.4

defined definition (refer to section 2.1) to optimize the threshold value of ozone vertical gradient and the ozone mixing ratio for identifying the ozone tropopause height over Reunion (southern subtropics). The study was conducted by decreasing the threshold value of vertical gradient of ozone mixing ratio and ozone mixing ratio in steps of 5. The result obtained from different kinds of threshold variations and the number of cases (in terms of percentage) where OT remains within  $\pm 0.15$  km is listed in Table 2. Finally, we ascertained that the OT defined by the vertical gradient of ozone mixing ratio exceeds 55 ppbv/km and ozone mixing ratio over 75 ppbv is found to be 88% of cases in agreement with OT differences within  $\pm 0.15$  km by the one defined with the vertical gradient of 60 ppbv/km.

### 3.2. Tropopause Characteristics: Frequency of Distribution

[12] The radiosonde-ozonesonde balloon flights that reached up to a minimum height of 20 km and above are used for a statistical study (275 observations). The three different tropopause heights are determined for each case using the definitions given in section 2.1. Thereby the frequency distributions based on three different kinds of tropopause height, such as cold-point tropopause (CPT), lapse rate tropopause (LRT) and ozone tropopause (OT), are obtained and shown in Figures 2a–2c. The distributions of all kinds of tropopause height (CPT, LRT and OT) are in the height range from 14 to 18 km with small differences in the maximum number of occurrences and also roughly depict a Gaussian shape. The CPT, LRT and OT show the maximum number of occurrences at 17.2 km, 16.0 km and 15.5 km, respectively. Relatively, it is noted that the highest tropopause corresponds to CPT followed by LRT and then by OT. The above obtained tropopause height characteristics are analogous to the results presented by *Seidel et al.* [2001], on tropical tropopause climatology by employing the radiosonde data from 83 stations located in the tropical belt from 30°N to 30°S. The result documented that the LRT varies from  $\sim 16.5$  km in the equatorial zone to less than 16 km in the subtropics. Similarly, the CPT is found to be resided at  $\sim 16.9$  km with very little north-south hemisphere variability. *Highwood and Hoskins* [1998] also found that the mean occurrence of CPT and LRT are 16 km and 13 km over tropics. They suggested that CPT is a reliable tropopause definition when the lower stratosphere is not close to being isothermal, i.e., within the deep tropics.

[13] Figures 3a–3c illustrate the frequency of occurrence of the differences between CPT, LRT and OT. The differences in distribution between CPT-LRT, CPT-OT and LRT-OT are respectively within  $-0.3$  km to  $+4.8$  km,  $-1.5$  km to

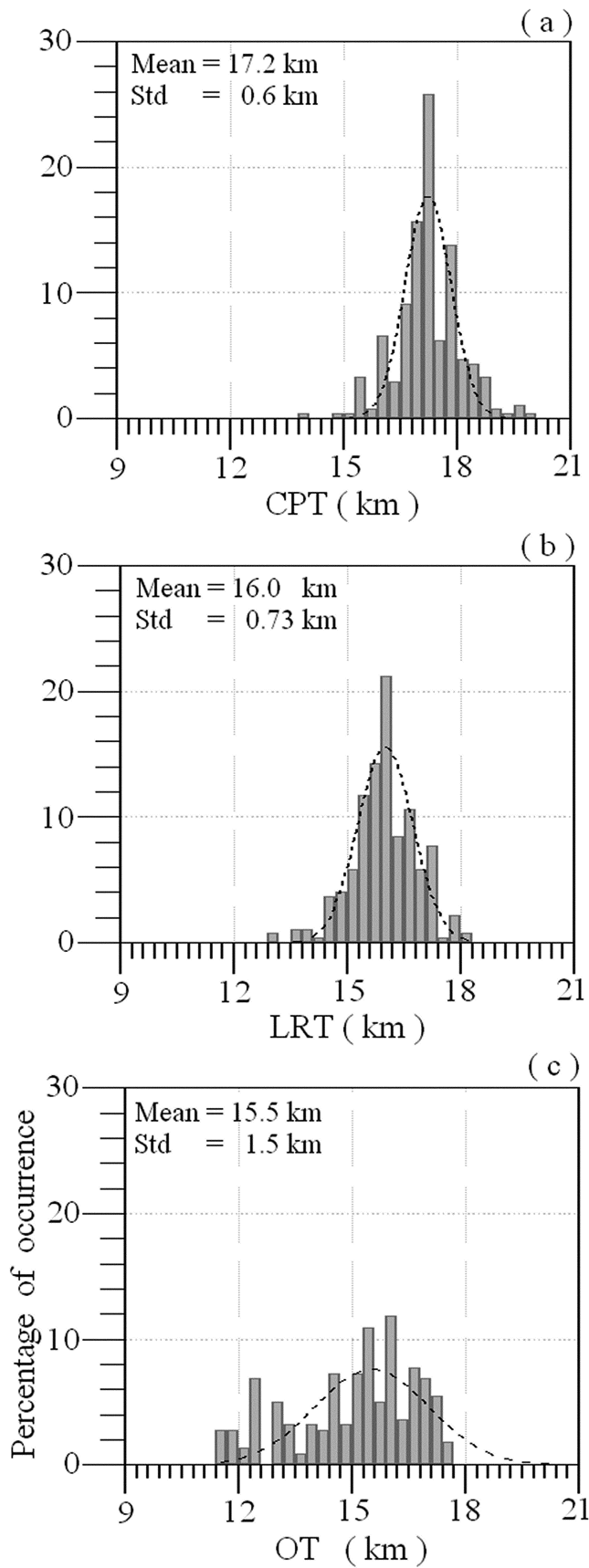
$+6.0$  km and  $-3.3$  km to  $+6.0$  km ranges. The maximum number of occurrence differences of CPT versus LRT, CPT versus OT and LRT versus OT correspond to positive values with mean differences at 1.1 km, 1.9 km and 0.4 km. The result again evidenced that OT is observed at lower height than LRT and CPT. The distribution is also highly weighted toward the positive sign and further verifies the tropopause height distribution, i.e., highest tropopause recorded for CPT followed by LRT and OT.

[14] The presented result shows that the differences between CPT and LRT are from  $-0.3$  km to  $+3.0$  km with 0.3 km differences for maximum number of times. Similarly, *Seidel et al.* [2001] reported in their study that the differences between CPT and LRT up to  $\sim 1$  km. They also proposed that the LRT and CPT are likely to meet at the same height, if the coldest point of a sounding is located at the base of an inversion layer deep enough (2 km) and it could be the case when there is a deep convection. *Folkins et al.* [1999] also argued that the difference between ozone tropopause and LRT or CPT is due to the convective detrainment of ozone-depleted marine boundary layer air above 14 km where the Hadley circulation occurs and convective penetration above this altitude is rare.

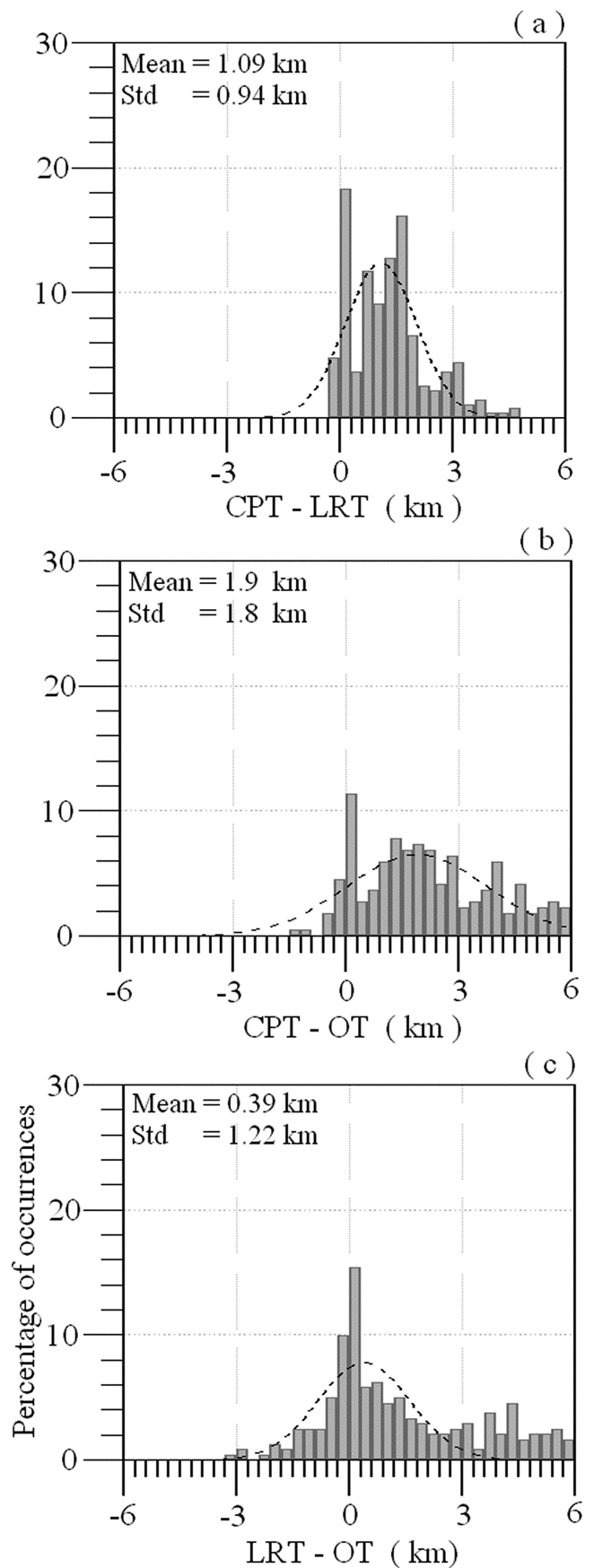
### 3.3. Sharpness of Detected Tropopause Height

[15] In this section, we present the result obtained on sharpness of detected LRT and OT heights. As explained in section 2.2, the sharpness determines the separation between troposphere and stratosphere region. So far, very few studies have been published for extratropics, and there are no results on sharpness of detection for tropics/subtropics using radiosonde data. Here, the tropopause sharpness is classified into three different categories: definite, intermediate and indefinite (refer to section 2.2). Table 3a shows the occurrence frequencies of LRT and OT based on the classified categories. It substantiates that the ozone tropopause of definite category is found to occur for a larger number of cases (98.2%) in comparison with LRT (24.7%). Next to the definite tropopause, the indefinite tropopause is more numerous for LRT than OT.

[16] The above results of more definite ozone tropopause detection are consistent with the earlier reported result revealing that the OT provides a definite one [*Kyro et al.*, 1992; *Bethan et al.*, 1996; *Pan et al.*, 2004]. They suggested that the ozone concentration and its gradient provide a more accurate and appropriate measure of tropopause height than the temperature lapse rate. Yet the ozone tropopause fails when there are interleaved layers of low and high ozone concentration in the upper troposphere (as in the case of STE). Earlier reports from Reunion suggest that there could be many occurrences of STE, tropopause folds induced by



**Figure 2.** Percentage of occurrence of three different kinds of tropopause height obtained from the radiosonde-ozone-sonde data.



**Figure 3.** Percentage of occurrence of mutual differences in the tropopause height by the definition used.

**Table 3a.** Sharpness of Detected Tropopause Height: Occurrence

	LRT	OT
Definite	68 (24.7%)	270 (98.2%)
Intermediate	148 (53.8%)	5 (1.8%)
Indefinite	59 (21.5%)	

subtropical jet streams [Baray *et al.*, 2000], tropical cyclones [Baray *et al.*, 1999] and cutoff lows [Baray *et al.*, 2003]. The changes in the LRT height may be due to prevailing different atmospheric conditions, due to convective activity, atmospheric waves and also due to the presence of high-level cirrus clouds. An earlier study [Cadet *et al.*, 2003] on climatological aspect of subvisible cirrus at Reunion Island, reports that the occurrence frequency is relatively high in December and less during July and August. The occurrence height is predominantly positioned within 11–14 km range, with maximum level during January. This also further elucidates that the detected cold-point tropopause is at higher height than the cirrus used to occur.

[17] Table 3b presents the mean tropopause height and its standard deviation obtained for the LRT and OT definitions and for the three categories (definite, intermediate and indefinite). The definite tropopause heights show the highest height (16.8 km) of occurrence for LRT than OT and a larger standard deviation for OT than LRT. The intermediate tropopause height reveals a high value with standard deviation for the cases of LRT than OT. The indefinite cases were found to be zero for OT in comparison with more in number for the LRT.

[18] More recently, Schmidt *et al.* [2005] studied the sharpness of LRT detection using the equation

$$S = \frac{\Gamma_+ - \Gamma_-}{\Gamma_{upper\ trop} - \Gamma_{strat}} = \frac{(\delta T/\delta z)_+ - (\delta T/\delta z)_-}{6.5} \quad (1)$$

where  $(\delta T/\delta z)_+$  and  $(\delta T/\delta z)_-$  are the mean temperature gradient above and below the detected tropopause height for the height region of about 1 km.

[19] They considered that the parameter (S) quantifies the order of separation between troposphere and stratosphere. The value 6.5 in the denominator is the difference between the lapse rate assuming that  $\Gamma_{strat}$  is 0 K/km and the upper troposphere  $\Gamma_{trop}$  as  $-6.5$  K/km. Here, we compare the obtained LRT sharpness result by applying the above equation. Since we have used  $-5.0$  K/km as the upper troposphere lapse rate and the sharpness height “h,” interval as 1.2 km (see section 2.2), we therefore use the same value here too. Values greater than 1 refer to high sharpness, or, in other words, it is a definite tropopause. The parameter S is computed for all 275 cases and it was found that  $\sim 38.5\%$  of cases had values greater than one. This is in agreement

**Table 3b.** Sharpness of Detected Tropopause Height: Mean Height and Its Standard Deviation

	LRT, km	OT, km
Definite	16.8 $\pm$ 0.7	14.0 $\pm$ 2.6
Intermediate	16.1 $\pm$ 0.7	10.2 $\pm$ 2.1
Indefinite	15.4 $\pm$ 1.2	

**Table 3c.** Modified Distribution of OT

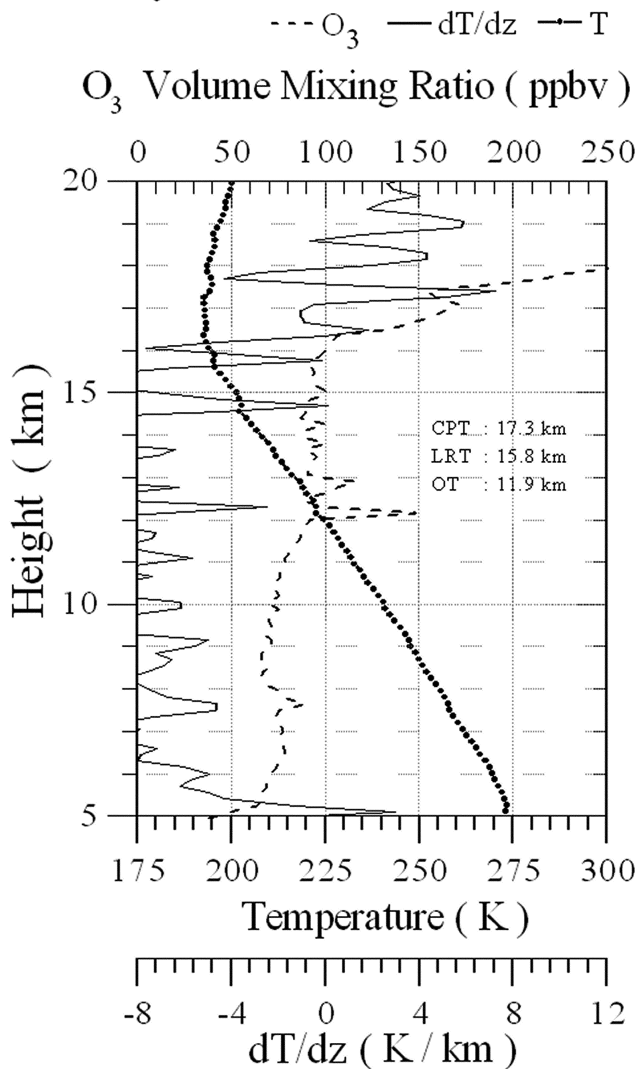
	Frequency and Percentage of Occurrence	Mean Height Distribution, km
Definite	260 (94.6%)	14.2 $\pm$ 2.5
Intermediate	14 (5.0%)	10.2 $\pm$ 1.6
Indefinite	1 (0.4%)	11.9

with the LRT sharpness result presented by using the criteria ( $h \leq 1.2$ ) and found for 24.7% as definite (see Table 3a). Further, it confirms that the threshold used is highly coherent and appropriate for the subtropical site.

[20] Our classification of OT sharpness reveals no indefinite case. Hence we modified the sharpness of tropopause definition followed by Bethan *et al.* [1996] for middle/high latitudes, which may not suit for subtropical stations, like Reunion (21°S, 55°E). To conform and get a clear view, we have introduced modification on the sharpness criteria for ozone tropopause height, i.e., we changed the fall of ozone mixing ratio of free troposphere ozone regions from 5 ppbv to 10 ppbv. The results obtained are presented in Table 3c. They exhibit again a similar distribution with very little variation in comparison with the earlier results. The mean height distributions for the definite and intermediate cases are almost the same except variation in standard deviation and now an indefinite case found at 11.9 km. Yet the modified distribution for indefinite ozone tropopause detected only one case, which further ascertains that the OT provides the exact location of tropopause for a subtropical station.

[21] The identified indefinite ozone tropopause case corresponds to the observation made on 3 January 2001. The height profile of ozone mixing ratio, temperature and the temperature gradient for the above day is shown in Figure 4. It is evident from the temperature gradient profile that a large perturbations just above and below to the tropopause. The ozone profile shows a significant perturbation in the ozone value. Though the figure illustrates the location of ozone tropopause just near to the LRT at  $\sim 16$  km, the method identifies the OT at  $\sim 11.9$  km. The figure displays a peak in the ozone values  $\sim 60$  ppbv just above  $\sim 11.85$ ; thereby the method pointed the OT at 11.9 km. This could be the reason for the detected indefinite ozone tropopause. The LRT sharpness definition followed by Schmidt *et al.* [2005] also illustrates the value of 0.22, which is again less than 1 and illustrating low sharpness. To examine the background synoptic situations on this day, we used wind and potential vorticity data from the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis. It is found that Reunion is located nearer to the entrance zone of a strong jet stream (in the anticyclone side) and the calculated potential vorticity (PV) at 350 K isentropic surface is greater than 1.5 PVU (data not shown). The high PV value suggests that there is a possibility of STE and of stratospheric ozone transfers into the troposphere heights. This background meteorological condition could probably be the reason for the detected indefinite tropopause. The theoretical interpretation by Shapiro and Kennedy [1981] suggested that zones of horizontal convergence and divergence appear at the entrance and exit zones of jet stream, and vertical ageostrophic winds are induced over and under these convergence and divergence zones. Hence the ob-

03 January 2001



**Figure 4.** Height profile of temperature, temperature gradient, and ozone obtained for 3 January 2001.

served indefinite case is influenced by the passage of jet stream and STE, which makes the proposed method, fails to identify the location of ozone tropopause.

[22] During summer, other mechanisms are known to influence the upper tropospheric and tropopause dynamics (severe convection, cyclones and ITCZ). Several cases of stratosphere-troposphere exchange near convection have been reported, over Reunion Island [Baray *et al.*, 1999], and over other locations [Poulida *et al.*, 1996; Stenchikov *et al.*, 1996; Folkins *et al.*, 1999]. However, the method has not detected many indefinite cases (except the one presented in Figure 4) during summer (December–February), when there are possibilities of severe convection, cyclone, or ITCZ over Reunion. This implies that a more sophisticated method is required to detect the tropopause height exactly, during convection, cyclone or ITCZ. Further, few results are published on chemical tropopause definition based on the O<sub>3</sub> and CO relationship and stated that the chemical tropopause provide a better result than one defined using

single traces gas (ozone) [Pan *et al.*, 2004; Zahn *et al.*, 2004a, 2004b].

#### 4. Summary and Conclusion

[23] In this paper, the tropopause characteristics using 13 years of in situ radiosonde-ozonesonde measurements from a subtropical site (Reunion; 21°S, 55°E) are presented. The following salient features are noted:

[24] 1. The performed sensitivity study on threshold to define the ozone tropopause has proven that the vertical gradient of ozone mixing ratio exceeds 55 ppbv/km and that the ozone mixing ratio over 75 ppbv is an appropriate for the site.

[25] 2. Three different kinds of tropopause height definitions, i.e., LRT, CPT and OT, have been investigated. The distribution of CPT is found to be at higher heights than LRT and OT with the maximum number of occurrences at 17.2 km, 16.0 km and 15.5 km, respectively.

[26] 3. Differences between the tropopause heights indicate that OT is found to be 1.9 km below the CPT and 0.4 km below the LRT for most of the cases. Mostly, the differences between CPT and LRT are within the height difference of ~1 km.

[27] 4. The performed analysis on sharpness of tropopause height evidenced that the OT acts as the more highly sensitive one (98%), even at the subtropical stations in comparison with LRT (24.7%). Also, the frequency of occurrence of indefinite tropopause height for OT is found to be lower (one case) for the subtropical site, Reunion (21°S, 55°E), in comparison with the midlatitude and high-latitude observations reported by Bethan *et al.* [1996]. The result suggests that the ozone tropopause also locates the tropopause height accurately for the subtropical site.

[28] 5. The LRT sharpness results are also found to be concurrent with the definition followed by Schmidt *et al.* [2005].

[29] 6. It was ascertained that the occurrence of the indefinite ozone tropopause is due to the occurrence of STE and divergence zone of the jet stream near the site location.

[30] Though the method of identification of tropopause sharpness detection is well suited for a subtropical site, like Reunion, it fails to reproduce the indefinite cases during the presence of a cyclone or ITCZ passage. Further improvements in the method are planned in future studies. The identification of tropopause height by isentropic potential vorticity and its comparison with other definitions may provide a better understanding of tropopause characteristics. The examination of tropopause identification failure with the help of classic/dynamic models is in perspective.

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## References

- Atticks, M. G., and G. D. Robinson (1983), Some features of the structure of the tropical tropopause, *Q. J. R. Meteorol. Soc.*, *109*, 295–308.
- Baldy, S., G. Ancellet, M. Bessafi, A. Badr, and D. Lan Sun Luk (1996), Field observations of the vertical distributions of tropospheric ozone at the island of la Reunion (southern tropics), *J. Geophys. Res.*, *101*, 23,835–23,849.
- Baray, J. L., G. Ancellet, T. Randriambelo, and S. Baldy (1999), Tropical cyclone Marlene and stratosphere-troposphere exchange, *J. Geophys. Res.*, *104*, 13,953–13,970.
- Baray, J. L., V. Daniel, G. Ancellet, and B. Legras (2000), Planetary-scale tropopause folds in the southern subtropics, *Geophys. Res. Lett.*, *27*, 353–356.
- Baray, J. L., S. Baldy, R. D. Diab, and J. P. Cammas (2003), Dynamical study of a tropical cut-off low over South Africa and its impact on tropospheric ozone, *Atmos. Environ.*, *37*, 1475–1488.
- Bethan, S., G. Vaughan, and S. J. Reid (1996), A comparison of ozone and thermal tropopause heights and the impact of tropopause definition on quantifying the ozone content of the troposphere, *Q. J. R. Meteorol.*, 929–944.
- Birner, T., A. Dörnbrack, and U. Schumann (2002), How sharp is the tropopause at mid latitudes?, *Geophys. Res. Lett.*, *29*(14), 1700, doi:10.1029/2002GL015142.
- Cadet, B., L. Goldfarb, D. Faduilhe, S. Baldy, V. Giraud, P. Keckhut, and A. Rechou (2003), A sub-tropical cirrus clouds climatology from Reunion Island (21°S, 55°E) lidar data set, *Geophys. Res. Lett.*, *30*(3), 1130, doi:10.1029/2002GL016342.
- Finger, F. G., R. M. Nagatani, M. E. Gelman, C. S. Long, and A. J. Miller (1995), Consistency between variations of ozone and temperature in the stratosphere, *Geophys. Res. Lett.*, *22*, 3477–3480.
- Folkins, I., M. Loewenstein, J. Podolske, S. J. Oltmans, and M. Proffitt (1999), A barrier to vertical mixing at 14 km in the tropics: Evidence from ozonesondes and aircraft measurements, *J. Geophys. Res.*, *104*, 22,095–22,102.
- Gaffin, D. J. (1993), Historical changes in radiosonde instruments and practices, *WMO/TD 541, Instrum. Obs. Methods Rep. 50*, 123 pp., World Meteorol. Organ., Geneva.
- Gaffin, D. J. (1996), A digitized metadata set of global upper-air station histories, *NOAA Tech. Memo. ERL-ARL 211*, 38 pp., Natl. Oceanic and Atmos. Admin., Silver Spring, Md.
- Highwood, E. J., and B. J. Hoskins (1998), The tropical tropopause, *Q. J. R. Meteorol. Soc.*, *124*, 1579–1604.
- Hoerling, M. P., T. K. Schaack, and A. J. Lenzen (1993), A global analysis of stratospheric-tropospheric exchange during northern winter, *Mon. Weather Rev.*, *121*, 162–172.
- Hoinka, K. P., M. E. Reinhardt, and W. Metz (1993), North Atlantic air traffic within the lower stratosphere: Cruising times and corresponding emissions, *J. Geophys. Res.*, *98*, 23,113–23,131.
- Kunyo, M. J., and S. Solomon (1990), Network for the detection of stratospheric change: A status and implementation report, NASA Upper Atmos. Res. Program and NOAA Clim. and Global Change Program, Natl. Aeronaut. and Space Admin., Washington, D. C.
- Kyro, E., et al. (1992), Analysis of the ozone soundings made during the first quarter of 1989 in the Arctic, *J. Geophys. Res.*, *97*, 8083–8091.
- Pan, L. L., W. J. Randel, B. L. Gary, M. J. Mahoney, and E. J. Hints (2004), Definitions and sharpness of the extratropical tropopause: A trace gas perspective, *J. Geophys. Res.*, *109*, D23103, doi:10.1029/2004JD004982.
- Parker, D. E. (1985), On the detection of temperature changes induced by increasing atmospheric carbon dioxide, *Q. J. R. Meteorol. Soc.*, *111*, 587–601.
- Parker, D. E., and D. I. Cox (1995), Towards a consistent global climatology rawinsonde database, *Int. J. Climatol.*, *15*, 473–496.
- Parker, D. E., M. Gordan, D. P. N. Cullum, D. M. H. Sexton, C. K. Folland, and N. Rayner (1997), A new global gridded radiosonde temperature database and recent temperature trends, *Geophys. Res. Lett.*, *24*, 1499–1502.
- Poulida, O., R. R. Dickerson, and A. Heymnsfield (1996), Stratosphere-troposphere exchange in a midlatitude mesoscale convective complex: 1. Observations, *J. Geophys. Res.*, *101*, 6823–6836.
- Randriambelo, T., J. L. Baray, and S. Baldy (2000), Effect of biomass burning, convective venting and transport on tropospheric ozone over the Indian Ocean: Reunion Island field observations, *J. Geophys. Res.*, *105*, 11,813–11,832.
- Reid, G. C. (1994), Seasonal and interannual temperature variations in the tropical stratosphere, *J. Geophys. Res.*, *99*, 18,923–18,932.
- Reid, G. C., and K. S. Gage (1996), The tropical tropopause over the western Pacific: Wave driving, convection, and the annual cycle, *J. Geophys. Res.*, *101*, 21,233–21,241.
- Schmidt, T., S. Heise, J. Wickert, G. Beyerle, and C. Reigber (2005), GPS radio occultation with CHAMP and SAC-C: Global monitoring of thermal tropopause parameters, *Atmos. Chem. Phys.*, *5*, 1473–1488.
- Seidel, D. J., R. J. Ross, J. K. Angell, and G. C. Reid (2001), Climatological characteristics of the tropical tropopause as revealed by radiosondes, *J. Geophys. Res.*, *106*, 7857–7878.
- Selkirk, H. B. (1993), The tropopause cold trap in the Australian monsoon during STEP/AMEX 1987, *J. Geophys. Res.*, *98*, 8591–8610.
- Shapiro, M. A., and P. J. Kennedy (1981), Research aircraft measurements of jet stream geostrophic and ageostrophic winds, *J. Atmos. Sci.*, *38*, 2642–2652.
- Shimizu, A., and T. Tsuda (2000), Variations in tropical tropopause observed with radiosondes in Indonesia, *Geophys. Res. Lett.*, *27*, 2541–2544.
- Stenchikov, G., R. Dickerson, K. Pickering, W. Ellis Jr., B. Doddridge, S. Kondragunta, O. Poulida, J. Scala, and W. K. Tao (1996), Stratosphere-troposphere exchange in a midlatitude mesoscale convective complex: 2. Numerical simulations, *J. Geophys. Res.*, *101*, 6837–6851.
- Thompson, A. M., et al. (2003a), Southern Hemisphere Additional Ozonesondes (SHADOZ) 1998–2000 tropical ozone climatology: 1. Comparison with Total Ozone Mapping Spectrometer (TOMS) and ground-based measurements, *J. Geophys. Res.*, *108*(D2), 8238, doi:10.1029/2001JD000967.
- Thompson, A. M., et al. (2003b), Southern Hemisphere Additional Ozonesondes (SHADOZ) 1998–2000 tropical ozone climatology: 2. Tropospheric variability and the zonal wave-one, *J. Geophys. Res.*, *108*(D2), 8241, doi:10.1029/2002JD002241.
- Thulasiraman, S. J. B. Nee, W. N. Chen, and J. H. Chen (1999), Temporal characteristics of tropopause and lower stratosphere over Taiwan during 1990–1995, *J. Atmos. Terr. Phys.*, *61*, 1299–1306.
- Zahn, A., C. A. M. Brenninkmeijer, and P. F. J. van Velthoven (2004a), Passenger aircraft project CARIBIC 1997–2002, Part I: The extratropical chemical tropopause, *Atmos. Chem. Phys. Discuss.*, *4*, 1091–1117.
- Zahn, A., C. A. M. Brenninkmeijer, and P. F. J. van Velthoven (2004b), Passenger aircraft project CARIBIC 1997–2002, Part II: The ventilation of the lowermost stratosphere, *Atmos. Chem. Phys. Discuss.*, *4*, 1119–1150.
- Zängl, G., and K. P. Hoinka (2001), The tropopause in the polar regions, *J. Clim.*, *14*, 3117–3139.

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