Tropopause Characteristics and Variability from 11 yr of SHADOZ Observations in the Southern Tropics and Subtropics

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ABSTRACT

In this paper, tropopause characteristics observed from tropical to subtropical Southern Hemisphere stations using Southern Hemisphere Additional Ozonesonde (SHADOZ) data are presented for the 11-yr period of 1998–2008. Three different definitions of tropopause—cold-point tropopause (CPT), lapse-rate tropopause (LRT), and ozone tropopause (OT)—are determined, and their variability for nine different SHADOZ sites is studied for the purpose of evaluating their usefulness as indicators of possible tropopause trends. For each station, the OT is uniquely defined by the ozone gradient and is found to be more variable than either LRT or CPT. The OT roughly coincides with the upper boundary of the region of most active convective mixing over the western Pacific Ocean and with the lower boundary of the transition region from the troposphere to the lower stratosphere that is generally referred to as the tropical tropopause layer. The monthly and year-to-year variations in the tropopause are examined, and the annual cycle in OT, the dominant signal, is described. The distance of separation of the OT from the CPT or LRT is smaller for the tropics (stations at 0°–15°S) than for the subtropics (15°–25°S). The decadal trend in tropopause heights is measured using a statistical model that accounts for natural variations expressed in El Niño–Southern Oscillation, the quasi-biennial oscillation, and the Indian Ocean dipole. The decadal trend estimation shows no statistically significant trend for the CPT and LRT in the tropics, in contrast to other studies. A decrease in altitude for the OT is significant. In the subtropics, the CPT and LRT decline significantly, by -240 and -190 m $(10 \text{ yr})^{-1}$, respectively, but the OT increases.

1. Introduction

The tropopause plays a vital role in the stratosphere–troposphere exchange (STE) and wave propagation between the troposphere and lower stratosphere (Holton et al. 1995; Sausen and Santer 2003; Fueglistaler et al. 2009). Temperature measurements from radiosonde data are used globally to characterize the tropopause and to study the temperature variability in the troposphere and lower stratosphere (Reid and Gage 1981, 1985, 1996; Murthy et al. 1986; Gage and Reid 1987; Selkirk 1993; Randel et al. 2000; Seidel et al. 2001). The cold-point tropopause (CPT) or the lapse-rate tropopause (LRT) is commonly used to identify the tropopause. Other definitions such as the ozone tropopause (OT), the isentropic potential vorticity tropopause, and the 100-hPa pressure level tropopause (PLT) may also be used. The CPT is normally defined as the height at which the tropospheric temperature is minimum and is frequently used to describe tropical tropopause features (Selkirk 1993). The LRT is defined as the lowest level at which the lapse rate

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is less than 2 K km^{-1} and it remains within this level for the next 2 km (World Meteorological Organization 1957). The OT is defined by Bethan et al. (1996) as the height at which the vertical gradient of ozone mixing ratio exceeds 60 ppbv km^{-1} and the ozone mixing ratio is greater than 80 ppbv (at and above this height) for a midlatitude location. Sivakumar et al. (2006) followed a similar definition for the ozone tropopause for a subtropical station (La Réunion) that is within the Southern Hemisphere Additional Ozonesonde (SHADOZ) network (Thompson et al. 2003a,b). The results of Sivakumar et al. (2006), in a somewhat similar way to those of Bethan et al. (1996), suggest that the tropopause for southern subtropical locations be set at the height at which the vertical gradient of ozone mixing ratio exceeds 55 ppbv km^{-1} and the ozone mixing ratio is greater than 75 ppbv (Sivakumar et al. 2006). Sivakumar et al. (2006) also studied the sharpness of LRT and OT height detections and found that the OT is more sharply defined than the LRT. Folkins et al. (1999, 2002) suggested that the level at which ozone starts to increase is basically the level at which convection stops efficiently mixing air. Further, Pan et al. (2004) and Zahn et al. (2004) proposed a chemical tropopause for extratropical latitudes that is based on ozone (stratospheric tracer) and carbon monoxide (tropospheric tracer) and concluded that uncertainty in the chemical tropopause height determination was ~150–200 m. More recent work by Sausen and Santer (2003) and Santer et al. (2004) proposed that a change in tropopause height be adopted as one indicator of anthropogenic climate change. Temperature or ozone variations linked to changes in the global tropopause thus become very important.

Tropopause height varies with latitude and is generally higher at the equator and decreases toward the poles. It is also highly variable from day to day and from season to season (Hoerling et al. 1993; Hoinka 1998). Seidel et al. (2001) used 40 yr of data collected from 83 radiosonde stations around the globe to study tropopause climatological characteristics. They studied the CPT, LRT, and PLT on the basis of temperature information over Northern and Southern Hemisphere regions and found that the annual-mean LRT height varies from 16.5 km in the equatorial zone to less than 16 km in the subtropics whereas the CPT remains at ~16.9 km with very little Northern–Southern Hemisphere variability. This CPT altitude was confirmed for the tropical equatorial Americas region (radiosondes and ozonesondes over Alajuela, Costa Rica; 10°N, 84°W) during a July–August 2007 field intensive (Tropical Composition, Clouds and Convective Coupling: TC4) by Selkirk et al. (2010), who noted that the thermal tropopause and ozonopause were lower than the CPT by 2–3 km. Both Selkirk et al. (2010) and an assessment of tropopause structure from nearby Panamanian ozonesondes (Las Tablas; 8°N, 80°W) during TC4 by Thompson et al. (2010) discuss evidence for wave activity, much of it generated by active convection throughout the equatorial Americas. An advantage of an OT definition over the CPT evident in the Selkirk et al. (2010) and Thompson et al. (2010; see the OT for Alajuela and Las Tablas in their Fig. 2) studies is that the OT but not the CPT appears to coincide with the bottom of the tropical tropopause layer (TTL; Fueglistaler et al. 2009), facilitating detailed analysis of mixing times, wave characteristics, and affected tracers within this zone. The OT is above the altitudes of maximum cloud outflow as shown by fast ozone profile data and a variety of tracers on DC-8 aircraft (Avery et al. 2010) but laminae of very low ozone are detected just below the OT in lidar ozone measurements [13 July 2007 of Thompson et al. (2010) and 17 July 2007 analyzed in detail by Petropavlovskikh et al. (2010)].

The distribution of wave activity and frequency detected in ozonesonde observations is more general (Thompson et al. 2011a,b) than the TC4 results. For example, gravity waves within the TTL appear in ~50% of all SHADOZ soundings, on average, and the altitude at which they maximize varies according to location of the OT at the given location. Variations in OT among SHADOZ stations point to other properties that differ among stations. The physical significance of the OT is evident in the Takashima and Shiotani (2007) description of seasonality in the convectively active upper-troposphere (UT) region across SHADOZ stations. Lee et al. (2010) used statistical analysis of ozone and temperature anomalies at four SHADOZ sites with varying OT over the period 1998–2005 to demonstrate different rates and even magnitude of ozone responses to quasi-biennial oscillation (QBO) impacts as they propagate from the lower stratosphere (LS) to the UT through the TTL. The CPT, on the other hand, is closer to the upper boundary of the TTL, just below the region where the Brewer–Dobson circulation dominates. Within the transition region, individual stations display different gradients in radiative and dynamical properties and in constituent concentrations (refer to Fig. 14 in Fueglistaler et al. 2009).

Randel et al. (2000) studied the interannual variability of the tropical tropopause based on National Centers for Environmental Prediction (NCEP) data and found negative trends in the CPT temperature [~0.5 K (10 yr)$^{-1}$]. They also noticed warming of ~1–2 K in the CPT temperature during volcanic eruptions (1982 and 1991) and lowering of the tropopause height by ~200 m. Chakrabarty et al. (2000) reported an increase in CPT

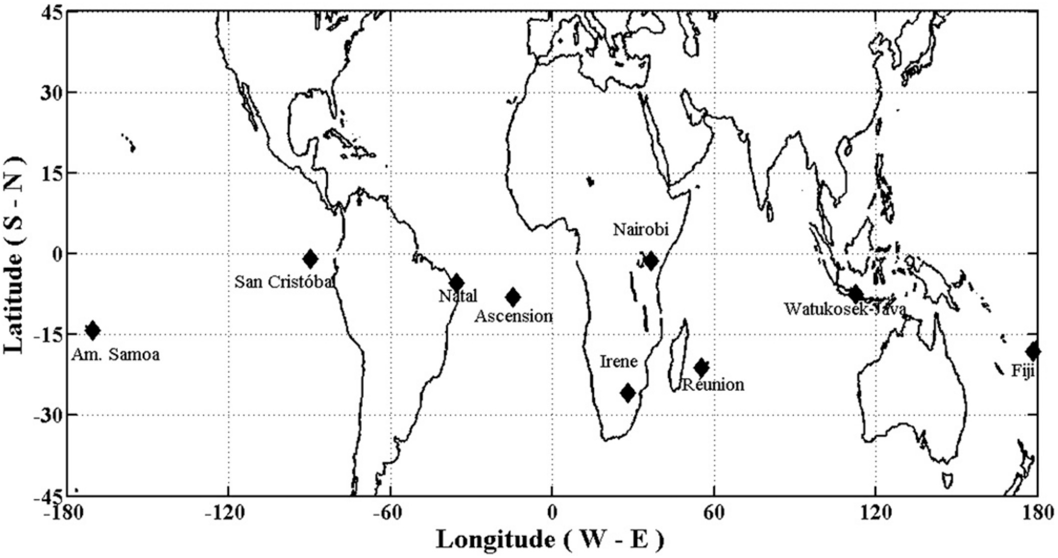

FIG. 1. The geographical positions of different SHADOZ stations used for this study.

height over India by $\sim$140 m (10 yr)$^{-1}$ based on 26–32 yr of radiosonde data. Forster and Tourpali (2001) determined an increase in tropopause heights of $\sim$330–520 m based on 27 yr of data (1970–96) from 11 Northern Hemisphere stations. Sausen and Santer (2003) found a decrease in the global tropopause pressure of $\sim$1.82 hPa (10 yr)$^{-1}$ based on the NCEP–National Center for Atmospheric Research analysis data from 1979 to 1997 and of $\sim$2.16 hPa from 1979 to 2000. Schmidt et al. (2004) derived tropical tropopause parameters from the global positioning system and found that the tropopause had a strong meridional variability in structure on the basis of 3 yr (2001–03) of data. Over the tropics (30°S–30°N), they found that the tropopause and the associated pressure were mostly similar (Seidel et al. 2001). In addition, they found that the LRT reached to a maximum of $\sim$16.5 km in the deep tropics (10°S–10°N), and in the tropics (30°S–30°N), the mean tropopause decreased to $\sim$15.8 km. On the basis of more recent radiosonde datasets, Seidel and Randel (2006) reported that the tropopause height increased by 64 ± 21 m (10 yr)$^{-1}$. The most recent study by Bègue et al. (2010) reported the importance of Indian Ocean dipole (IOD) forcing in the trend estimation and noted a rate of cooling of $\sim$0.1 K (10 yr)$^{-1}$ at the CPT by considering the IOD. The IOD is characterized by a positive (negative) phase when sea surface temperature (SST) is anomalously cooling (warming) in the eastern (western) equatorial Indian Ocean (Behera and Yamagata 2003).

In this paper, we present the tropopause characteristics and their spatiotemporal variability over the Southern Hemisphere using datasets from the SHADOZ network. The network has been very useful to many researchers for studying the Brewer–Dobson circulation (Randel et al. 2007); the QBO in the mid- to lower stratosphere (Logan et al. 2003; Witte et al. 2008; Lee et al. 2010); troposphere ozone variability (Thompson et al. 2003a,b); the structure of convection, wave signatures, and ENSO in the TTL (Thompson et al. 2011a,b); and the transport of stratospheric ozone from the extratropics to the subtropics (Semane et al. 2006; Bencherif et al. 2007). This paper extends the earlier published work by Sivakumar et al. (2006) that defined the OT for La Réunion (southern subtropics) and characterized the tropopause heights, including their sharpness of detection. This study uses 11 yr of archived SHADOZ data from nine sites (see Fig. 1) to characterize the seasonal and interannual variability of the tropopause. One aim of the paper is to investigate the relationship among OT, CPT, and LRT zonally across the southern tropics and from equatorial stations to 25°S. Here, tropical refers to the area from 0° to 15°S and subtropical is reserved for 15° to 25°S. Second, the three definitions of tropopause are used in a regression analysis model to detect possible trends during the 11-yr SHADOZ record, noting that the time covered is relatively short and is affected by several QBO cycles, ENSO, and IOD events. The paper is organized as follows. Section 2 discusses the data used and the method of detection of the different tropopause measures (CPT, LRT, and OT). Section 3 presents the monthly and interannual variability of CPT, LRT, and OT, and the decadal-trend estimation is described. The last section summarizes the main findings from this study.

2. Data and method

a. Data

This study is based on 11-yr (1998–2008) radiosonde–ozonesonde datasets collected over nine SHADOZ sites: San Cristobal (0.92°S, 89.60°W), in the Galapagos Islands; Nairobi, Kenya (1.27°S, 36.8°E); Natal, Brazil (5.42°S, 35.38°W); Watukosek, Java (7.57°S, 112.65°E); Ascension Island, in the South Atlantic Ocean (7.98°S, 14.42°W); American Samoa (14.23°S, 170.56°W); Fiji (18.13°S, 178.40°E); La Réunion (21.06°S, 55.48°E); and Irene, South Africa (25.9°S, 28.22°E) (Thompson et al. 2003a,b and references therein).

Ozone measurements at SHADOZ sites are made by electrochemical concentration cell ozonesondes (Thompson et al. 2000, 2003a) with temperature, pressure, and humidity recorded by standard radiosondes (Vaisala, Inc., RS-80 or RS-92, and Sippican, Inc., instruments at two stations) launched with each ozonesonde. The effective resolution of the ozone data is 50–100 m (Smit et al. 2007; Thompson et al. 2007). Further details for instrument types and sensing solutions in the ozonesonde are given online (http://croc.gsfc.nasa.gov/shadoz). The precision of the ozone measurement is 5%–7% throughout the troposphere and lower stratosphere (Smit et al. 2007) and the accuracy of the ozone below 20 km is also ~5% (Thompson et al. 2003a, 2007). Slight variations in ozonesonde solution, calibration, and instrument type (Smit et al. 2007; Deshler et al. 2008; Vömel and Diaz 2010) can introduce errors and biases in ozone readings among individual SHADOZ sites (Fig. 8 in Thompson et al. 2007). In this study, calibration errors are minimized by taking monthly averages. The biases do not affect the gradient calculations within given profiles (i.e., the tropopause calculation) nor the trend calculations because a consistent technique is employed at each station. The highest numbers of observations in 1998–2008 were recorded for Ascension, and the lowest numbers were recorded for Irene. The monthly distributions of available datasets for the above SHADOZ stations vary from 20 to 48.

b. Method of analysis

The determinations of CPT and LRT follow those reported by earlier researchers and were introduced in section 1. In this section, we describe the method of detection of the OT.

Sivakumar et al. (2006) defined the ozone tropopause as the height at which the vertical gradient of ozone mixing ratio exceeds 60 ppbv km^{-1} and the ozone mixing ratio is over 80 ppbv for a subtropical station (La Réunion); their results show some changes in the definition for the subtropics when compared with the convention of Bethan et al. (1996). Thus, a single OT definition is not necessarily suitable for all SHADOZ stations (from equatorial to subtropical), and therefore we performed a sensitivity analysis by changing the ozone mixing ratio and gradient for each station as described by Sivakumar et al. (2006). We find the maximum frequency of cases for which the earlier (given mixing ratio and gradient value) and newer (by introducing variations in either mixing ratio or gradient) thresholds show a difference in tropopause height within a height resolution of 150 m. A detailed step-by-step analysis for the Réunion station is sketched in the flow diagram (see the appendix). Here, the initial values are chosen from results published earlier by Sivakumar et al. (2006) for Réunion; the modified value is based on the above sensitivity analysis. After applying the different permutations on both the ozone mixing ratio and the vertical gradient, we have optimized the suitable values for each station. Table 1 summarizes the ozone mixing ratio and associated vertical gradient criteria followed for each station to determine the ozone tropopause.

TABLE 1. Ozone (O_3) tropopause criteria followed for SHADOZ stations [note that although a Costa Rican site (Heredia from 2005 to 2006 and Alajuela from 2006 to the present) is part of SHADOZ (Thompson et al. 2010) the sounding record does not extend back to the 1998–99 start of the archive].

Station and location	O_3 (ppbv)	dO_3/dz (ppbv km^{-1})
San Cristobal (0.92°S, 89.60°W)	75	50
Nairobi (1.27°S, 36.8°E)	80	55
Natal (5.42°S, 35.38°W)	75	50
Watukosek (7.57°S, 112.65°E)	70	45
Ascension (7.98°S, 14.42°W)	65	50
American Samoa (14.23°S,170.56°W)	75	55
Fiji (18.13°S, 178.40°E)	75	50
La Réunion (21.06°S, 55.48°E)	75	60
Irene (25.9°S, 28.22°E)	75	60

Figure 2 shows the height profiles of temperature and ozone as observed on 16 November 2001 for the American Samoa station. The profiles show that temperature and ozone partial pressure values recorded by radiosonde/ozonesonde are well defined up to the height region of 30 km. By applying the definitions of OT, LRT, and CPT to these profiles, the tropopause heights are found to be 13.6, 15.6, and 16.8 km, respectively.

3. Results and discussion

a. Monthly variation of tropopause height

Individual temperature and ozone profiles are analyzed to determine the CPT, LRT, and OT, as described

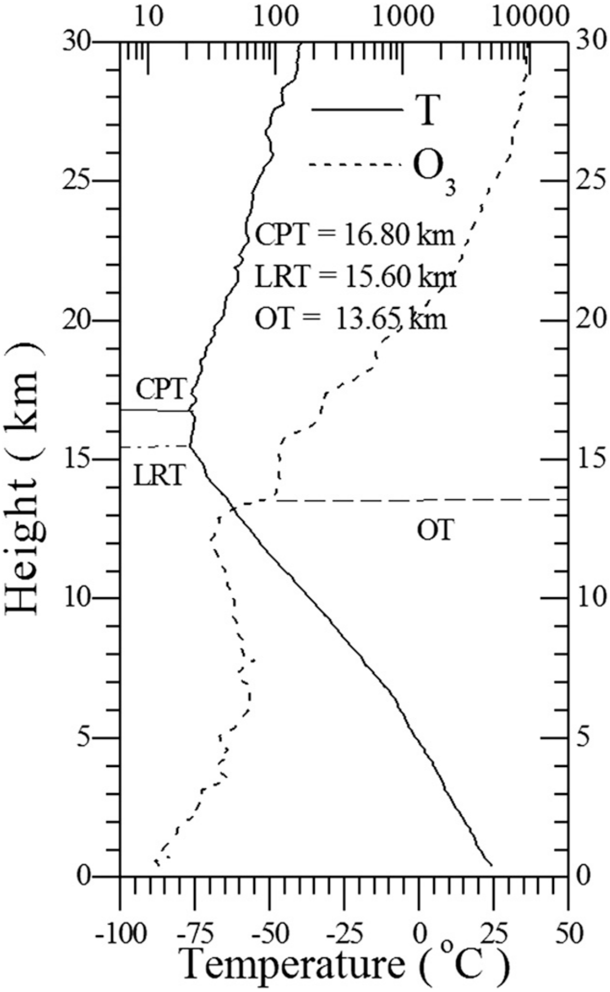

FIG. 2. Height profile of temperature (solid line; °C) and ozone mixing ratio (dashed line; ppbv) observed over American Samoa on 16 Nov 2001, with heights of the OT, LRT, and CPT indicated.

in section 2b. The calculated CPT, LRT, and OT are then grouped into months, irrespective of the years. Figure 3 shows the monthly variations of CPT, LRT, and OT for all of the stations. The vertical line in Fig. 3 illustrates the standard deviations. It is clear that all of the stations record a high tropopause for CPT followed by LRT and OT, and this is in agreement with other studies (Seidel et al. 2001; Sivakumar et al. 2006). The differences in the tropopause height among CPT, LRT, and OT are found to be smaller over equatorial sites than over tropical or subtropical stations. This is due to the fact that subtropical and tropical stations are greatly influenced by both the prevailing convective system and the mass exchange between the tropics and midlatitudes (Baray et al. 2000; Portafaix et al. 2003; Bencherif et al. 2007; Clain et al. 2009). For sites closer to the equator (such as San Cristobal), LRT and OT are generally similar over the year, except for during a few months (June–July or August–September) in which they show small differences in height of ~300 m.

Overall, the OT is found to have more monthly variability than the other two tropopause heights. Variability is defined as the associated standard deviation. At all of the stations, the CPT, LRT, and OT variations exhibit a prevailing annual oscillation (AO) with a minimum during winter/spring months (July or August). For a few stations (Ascension, Réunion, Fiji, and Irene), the OT shows a minimum during October. Such a minimum might be due to the influence of stratospheric–tropospheric intrusions or exchanges that are common during September–November over the tropics/subtropics (La Réunion and Irene) (Baldy et al. 1996; Randriambelo et al. 2000; Thompson et al. 2003b; Diab et al. 2004). More recent studies by Sauvage et al. (2006) confirm that the maximum tropospheric ozone during September–November near equatorial Africa also includes contributions from biomass burning and lightning. Figure 3 shows that the AO is clearly visible for equatorial stations but is less clear as one moves southward from the equator to the subtropics. In fact, almost all of the equatorial-latitude stations (San Cristobal, Nairobi, and Natal) show a clear annual oscillation with maximum and minimum heights during summer (December–January) and winter (July–August), respectively. Watukosek and Ascension exhibit very similar CPT variations, with a minimum during June–July and a maximum during January–February. La Réunion and Irene exhibit similar trends except that La Réunion shows a high standard deviation by the end of austral summer (March). In general, almost all of the stations exhibit higher variability in the tropopause during austral summer (September–December) than during winter (May–August). Such variations could arise from the existence of atmospheric wave dynamics (gravity, planetary, Rossby, and equatorial waves) that differ from season to season and from the tropics to the subtropics. More recent studies by Thompson et al. (2010, 2011a,b) confirm that convection and its associated waves (gravity and Rossby) influence tropical tropopauses—in particular, the OT—by ozone transport through meridional and vertical exchanges. Note that seasonal changes in solar radiation also affect the tropopause height, especially during summer as a result of increased convection (Reid and Gage 1981, 1996; Schmidt et al. 2004; Sauvage et al. 2006; Randel et al. 2007; Fueglistaler et al. 2009).

The variations found at the tropopause heights are greater for tropical and subtropical stations. The Irene and La Réunion sites show the largest variability (defined as the standard deviation). During spring and early summer (September–December), the OT differs

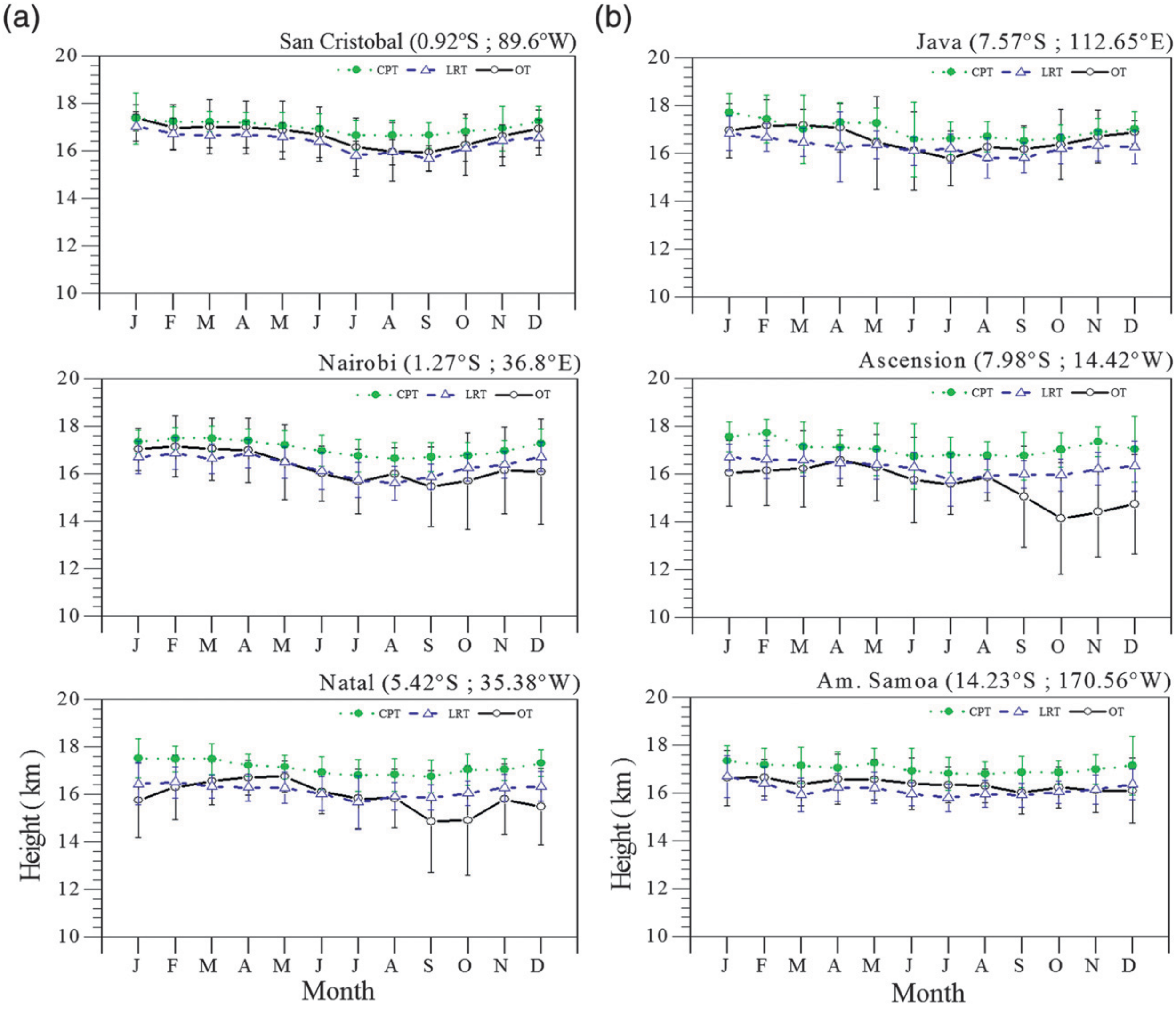

FIG. 3. (a) Monthly mean tropopause heights (CPT, LRT, and OT) for San Cristobal, Nairobi, and Natal. Vertical lines denote the corresponding standard deviations. (b) As in (a), but for Java, Ascension, and American Samoa. (c) As in (a), but for Fiji, La Réunion, and Irene.

greatly from the CPT and LRT values for Ascension, La Réunion, and Irene. The variations are found to be less during winter at ~0.8–1.2 km within the tropopause (especially between CPT/LRT and OT) and ~2.4–3.6 km during the spring and early summer periods. At Irene, such a large variability may be associated with a fewer number of observations used for obtaining the monthly mean values. Note that CPT standard deviations (Fig. 3) for both La Réunion and Irene, the sites farthest from the equator, do not show any sensitivity to the number of monthly processed profiles. A number of studies with ground-based and global observations have shown how the subtropics (La Réunion and Irene) are under the influence of isentropic exchange between the tropics and midlatitude regions (Bencherif et al. 2003, 2007; Portafaix et al. 2003), tropopause folding, and midlatitudinal baroclinic disturbances (Diab et al. 2004; Clain et al. 2009). These processes influence the transport of air (including ozone) from the tropics to the midlatitudes by planetary-scale waves and by tropospheric cyclonic-scale disturbances [see evidence for extratropical intrusions and waves at tropical sites in Thompson et al. (2010)]. This may partially explain the observed variability (standard deviation) over La Réunion and Irene.

In comparison with CPT and LRT, monthly mean heights of OT are found to be lower for all stations. Few stations exhibit intermediate OT values, that is, between CPT and LRT (San Cristobal, American Samoa, and Fiji). It is noticeable from Fig. 3 that OT heights have the largest standard deviations (variability) when compared

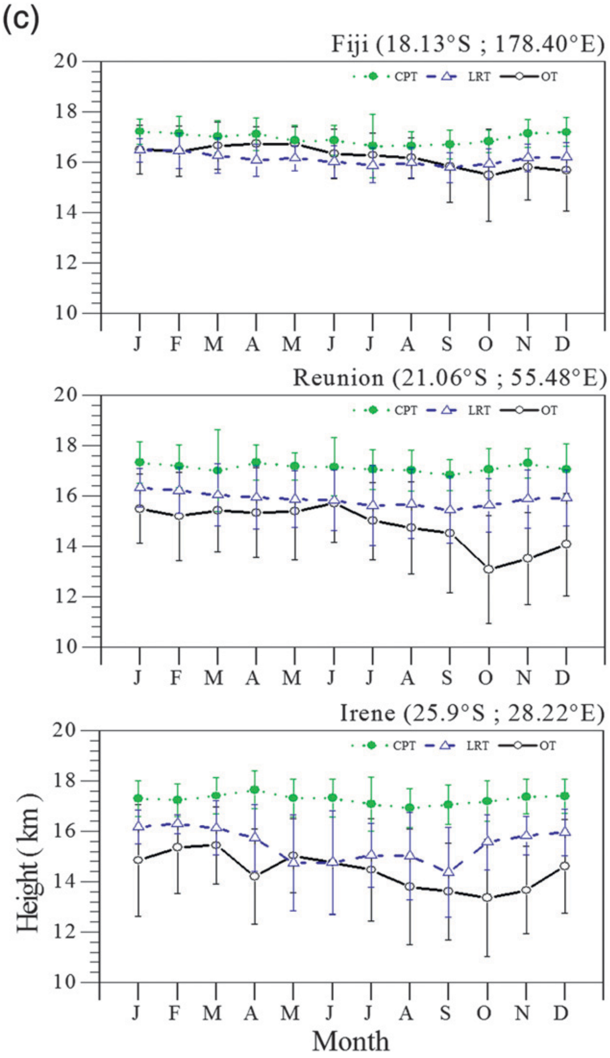

FIG. 3. (*Continued*)

with CPT and LRT heights, presumably because of the influence of local and meridional dynamical events on ozone. A few sites show decreasing OT heights from April–May to September–October, with the minimum appearing by October. The lowest OT heights occur over subtropical Irene and La Réunion. Only the Ascension OT shows a similarly variable OT as low as 14.2 km by October. In general, the mean LRT, CPT, and OT vary with latitude and from station to station. The variations among the stations are relatively small (within 450 m) for CPT and are slightly higher (within 0.6 km) for LRT. The OT shows significant variations over latitude and is highest for low-latitude stations such as Watukosek and is lower for subtropical stations (Irene, 14.4 km; La Réunion, 14.8 km).

We combined the above stations into tropical and subtropical categories and calculated the monthly mean variations of three different tropopauses (CPT, LRT, and OT). The results are presented in Fig. 4, along with their standard deviation. Here, the results show distinctions similar to those observed for individual stations when the tropics and subtropics are compared. The tropical stations have the higher CPT and a very clear AO with a minimum during July; similar variations are noted for LRT. The OT is found between the LRT and CPT during October–December; otherwise, it lies below the LRT. In comparison with the tropics, the subtropics do not show much variation for CPT (standard deviation of less than ±0.2 km), whereas LRT and OT show deviations of more than ±1.2 km. The subtropics have OT well below the LRT although we note that the number of stations in the tropical category (six) is twice that of the subtropics (three); fewer data might be generating an apparently greater standard deviation.

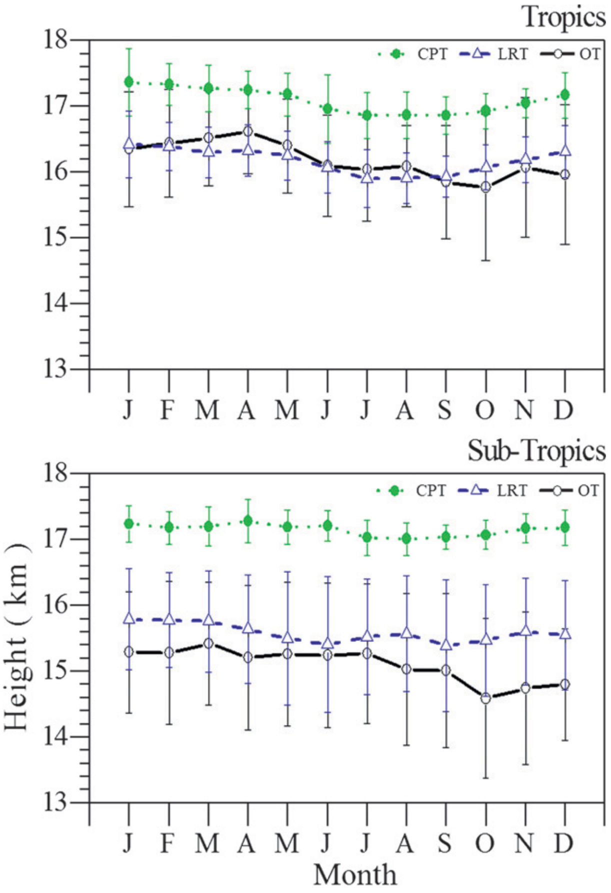

FIG. 4. As in Fig. 3, but for tropical (San Cristobal, Nairobi, Natal, Java, Ascension, and American Samoa) and subtropical (Fiji, La Réunion, and Irene) stations.

CPT, LRT, and OT heights have less variability and are within ±0.4–0.8 km difference for the Pacific Ocean

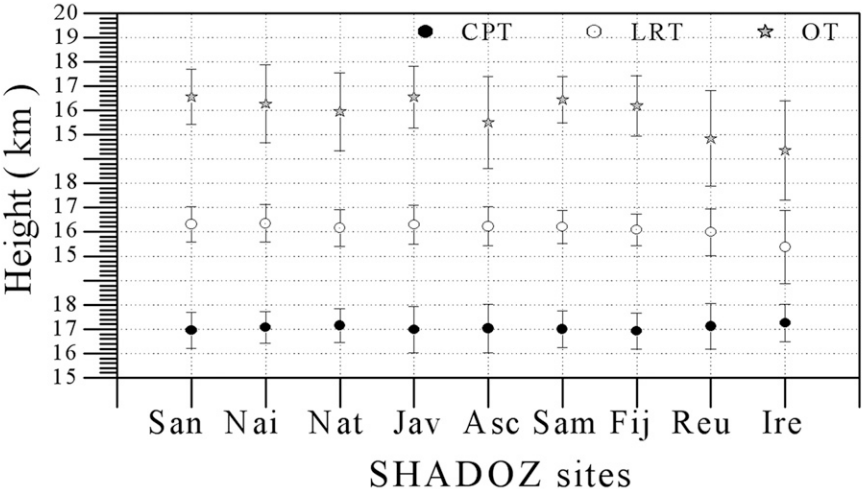

FIG. 5. Overall mean CPT, LRT, and OT for the nine SHADOZ stations.

stations (San Cristobal, American Samoa, and Fiji; Fig. 5). This is similar for the Indian Ocean tropical stations (Nairobi and Watukosek). The Indian Ocean subtropical stations (La Réunion and Irene) exhibit a greater degree of separation among the tropopauses, with the Atlantic Ocean sites (Natal and Ascension) exhibiting moderate values of separation. Figure 5 reflects the individual station behavior (cf. Fig. 3) in terms of tropopause variation from the equator to the subtropics.

b. *Year-to-year variations in the tropopause height*

The tropopause at any tropical location is subject to large variations by day, month, and year. In this section, we study the long-term variations in the tropopause using the 11 yr of SHADOZ data, from 1998 to 2008, and describe the results for the tropics and subtropics in terms of the three different tropopauses.

Figure 6 illustrates the temporal evolution of monthly variations of CPT, LRT, and OT for the nine SHADOZ stations over the 11-yr time period. Figure 6 highlights the individual yearly variations, which have considerable effect on the overall monthly seasonal variations presented in Fig. 4. The aim is to elucidate year-to-year tropopause variations. Note that in some years a few stations (especially for the subtropics) have data gaps that are left blank in the figure.

Although the results show similar variations as noted in the monthly variations, the CPT is found to be higher for all of the stations, and the difference between CPT and LRT/OT increases from the tropics to the subtropics. Subtropical stations show a remarkable separation between LRT and OT. On the other hand, tropical stations show similar variations of LRT and OT. We notice few variations between the years for the tropics. For these stations, the tropopause height is found to vary between 15.2 and 17.6 km without any variation among LRT, CPT, and OT values. The OT is usually found between the CPT and LRT; on occasion, the OT and LRT coincide. This agrees with the climatological description of Seidel et al. (2001).

Because LRT and CPT variations have been studied more widely, we concentrate here on remarkable features in the OT. Low OT values occur in a few years for which the OT is below ~15.2 km for the tropics and below 14.6 km for subtropics. Such low tropopause anomalies might be due to the existence of intrusions from the stratosphere to the troposphere (STE). To be specific, low OT was observed for the tropics during 2002, 2003, and 2006 and low OT in the subtropics appeared in 1998, 2001, 2004, 2005, and 2006. Looking at monthly data for individual stations, it is found that the 1998 OT anomaly occurred at Irene and the anomalies for 2005 and 2006 correspond to Réunion. Lee et al. (2010) studied QBO and ENSO variability over four different SHADOZ sites, including Natal, where OT variations are qualitatively similar to those for Ascension in most of the 11-yr record. They find significant ozone anomalies near the tropopause responding to ENSO with positive (negative) anomalies in the region of downwelling (upwelling). The 2006 low OT variations might reflect influences of the 2006 ENSO. The subtropical tropopause height variations (CPT, LRT, and OT) are found to be similar to our Réunion results (Sivakumar et al. 2006). There are a few cases in which a low ozone tropopause height (<14.2 km) is recorded. We examined those cases and found that these ozone layers result from filaments introduced into the region by STE.

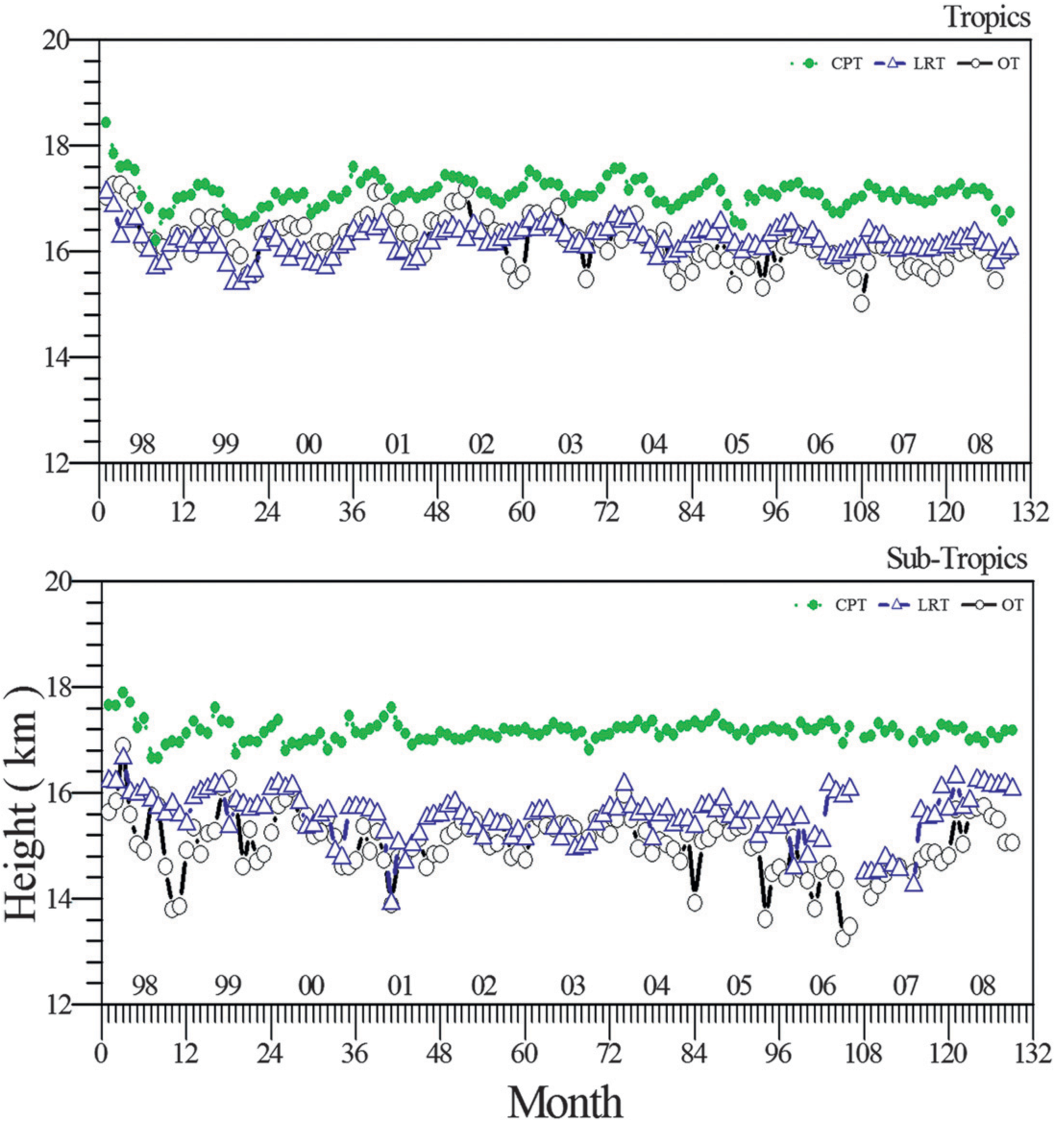

FIG. 6. Temporal variations of monthly mean tropopause heights (CPT, LRT, and OT) for tropical (San Cristobal, Nairobi, Natal, Java, Ascension, and American Samoa) and subtropical (Fiji, La Réunion, and Irene) stations for the period from 1998 to 2008.

c. *Tropopause height: A decadal trend estimation*

Using the 11 yr of SHADOZ data, we investigated trends using the Trend-Run model, which is a multiregression model adapted from the Adaptive Model Unambiguous Trend Survey (AMOUNTS) and AMOUNTS-O3 models at La Réunion University (Hauchecorne et al. 1991; Keckhut et al. 1995). Trend-Run is based on a multivariate least squares method that includes terms for AO and semiannual oscillations (SAO), QBO, ENSO, and the 11-yr solar cycle. Earlier studies (Bencherif et al. 2006) did not consider the IOD (Saji et al. 1999; Thompson et al. 2001) while calculating the linear trend. In its present version, the Trend-Run model is modified to include the IOD as a potential source of tropopause variability (Bègue et al. 2010), using the dipole mode index (DMI; information online at http://ioc3.unesco.org/oopc/state_of_the_ocean/sur/ind/dmi.php). DMI is defined as the abnormal difference in SST between the western and eastern tropical Indian Ocean (Behera and Yamagata 2003). Here, we have studied the tropopause height variations with and without the IOD values. More recent results by Morioka et al. (2010) also revealed that IOD acts as a major climate mode in the southern Indian Ocean.

TABLE 2. The measured decadal tropopause trend values [m (10 yr)$^{-1}$] with and without the Indian Ocean dipole.

	With IOD			Without IOD		
	CPT	LRT	OT	CPT	LRT	OT
Tropics	67 ± 211	213 ± 244	−150 ± 135	79 ± 197	163 ± 230	−101 ± 130
Subtropics	−242 ± 75	−487 ± 89	87 ± 173	−224 ± 72	−464 ± 86	160 ± 168

The linear trend is obtained from a regression model defined as follows:

$$Y_t = \alpha_0 + \alpha_1 t + c_1\mathrm{SAO}_t + c_2\mathrm{AO}_t + c_3\mathrm{QBO}_t + c_4\mathrm{IOD}_t + c_5\mathrm{ENSO}_t + c_6\mathrm{SSN}_t + \varepsilon_t, \qquad (1)$$

where α_0 is a constant, α_1 is the trend per month, and ε_t is the residual term, with t denoting the number of months beginning from the time series. The least squares method is applied for calculating the coefficients c_i to minimize the residual sum of squares. More details on Trend-Run are available in Bencherif et al. (2006) and Bègue et al. (2010).

The trend uncertainties are derived by the method of Logan (1994) as

$$\sigma_a^2 = \mathbf{v}(k)\sigma_s^2\frac{1+\varphi}{1-\varphi},$$

where σ_s^2 represents the variance of the residual term, $\mathbf{v}(k)$ represents the covariance matrix of different forcings taken into account by the regression model, and φ is the autocorrelation coefficient. It is noted here that the trend uncertainties are not given only by standard deviation term; it takes into account the autocorrelation coefficient φ. The degree of data independency is estimated through the autocorrelation coefficient φ of the residual. It should be low for a good estimation of trend (Weatherhead et al. 1998; Tiao et al. 1990).

For the estimation of trend values, we have grouped the data into two datasets, illustrated for the tropics (San Cristobal, Nairobi, Natal, Watukosek, Ascension, and American Samoa) and the subtropics (Fiji, La Réunion, and Irene). The estimated trend values for the above two groups of SHADOZ stations, with and without IOD, are shown in Table 2. Because we have data from a quasi-continuous 11-yr period, the trend values presented pertain to a decade. Data gaps for some stations and during some months are filled with the average between the respective previous and subsequent year's monthly mean values. In general, the trend values are fairly similar with and without IOD. The trend values for tropical CPT and LRT are not statistically significant, however, and the trend for OT, −150 ± 135 m (10 yr)$^{-1}$, is only marginally significant. This is at odds with several previous studies (e.g., Forster and Tourpali 2001). Forster and Tourpali (2001) analyzed ozonesonde data at 11 Northern Hemisphere sites and found tropopause height increases of 330–520 m on the basis of data from 1970 to 1996/97. Santer et al. (2003) reported a global tropopause trend of −1.13 hPa (10 yr)$^{-1}$ based on 15 yr (1979–93) of European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis data; their value is an order of magnitude higher than the estimates of Hoinka (1998). When Santer et al. (2004) used 40 yr of ECMWF Re-Analysis data, they found the global tropopause trend values to be −2.36 ± 0.47 hPa (10 yr)$^{-1}$. Thus, the amount of data used appears to have an impact on the results. Seidel and Randel (2006) reported an increase in LRT trend of 64 ± 21 m (10 yr)$^{-1}$ on the basis of data from 25 yr (1980–2004) of radiosonde data, but they also noticed variations in the trend value when the data were limited to different times.

The subtropical stations show a statistically significant negative trend value (decrease in tropopause height trend) for both CPT and LRT and a positive (increase) nonsignificant trend value for OT. The individual trend coefficients illustrate that the AO dominates tropopause variability in both the tropics and subtropics. The regression coefficients R^2 are found to be higher than 75% for the tropics and greater than 62% for the subtropics. The measured parameter R^2 confirms that the simulated variability from Trend-Run is close to the observed and indicates that the physical forcing in the model is well represented (higher for the tropics). The IOD is found to be more significant in the subtropics than in the tropics. In general the IOD contributions are within 5% for most of the cases and for all of the tropopauses. Bègue et al. (2010) also noted that the IOD and ENSO explain the variation of 12.3% at the CPT for La Réunion. A more recent study of SST by Morioka et al. (2010) has noted that the reappearance of positive and negative anomalies concurrent to a particular phase of IOD over the Southern Hemisphere may be linked to decadal variations of subtropical highs (Allan et al. 1995) or remote forcing from the high latitudes (Fauchereau et al. 2003).

4. Summary and concluding remarks

We have presented monthly and interannual variations of CPT, LRT, and OT over Southern Hemisphere regions from the tropics to the subtropics (25°S) on the

TABLE A1. Sensitivity of the ozone tropopause height detection using different thresholds.

Criteria parameters				Tropopause height remains unchanged (%)
Reference threshold		Modified threshold		
O_3 (ppbv)	dO_3/dz (ppbv km^{-1})	O_3 (ppbv)	dO_3/dz (ppbv km^{-1})	
80	60	75	55	65.1
75	60	75	55	73.9
80	60	75	60	76.8
80	55	75	55	74.9
75	55	75	50	72.0

basis of 11 yr of SHADOZ data from 1998 to 2008. The major findings from our study are as follows:

- CPT, LRT, and OT heights were computed for nine SHADOZ stations. The difference between CPT and OT (2–3 km) is larger than the difference between LRT and OT (~1 km), with greater differences in the subtropics than at the equator.
- The CPT is found to have the highest level of tropopause, typically without significant variations over latitude, followed by LRT and OT.
- The tropopause heights are found to exhibit an annual oscillation, and the height ranges are similar in magnitude to results found in prior work.
- The OT is found to be more useful for capturing dynamic month-to-month variability than are either LRT or CPT (especially over the subtropics) and for distinguishing potentially important variations among individual stations.
- It is found that the variations in the tropopause decrease from the equator to the tropics and that very low values (~15.4 km) are recorded for subtropical stations. The subtropical stations, La Réunion and Irene, show a low OT of ~14.2 km.

Decadal trends for tropopause heights show strong variability among sites, ranging from −490 to +213 m (10 yr)$^{-1}$. Taken as a whole, however, only a decrease in OT height over the tropics and decreases in CPT and LRT heights over the subtropics are statistically significant. This study serves as a benchmark for various tropopauses that can be delineated with the SHADOZ data as well as trends over the past decade or so. It is hoped that the features identified are valuable for evaluating model simulations of ozone and climate parameters.

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APPENDIX

Ozone Tropopause Height Detection

The ozone tropopause has been defined in terms of ozone vertical gradient and the ozone mixing ratio. The sensitivity or optimized value for each station has been determined on the basis of the different permutations on both the ozone mixing ratio and their vertical gradients. For example, the OT is defined for La Réunion as the height at which the vertical gradient of the ozone mixing ratio exceeds 55 ppbv km^{-1} and the ozone-mixing ratio is over 75 ppbv. The values have been optimized by decreasing the threshold value of the vertical gradient of the ozone mixing ratio and the ozone mixing ratio in steps of 5. The results obtained from different kinds of threshold variations and the number of cases (in terms of percentage) for which OT remains within ±0.15 km are listed in Table A1. We ascertained that in 77% of cases the OT defined by having the vertical gradient of the ozone mixing ratio exceed 60 ppbv km^{-1} and the ozone

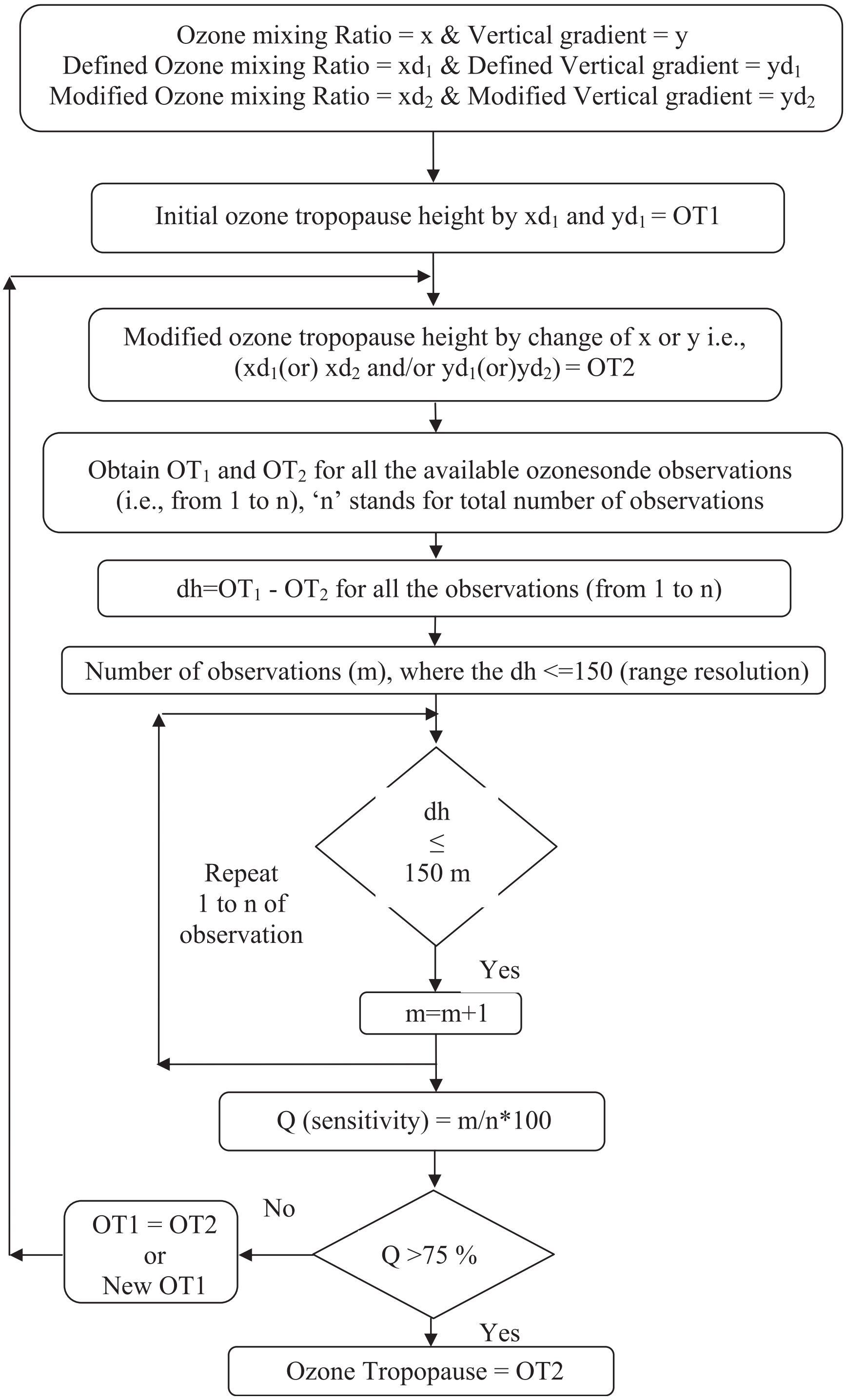

FIG. A1. Flow diagram that explains the OT sensitivity analysis.

mixing ratio be over 75 ppbv is found to be in agreement with (OT differences within ±0.15 km) the one defined by a mixing ratio of 80 ppbv. The above sensitivity analysis is summarized graphically in Fig. A1.

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