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Observed Long-Term Changes in Global Tropopause Characteristics

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Abstract. Variability or long-term change in tropopause characteristics has important implications for climate, especially since its temperature—to a large extent—dictates the amount of water vapor (a critical greenhouse gas) in the stratosphere. While conventional observations sufficient for examining tropopause characteristics provide limited geographic coverage, the growing global navigation satellite system radio occultation record provides relatively unlimited geographic coverage continuously since early 2001. This study applies the temperature lapse-rate tropopause (LRT) and potential temperature gradient tropopause (PTGT) definitions to the most recent 23-year radio occultation data period (2003–2025, inclusive) to create robust climatologies and assess long-term changes (statistically significant positive/negative trends) in the altitude, temperature, and sharpness of the primary tropopause and in the occurrence of multiple tropopauses. Regardless of definition, primary tropopause altitudes and temperatures are found to be increasing in most locations globally, consistent with other studies. A narrow region of decreasing tropopause altitudes in the subtropics and over the southern hemisphere east Pacific ocean basin is found to be driven by localized tropical narrowing, while the width of the tropics (based on tropopause altitude) is found to be increasing otherwise, especially throughout the northern hemisphere. Primary tropopause sharpness is also found to be increasing in most locations, but especially so in the tropics, where it is driven by both upper troposphere stability decreases and lower stratosphere stability increases. Finally, double and triple tropopauses are becoming more frequent in both the tropics and midlatitudes.

1 Introduction

The transition layer between the upper troposphere and lower stratosphere (UTLS), known as the *tropopause*, is well recognized as a critical feature of Earth's weather and climate (e.g., Danielsen, 1959; Holton et al., 1995; Hoinka, 1997; Stohl et al., 2003; Fueglistaler et al., 2009; Gettelman et al., 2011). Distinguished by significant changes in composition, dynamics, and stability in the UTLS, the tropopause vertically (and in some cases, horizontally) separates the well-mixed troposphere from the stably stratified stratosphere. Its altitude, temperature, sharpness, and other characteristics have been widely examined in the past several decades. Moreover, the tropopause has been shown to be important to facilitating or preventing exchanges of air between the troposphere and stratosphere (stratosphere-troposphere exchange, or STE), to diagnosing long-term changes of the atmosphere (Shepherd, 2002; Santer et al., 2003), and to controlling the amount of water vapor and other trace greenhouse

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gases that circulate for long periods in the stratosphere via the equator-to-pole overturning Brewer-Dobson Circulation (BDC) and impact climate (e.g., Brewer, 1949; Dobson, 1956; Mote et al., 1996; Randel et al., 2010; Randel and Park, 2019).

Because of the myriad parameters that commonly exhibit significant change in the tropopause transition layer, numerous definitions have been developed to diagnose the tropopause, each having unique strengths and weaknesses (see discussion in Tinney et al., 2022, and references therein). Some definitions allow for identification of more than one tropopause in a profile, but the primary (or first) tropopause is often of greatest interest. Regardless of definition, the primary tropopause is known to exist at uniformly high altitudes and low temperatures in the tropics and uniformly low altitudes and relatively high temperatures in the extratropics. Furthermore, a sharp discontinuity in tropopause altitude exists between tropics and extratropics on the poleward edge of the subtropical jet streams in each hemisphere and is commonly referred to as the tropopause "break" (Randel et al., 2007a; Pan and Munchak, 2011; Homeyer and Bowman, 2013; Xian and Homeyer, 2019).

Near the subtropical and higher-latitude jets in each hemisphere, the tropopause is commonly distorted (lowered and folded) due to cross-jet ageostrophic vertical circulations, making definition challenging and often resulting in multiple tropopauses in a profile (Reed, 1955; Danielsen, 1968; Shapiro et al., 1987; Sprenger et al., 2003). Multiple tropopauses can be generated otherwise by dynamic effects including vertical stretching/shrinking (Wang and Polvani, 2011; Peevey et al., 2014), STE via poleward (equatorward) transport of tropical upper troposphere (extratropical lower stratosphere) air into the extratropical lower stratosphere (tropical upper troposphere; Pan et al., 2009; Castanheira and Gimeno, 2011; Peevey et al., 2012; Liu and Barnes, 2018), by radiative processes (Randel et al., 2007b; Ferreira et al., 2016), and by convection introducing a false low-altitude primary tropopause in the tropics (Biondi et al., 2012). Multiple tropopauses are most common in the subtropics and midlatitudes, especially poleward of the subtropical jets (Schmidt et al., 2006; Randel et al., 2007a; Añel et al., 2008).

The sharpness of the tropopause—i.e., the depth or magnitude of the step change in stability, composition, or another property—has been less examined, but shown to vary from as little as 10s of meters deep to several kilometers (Hegglin et al., 2009; Homeyer et al., 2010; Tilmes et al., 2010), to exhibit the largest stability change in altitude in the tropics and summer hemisphere extratropics, and to exhibit the weakest stability change along the subtropical jets near the tropopause breaks (Schmidt et al., 2005; Gettelman et al., 2011; Son et al., 2011). Relatedly, a key structural feature of the tropopause that is routinely exhibited in the extratropics is the so-called tropopause inversion layer (TIL), which is a temperature (and stability) inversion that exists in a layer 1–3 km above the primary tropopause (Birner et al., 2002; Birner, 2006; Randel et al., 2007b; Bell and Geller, 2008; Gettelman and Wang, 2015). The TIL typically represents the largest stability change in a profile and correlates well with observed composition change (Pan et al., 2004; Schmidt et al., 2010).

Long-term changes in tropopause characteristics have been the subject of both observational and modeling studies in the past several decades. A consistent result of such studies is that the altitude of the primary tropopause is found to be mostly increasing globally, with regional variability in the area of greatest change depending on the time period analyzed (e.g., Seidel and Randel, 2006; Xian and Homeyer, 2019; Meng et al., 2021; Ladstädter et al., 2025). Many of these studies show less consistent results on the sense of long-term changes of primary tropopause temperature, which likely reflects the complexity of competition between observed tropospheric warming, stratospheric cooling, and circulation change as discussed in Shepherd (2002). However, the most recent period mostly exhibits primary tropopause warming associated with the increasing altitudes,

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especially in the tropics and subtropics (Zolghadrshojaee et al., 2024; Ladstädter et al., 2025). Such tropopause warming is related to increased stratospheric water vapor and an apparent weakening of the BDC during the past two decades (Minschwaner et al., 2016; Randel and Park, 2019; Zolghadrshojaee et al., 2024).

Long-term changes in the latitude of the tropopause break have also been examined, mostly in a zonal mean sense and based on either the frequency of high-altitude tropical tropopause heights or the latitudinal gradient of tropopause altitude. Although sensitivities to threshold choices exist, these studies indicate weak-to-moderate widening of the tropics (i.e., poleward expansion of the tropopause break latitudes; Seidel and Randel, 2007; Lu et al., 2009; Birner, 2010; Davis and Rosenlof, 2012; Ao and Hajj, 2013). Regionally-varying assessments of tropopause break latitude change indicate that, although weak poleward migration is found at most longitudes, significant equatorward migration (i.e., tropical narrowing) is found over the east Pacific ocean basin, especially in the southern hemisphere (Martin et al., 2020; Zou et al., 2023).

To the authors' knowledge, long-term changes in tropopause sharpness have not been thoroughly examined. Only one study, Gettelman and Wang (2015), provides some assessment of such long-term changes. Namely, they explore 1980–2011 zonal mean trends in the difference magnitude and depth between the upper troposphere stability minimum and above-tropopause stability maximum using reanalysis and reveal that both quantities are significantly decreasing, thus providing conflicting interpretations of tropopause sharpness change. Long-term changes in double tropopauses have been assessed using both radiosondes and reanalyses and demonstrate significant increases in double tropopause frequency in recent decades, especially in the midlatitudes (Castanheira et al., 2009; Xian and Homeyer, 2019). Long-term changes in additional tropopauses (e.g., triple tropopauses) have not been explored and otherwise have received limited attention in the peer-reviewed literature, especially so for global analysis (Añel et al., 2008).

Most prior studies utilize radiosonde observations or model output to examine global tropopause characteristics and assess long-term changes. However, radiosonde observations with sufficient records exist for few fixed locations globally and are only available over land. While spatially continuous, models often fail to capture the sense or magnitude of diagnosed changes in comparison to radiosonde observations. Global navigation satellite system - radio occultation (GNSS-RO) profiles provide expansive high-vertical-resolution observations that are now emerging as a robust climate dataset for assessment of long-term changes in UTLS temperatures and tropopause characteristics, having now generated more than 25 years of continuous observations. Recent analyses of long-term primary tropopause height and temperature change using GNSS-RO have already enabled new insights into regional variability and their implications (e.g., Zolghadrshojaee et al., 2024; Ladstädter et al., 2025). Motivated by this development and the need to better understand changes in tropopause characteristics, this study utilizes GNSS-RO observations to assess gridded long-term changes in primary tropopause height, temperature, and sharpness, tropical tropopause frequency, and multiple tropopause frequencies, for the most recent 23 years of the observational record. To increase confidence in and aid interpretation of the resulting long-term changes, more than one tropopause definition is employed and several sources of climate variability known to impact the tropopause are accounted for. To the authors' knowledge, this effort is the first to examine geographic patterns in long-term changes of the primary tropopause sharpness, tropical tropopause frequency (tropopause break latitudes), and multiple tropopause frequency using GNSS-RO data.

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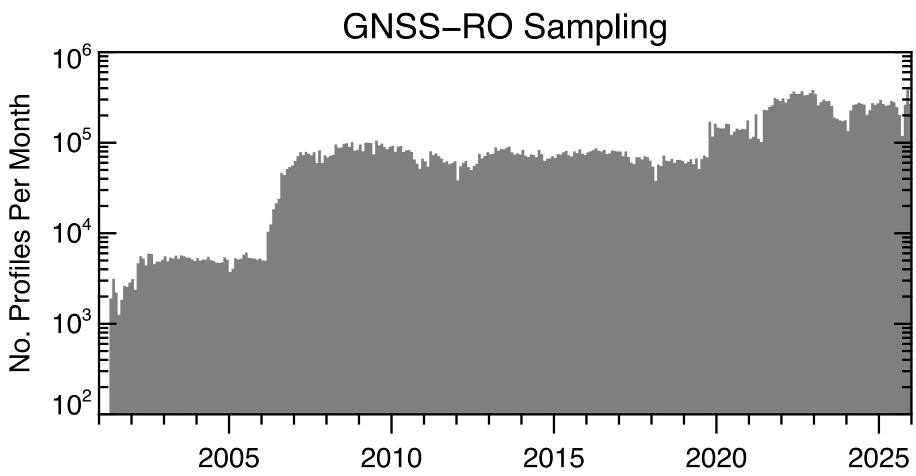

Figure 1. The number of GNSS-RO atmospheric profiles available per month for analysis in this study.

2 Data and Methods

2.1 Radio Occultation Profiles

GNSS-RO data have been collected continuously by several dozen publicly-funded and commercial satellites since early 2001. Multiple organizations process the RO data with customized inversion algorithms to generate various products for analysis, including the atmospheric profile retrievals used in this study. Specifically, we leverage GNSS-RO profiles from all publicly available, quality-controlled datasets processed by the COSMIC Project Office at the University Corporation for Atmospheric Research (UCAR) and hosted in the version 1.1 Amazon Web Services archive (Leroy et al., 2024). Figure 1 shows the number of atmospheric profiles available per month during the period from 2001 through 2025. Significant increases in observational density occur during years 2006 and 2019.

This study's analysis is restricted to a continuous 23-year period with appropriately dense sampling, 2003–2025 (inclusive). Since RO data are an atmospheric limb measurement, the horizontal resolution is somewhat coarse (<2 km wide by 200–300 km long), but the intrinsic vertical resolution is comparably fine at 100–200 m in the UTLS. Nevertheless, retrieved atmospheric profiles from RO data are reported at an average reference location of the limb path (longitude and latitude centroid) and 100-m intervals in altitude. To enable global analysis of long-term changes in tropopause characteristics, the RO data must be binned monthly on a uniform longitude-latitude grid. Results reported herein were generally insensitive to grid resolution and step changes in profile density (e.g., as also found in Ladstädter et al., 2025), and we used the finest grid size which provided reliable and coherent statistics during the analysis period: 15° longitude × 8° latitude. The analysis domain spans 80° S to 80° N latitude, due to sparse RO sampling near the poles.

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2.2 Tropopause Identification

All tropopause analyses in this study are executed using the two "universal" definitions which exist: the WMO temperature lapse rate tropopause (LRT; World Meteorological Organization, 1957) and the potential temperature gradient tropopause (PTGT; Tinney et al., 2022). These definitions are considered universal because they can be easily applied to conventional observations and model output and are functional at all latitudes. The LRT and PTGT definitions are also the only two which include instructions for multiple tropopause identification. In either case, these stability-based definitions aim to reliably capture the primary stepwise increase in static stability from troposphere to stratosphere (and additional significant step changes at higher altitudes indicative of multiple tropopauses). The LRT is historically the most utilized tropopause definition and is well characterized, performing reliably in most circumstances and having some well-known failure cases. Though relatively new, the PTGT was developed in part to resolve the failure cases of the LRT and otherwise to provide a stability-based tropopause definition that most consistently captures the altitude of greatest change in atmospheric composition in the UTLS. This is the first study to climatologically evaluate the PTGT and concurrently the LRT. For more extensive discussion on methods for tropopause identification and the performance of the LRT, the reader is once again referred to Tinney et al. (2022).

Due to its aforementioned relevance to the stratospheric water vapor budget, one additional definition–the cold-point tropopause (CPT)–is also evaluated within the tropics (all longitude-latitude bins within 32° latitude of the equator). In this case, only CPT altitude and temperature are examined since additional tropopause characteristics are better-captured, globally available, and consistently demonstrated in the LRT and PTGT analysis. CPT characteristics are only calculated for GNSS-RO profiles which exhibit tropical LRT altitudes ($\geq$14 km), as the CPT is not a reliable diagnostic of the tropopause transition layer in the mid-latitudes and polar regions.

Tropopause sharpness has been assessed using several methods in prior literature, but we apply a measure which emphasizes the magnitude of stability change at the tropopause and can be applied regardless of tropopause definition. Namely, we consider the sharpness to be indicated by the difference between the potential temperature gradient or temperature lapse rate between the 1-km layer above and below the tropopause, as employed in Schmidt et al. (2005) and Son et al. (2011). Since the key elements of the results we emphasize in this study are insensitive to the choice of stability metric, only the sharpness based on the difference in lower stratosphere and upper troposphere potential temperature gradient is shown.

2.3 Trend Analysis

Long-term changes in tropopause characteristics are diagnosed for each longitude-latitude grid box of the analysis domain using monthly timeseries of the average observation in the bin. A low-pass Fourier filter is used to deseasonalize the time series, removing power for all scales at and below 12 months. Multiple linear regression is applied to each deseasonalized time series, accounting for the time trend, the El Niño-Southern Oscillation (ENSO), and the Quasi-Biennial Oscillation (QBO) in the regression. The ENSO and QBO are included because they have been demonstrated to correlate with tropopause behavior, especially in the tropics (e.g., Reid and Gage, 1985; Randel et al., 2000; Wilhelmsen et al., 2020; Zolghadrshojaee et al., 2024). Namely, we use reference monthly time series of QBO zonal wind at 50 hPa from the conventionally-used Singapore

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radiosonde record processed by NASA Goddard (NASA Goddard, 2026) and the multivariate ENSO index version 2 from the NOAA Physical Sciences Laboratory (NOAA PSL, 2026) – a standardized index that includes atmospheric and oceanic indicators of ENSO and is based on the methods in Wolter and Timlin (2011). The resulting time trends are used to identify long-term changes in all tropopause characteristics and are considered to be statistically significant over the 23-year record if the sign of the change (positive/negative) does not vary across the 99% confidence interval. Statistically insignificant results are thus marked by an "X" in each analysis map.

3 Results

The GNSS-RO global climatology of PTGT and LRT altitude and temperature is shown in Figures 2 and 3, respectively. Both definitions demonstrate the anticipated result of uniformly high tropopause altitudes and low temperatures in the tropics and the opposite in the extratropics. As also expected based on the development efforts of Tinney et al. (2022), although the resulting primary tropopause climatology is similar, PTGT altitudes are slightly lower than LRT altitudes and PTGT temperatures are slightly higher. One meaningful result of this difference is that the tropics will be slightly narrower when using the PTGT definition. Otherwise, no significant differences exist between this climatology (i.e., that for the LRT) and prior work.

The time trends of the PTGT and LRT altitudes and temperatures are shown in Figures 4 and 5, respectively. As for the climatology, the sign, magnitude, and geographic variability of trends are broadly consistent across the two definitions. Primary tropopause altitudes are found to be significantly increasing in most locations, with the greatest upward trends in the middle and high latitudes and the weakest trends in the tropics. One notable exception to the broad increasing trends is a latitudinally narrow region of significantly decreasing tropopause altitudes over the southern hemisphere (SH) east Pacific ocean basin. Primary tropopause temperature changes are less significant and exhibit moderate warming in the tropics, with larger warming across the SH subtropics, maximizing at a similar location to the decreasing altitude trends over SH East Pacific. At higher latitudes, there are some weak, regionally-limited significant tropopause cooling trends in each hemisphere. Unsurprisingly, these results are very similar to those from Ladstädter et al. (2025), who also use GNSS-RO data but complete the analysis with a 23-year period offset 1 year earlier from this study and employ slightly different grid resolution and ENSO & QBO indices. The only notable difference is that the global coverage of significant height trends is more extensive in the present study, especially in the tropics and midlatitudes. The near-global increase in tropopause altitude is thought to be primarily driven by long-term tropospheric warming, but BDC changes may also play a role in the tropics. Of greater interest is the reason for the observed significant decrease in tropopause altitude and corresponding increase in temperature over the SH east Pacific ocean basin. As mentioned in the Introduction, the latitude of the tropopause break in this region has been demonstrated to be moving equatorward during the past few decades, which would undoubtedly result in such trends. As such, this mechanism is further examined as a potential factor in Section 3.1.

The increases in PTGT and LRT primary tropopause altitude and temperature in the tropics have important implications for entry-level stratospheric water vapor to the BDC. However, these tropopause definitions are not necessarily aligned with the coldest temperature in a profile which is the physical constraint that determines the entry-level water vapor mixing ratio

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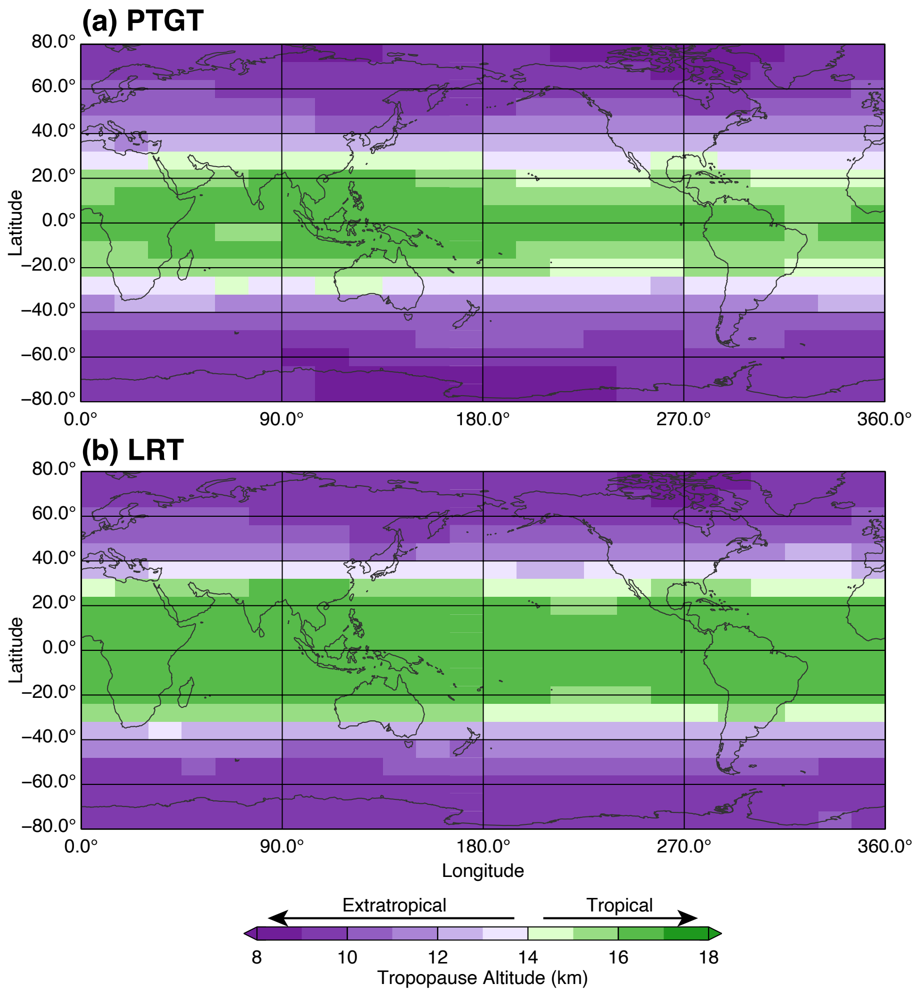

Figure 2. Maps of annual mean GNSS-RO primary tropopause altitude based on the (a) PTGT and (b) LRT tropopause definitions.

(i.e., the minimum saturation mixing ratio). Instead, the CPT is commonly analyzed in the tropics to diagnose such change. Thus, to examine consistencies between PTGT, LRT, and CPT trends, we apply the same techniques to the CPT in Figure 6. The resulting climatology and trends in CPT altitude and temperature mostly mirror the variability and geographic distribution found for the LRT in the tropics, with more robust significant trends in CPT altitude and slightly weaker trends in CPT temperature, especially near the tropical edge latitudes. Such a result is expected since the LRT and CPT closely coincide in the deep tropics and exhibit increasing separation toward the subtropics (Munchak and Pan, 2014). The diagnosed trends in CPT temperature also compare well with those from Zolghadrshojaee et al. (2024), who employ similar methods to GNSS-RO data from a slightly shorter and earlier time period (2002–2022).

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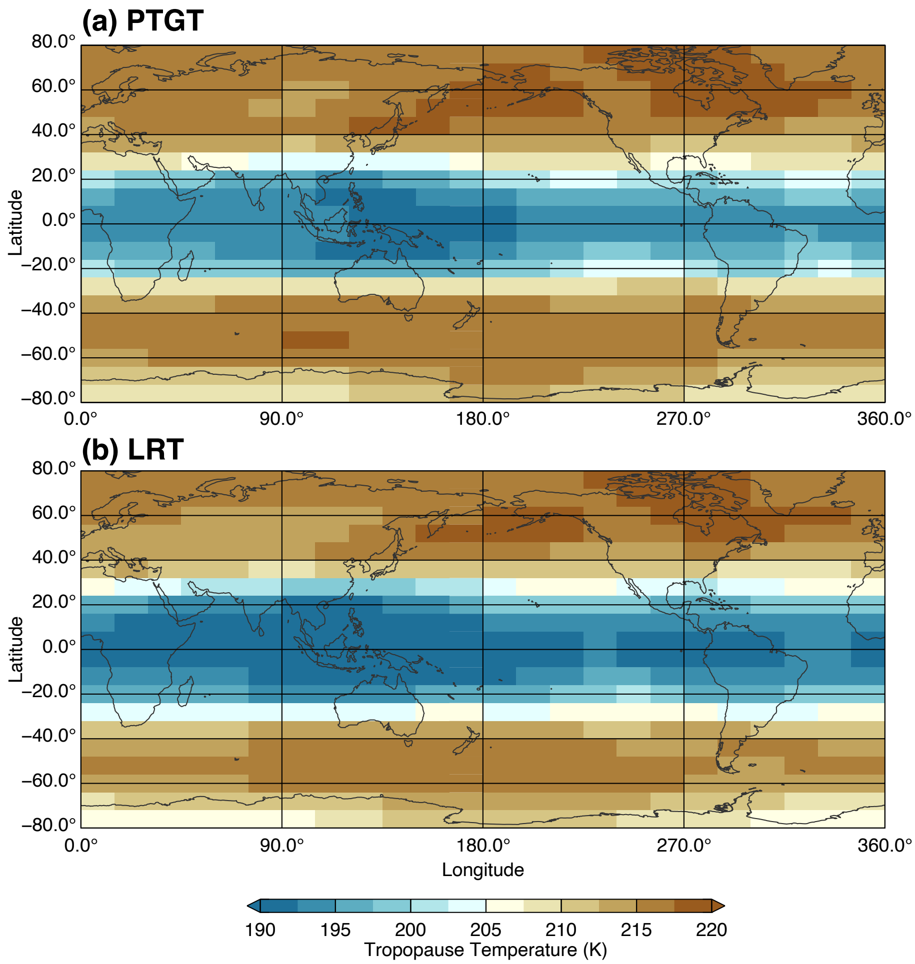

Figure 3. As in Fig. 2, but for primary tropopause temperature.

3.1 Tropical Tropopause Frequency

The documented change in tropopause break latitudes during the past several decades is likely to project upon diagnosed trends in primary tropopause height and temperature significantly due to the bimodality of tropical and extratropical tropopauses. In particular, locations where the tropopause break is migrating poleward would be expected to have significant and large increases in primary tropopause altitude and decreases in temperature since the occurrence of high-altitude tropical tropopause altitudes will increase. Conversely, locations where the tropopause break is migrating equatorward would be expected to have significant and large decreases in tropopause altitude and increases in temperature. Lastly, in the absence of tropopause break latitude trends, locations where the tropopause break latitude is becoming more (less) variable should result in altitude and temperature trend dipoles in the bins spanning the break latitudes, exhibiting a negative-positive (positive-negative) equator-to-pole dipole in altitude trends (or vice versa for temperature).

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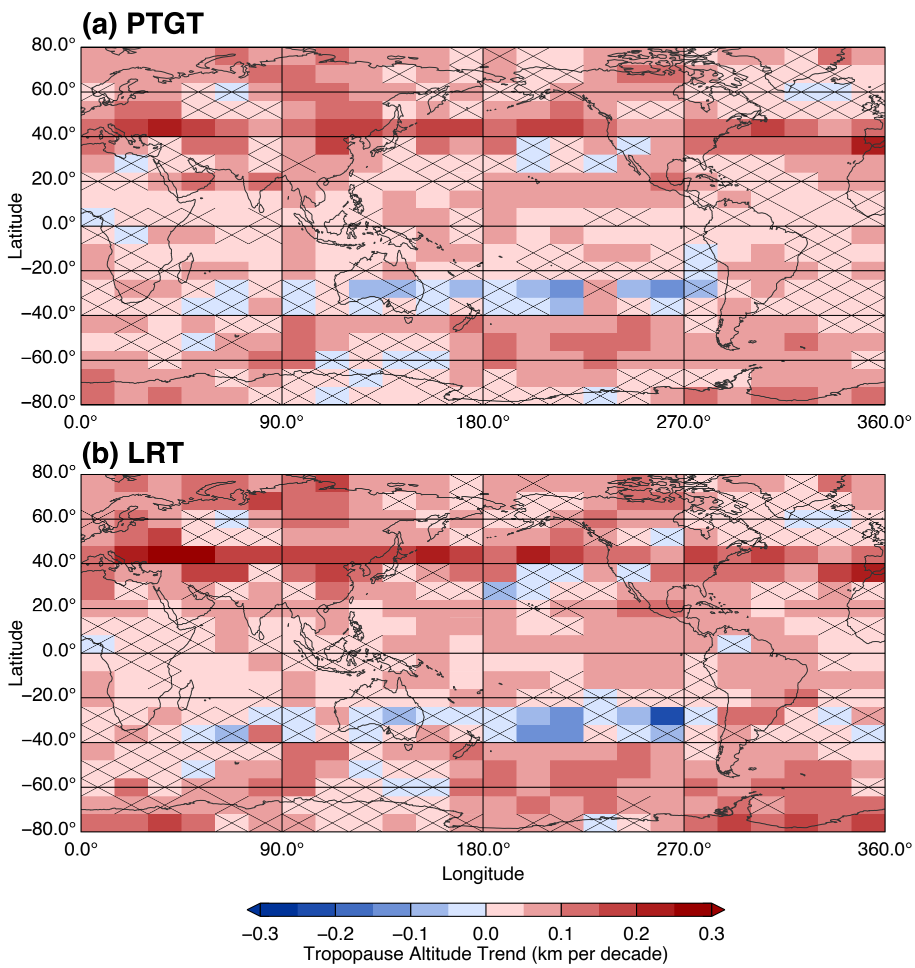

Figure 4. Maps of GNSS-RO time trends for the primary tropopause altitude based on the (a) PTGT and (b) LRT tropopause definitions. Longitude-latitude bins with statistically insignificant trends are marked with an “X”.

To enable interrogation into tropopause break latitudes and observed location changes, the tropical tropopause altitude (≥14 km) occurrence is considered in each bin of the analysis domain. The threshold altitude of 14 km was selected as it represents the minimum-frequency altitude between extratropical and tropical altitude modes for both PTGT and LRT definitions in global frequency distributions. Figure 7 shows the resulting climatological tropical tropopause frequencies during the study period. As implied by the primary tropopause altitude climatology, the latitude of the tropopause break based on the PTGT definition must be further equatorward than that for the LRT given the offset in the latitude bins of greatest tropical tropopause frequency in each hemisphere. Otherwise, the geographic variability shows consistent features between the two definitions. Figure 8 shows the time trend in tropical tropopause altitude frequency. Significant trends are largely confined to the subtropics in each hemisphere, within latitude bins that are on the poleward edge of the large equator-to-pole gradient in the climatology.

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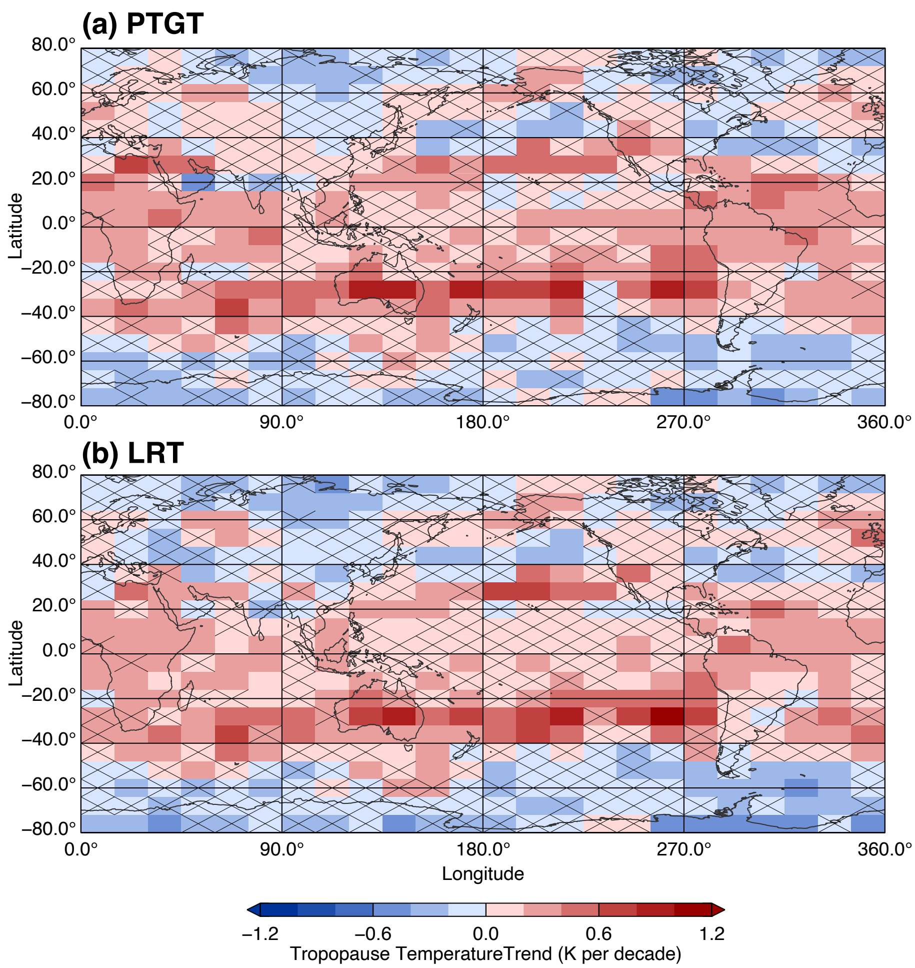

Figure 5. As in Fig. 4, but for primary tropopause temperature.

They are also broadly consistent between PTGT and LRT definitions and reveal significant increasing trends throughout the northern hemisphere (NH) and a mix of weak-to-moderate increasing trends in the SH over South America and the Atlantic ocean basin and large decreasing trends over the east Pacific ocean basin. The contrast between prevailing (i.e., zonal mean) NH and SH trends is consistent with prior analyses using models and observations (including GNSS-RO data), which routinely exhibit significant increasing tropopause break latitude in the NH and weak or unchanging tropopause break latitude in the SH (e.g., Ao and Hajj, 2013). The decreasing trend over the SH east Pacific ocean basin implies that the tropopause break latitude is moving equatorward there, which is both consistent with the aforementioned regionally-varying assessments of tropopause break latitudes and helps explain the decreasing primary tropopause altitudes and increasing primary tropopause temperatures found in Figs. 4 & 5.

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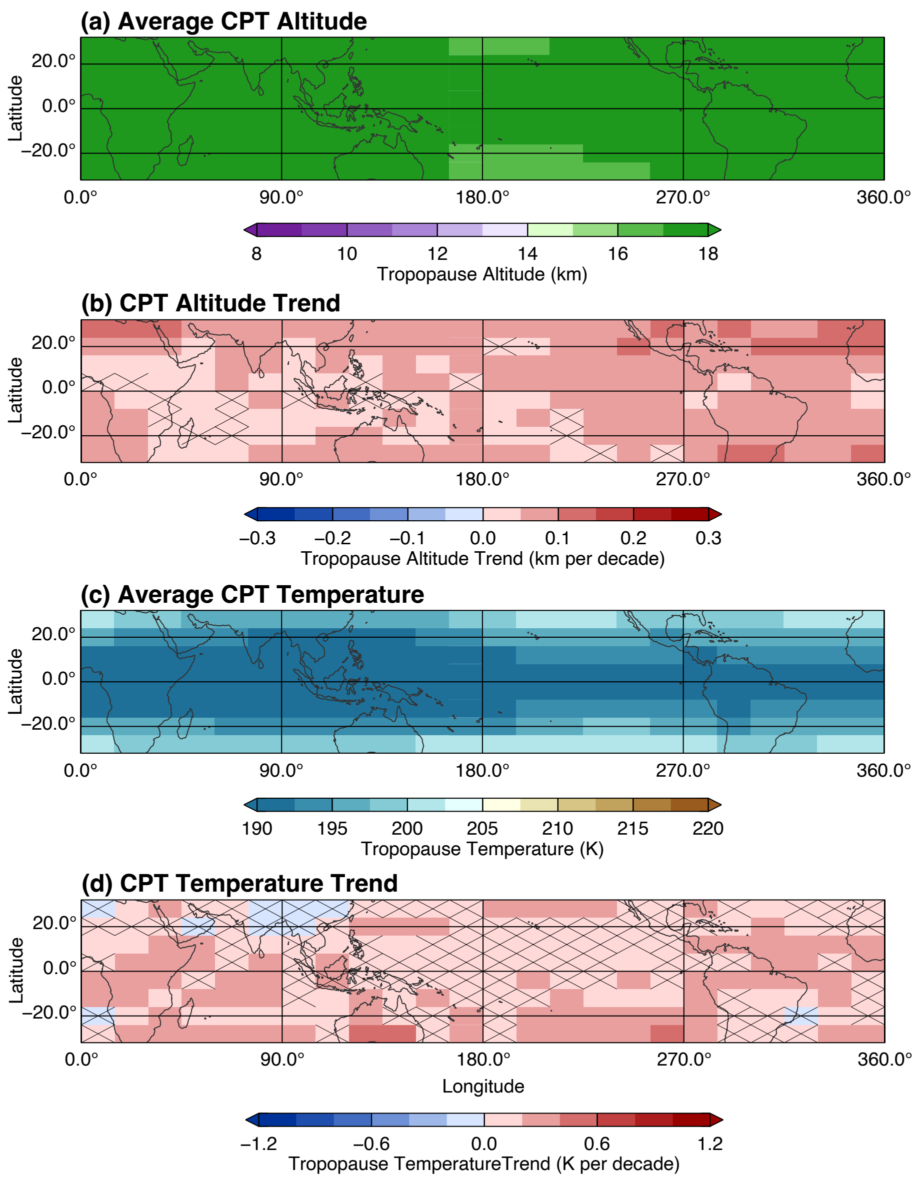

Figure 6. Maps of GNSS-RO (a) annual mean CPT altitude, (b) time trend of CPT altitude, (c) annual mean CPT temperature, and (d) time trend of CPT temperature. In (b) and (d), statistically insignificant trends are marked with an "X".

3.2 Tropopause Sharpness

While few studies, apart from those focused on the TIL, have comprehensively assessed the sharpness of the primary tropopause as determined by the magnitude of the difference in static stability between shallow LS and UT layers that bound it, it is relevant to the efficiency and occurrence of UTLS processes including STE. The early GNSS-RO analyses by Schmidt et al.

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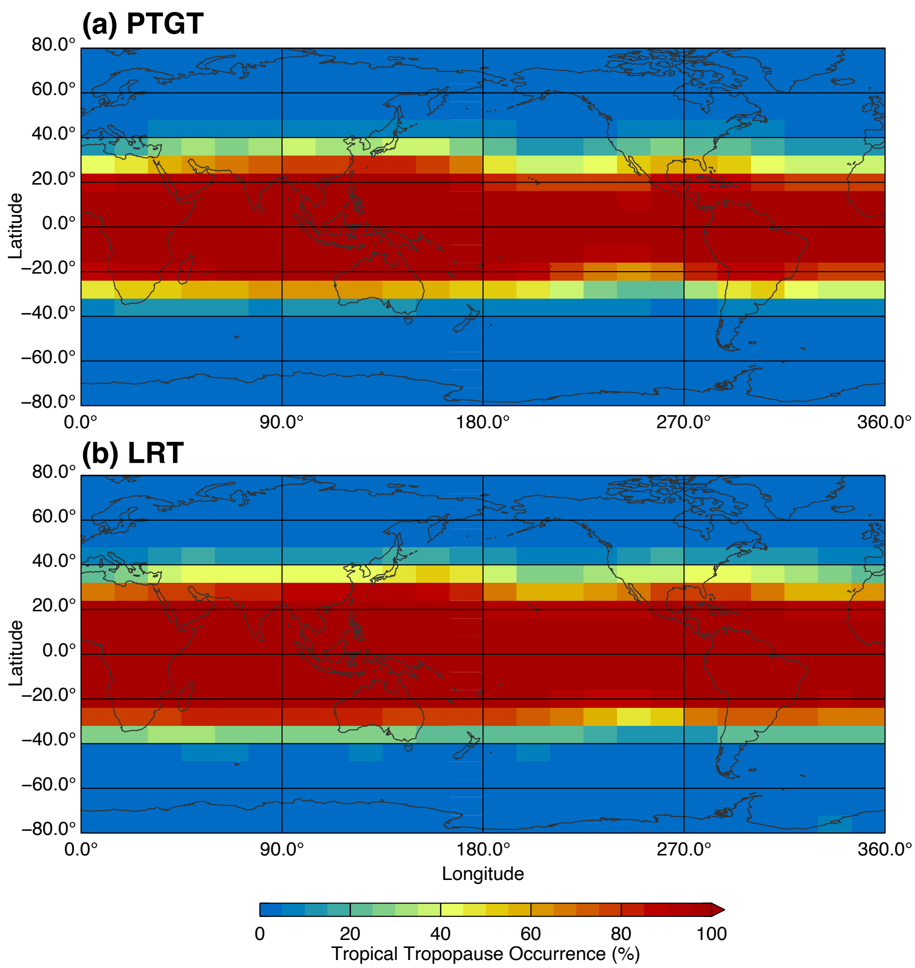

Figure 7. As in Fig. 2, but for tropical tropopause occurrence.

(2005) and Son et al. (2011) are the only such studies available for direct comparison, though each produced a climatology based on only 3–3.5 years of data for the LRT. Figure 9 shows the climatological PTGT and LRT sharpness for the 23-year analysis period of this study, which reproduces the overall geographic patterns documented in prior studies. Namely, the sharpest tropopauses are found in the tropics and the least sharp in the subtropics. The weak longitudinal variability in tropopause sharpness in the extratropics is also broadly consistent with prior work, especially the locations of local maxima and minima. Differences between PTGT and LRT sharpness are greatest in the subtropics and tropics, where the PTGT sharpness is universally weaker. PTGT and LRT sharpness are remarkably similar in the middle and high latitudes, which likely reflects their common coincidence at such latitudes (Tinney et al., 2022).

Despite the differences in sharpness magnitudes between the PTGT and LRT definitions, global trends in tropopause sharpness in Figure 10 demonstrate great consistency and show that the tropopause is becoming significantly sharper in most loca-

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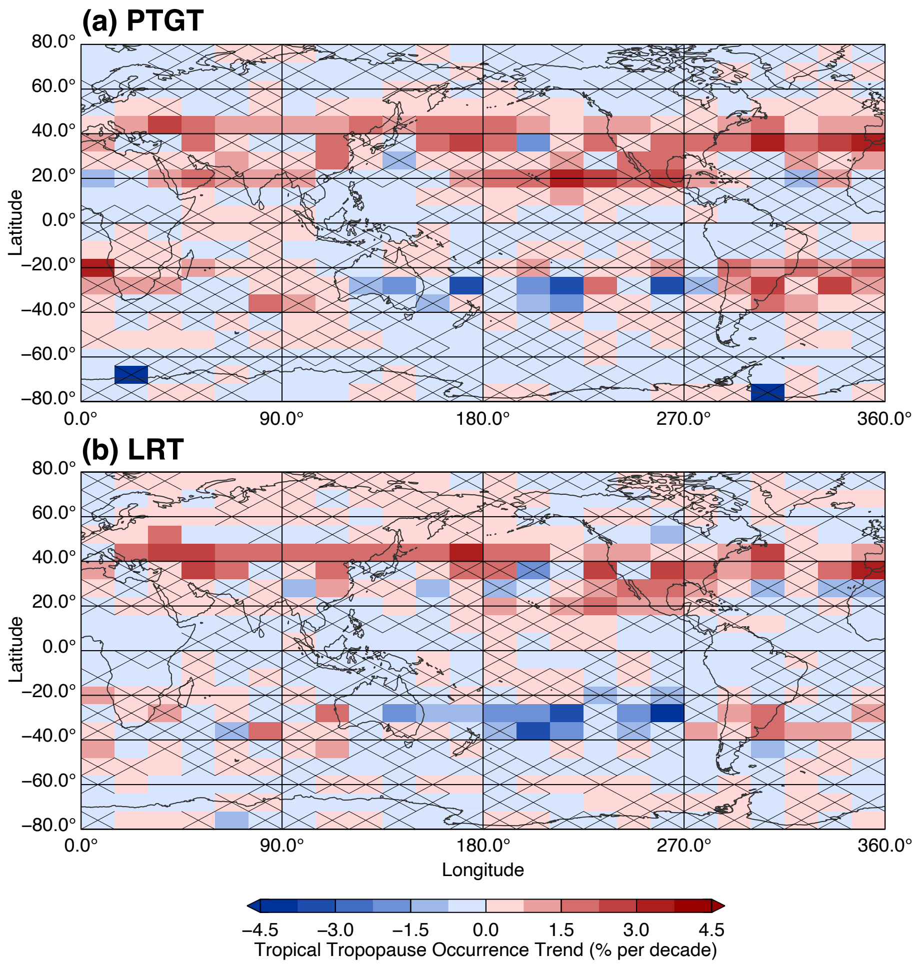

Figure 8. As in Fig. 4, but for tropical tropopause occurrence.

tions. The greatest increases in tropopause sharpness are found throughout the tropics, with two broad maxima over the west Pacific and east Atlantic/equatorial Africa. In the NH subtropics and midlatitudes, larger increases in tropopause sharpness are mostly confined to the Pacific and Atlantic ocean basins, where the exit and entrance regions of subtropical jet segments typically overlap in longitude. Thus, the diagnosed sharpness changes may be related to changes in jet structure in these regions. In the SH, increasing tropopause sharpness is found throughout the midlatitudes, with comparatively minimal longitudinal variability.

An obvious question that arises from the diagnosis of tropopause sharpness trends is whether the significant trends are driven predominantly by changes in the UT, LS, or both. Thus, Figures 11 and 12 show the trends for the vertical gradient of potential temperature in the UT and LS, respectively (i.e., each term of the sharpness calculation). Decreasing trends in the UT potential temperature gradient and increasing trends in the LS potential temperature gradient would equally contribute to

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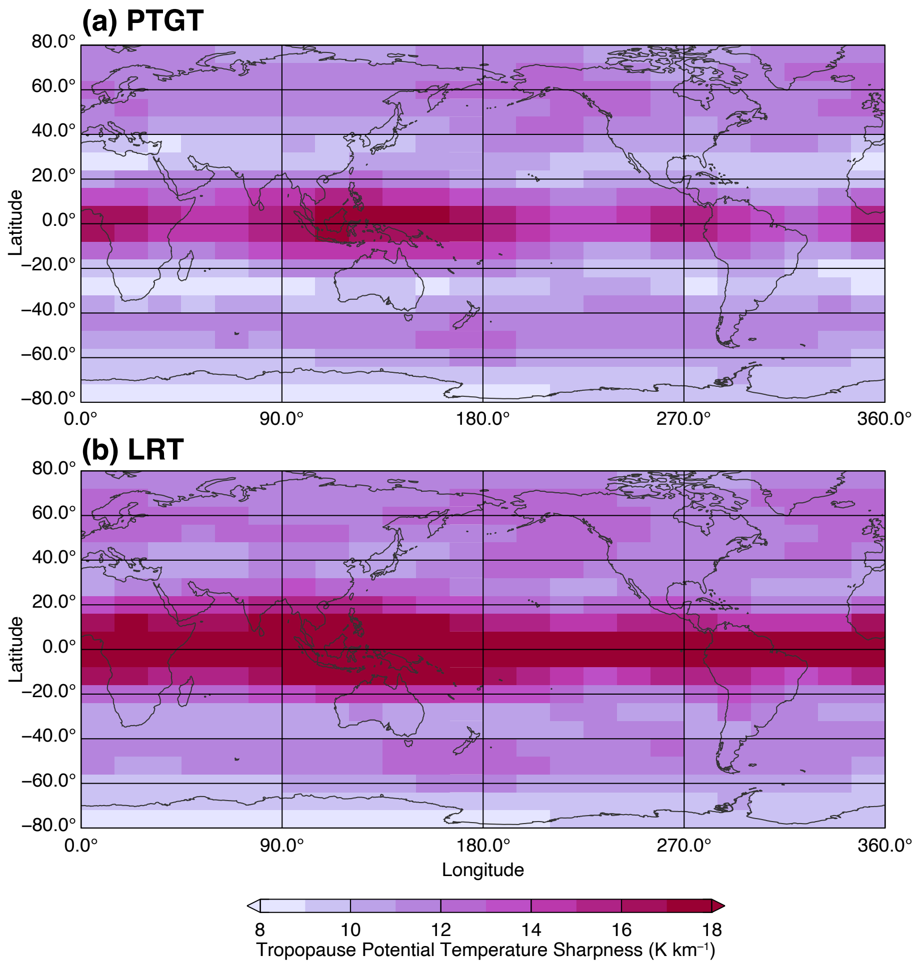

Figure 9. As in Fig. 2, but for primary tropopause sharpness.

increasing tropopause sharpness. Figure 11 demonstrates that the UT potential temperature gradient is decreasing significantly throughout the tropics and SH subtropics, minimally elsewhere, and exhibits weak longitudinal variability in the tropical trends. In comparison, the LS potential temperature gradient is increasing substantially in both the tropics and midlatitudes (Fig. 12) and exhibits greater longitudinal variability that is more consistent with the broad maxima in tropopause sharpness trends in the tropics. Together, these results imply that the tropopause is becoming sharper in the tropics due to decreasing UT stability and enhanced by increasing LS stability (especially over the west Pacific) and sharper in the extratropics due primarily to increasing LS stability (i.e., a strengthening of the TIL).

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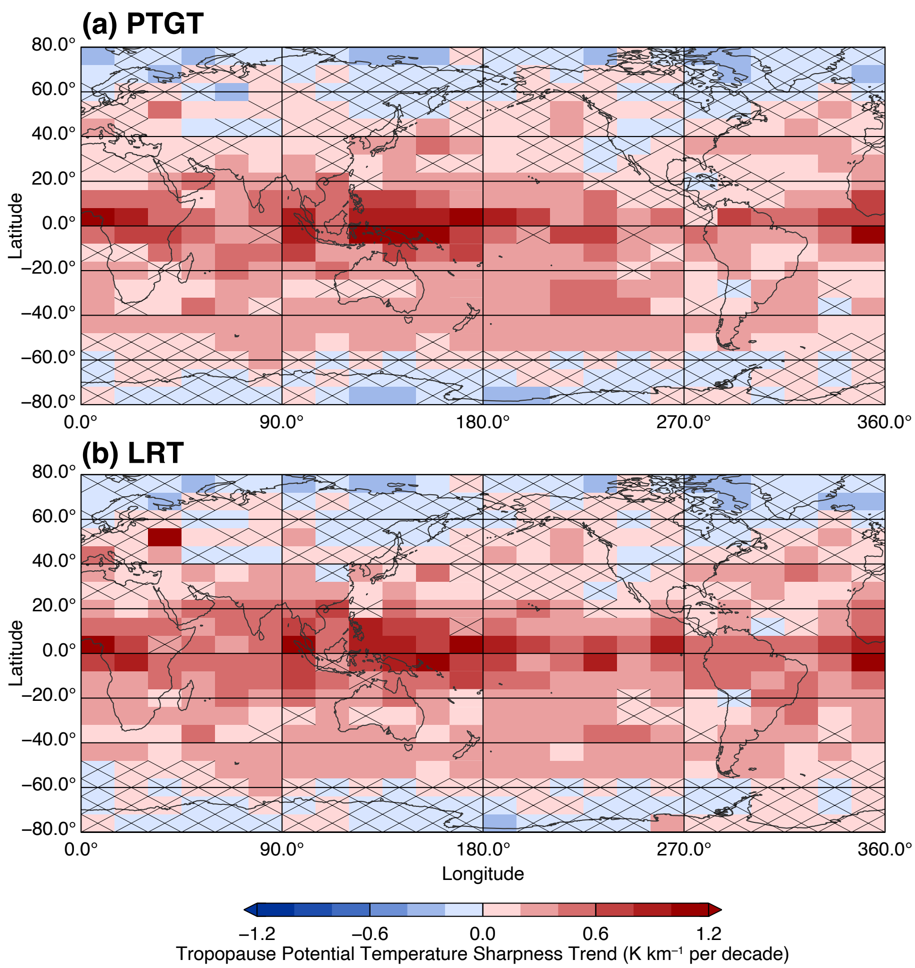

Figure 10. As in Fig. 4, but for primary tropopause sharpness.

3.3 Multiple Tropopause Frequency

The final tropopause characteristic of interest in this study is the occurrence of multiple tropopauses. Only double and triple tropopauses are evaluated because additional tropopauses are too infrequent for meaningful trend analysis (primarily for the PTGT) and have otherwise not been a focus of prior studies. Figures 13 and 14 show the climatology of double and triple tropopause occurrence, respectively. Both PTGT an LRT definitions result in high-frequency, globe-encircling double-tropopause belts throughout the subtropics and midlatitudes, which have been frequently characterized using the LRT in prior work and lie mostly poleward of the subtropical jet streams in each hemisphere. Triple tropopauses can only exist where double tropopauses are found and, in addition to being far less frequent, are less spatially extensive for both the PTGT and LRT, though key patterns are broadly consistent across the two definitions. Beyond these general aspects, the PTGT and LRT both identify a weak local maximum in double tropopause occurrence along the equator over the Indian ocean basin, but the

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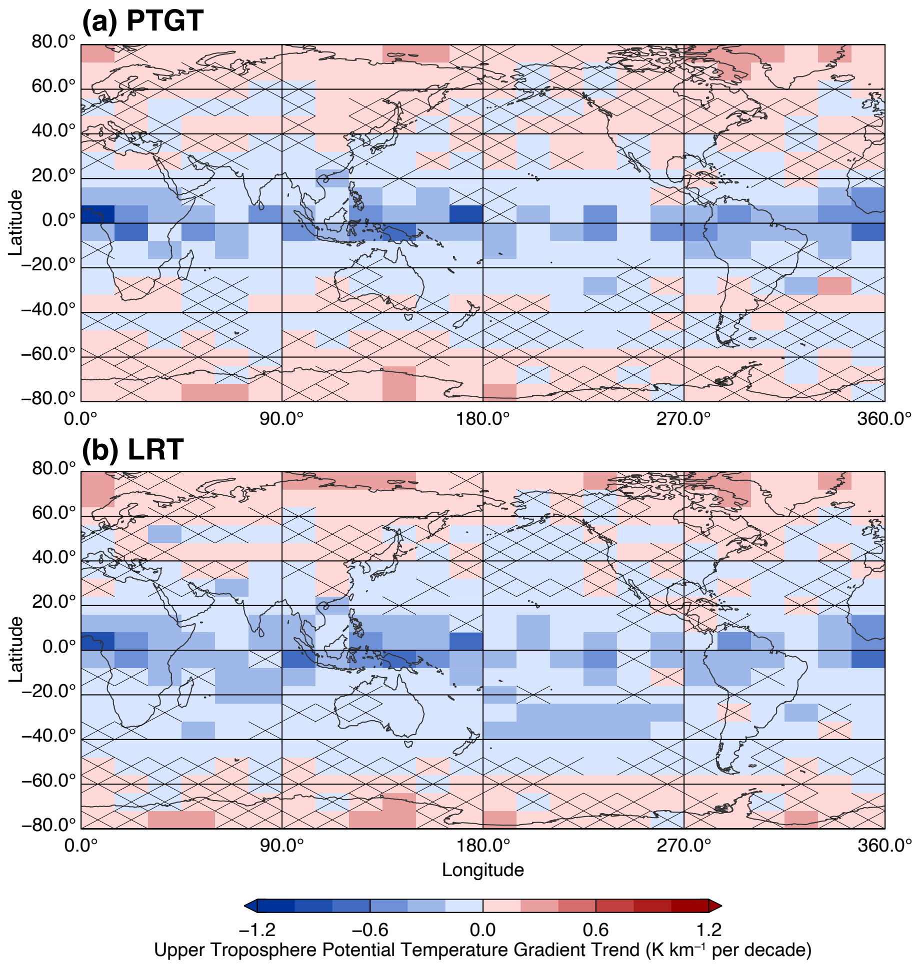

Figure 11. As in Fig. 4, but for the upper troposphere potential temperature gradient.

LRT maximum spans a greater range of longitudes and extends over the Atlantic ocean basin. Large differences between the PTGT and LRT multiple tropopause climatologies are found mostly at high latitudes, where the LRT definition identifies many multiple tropopauses where the PTGT definition does not. The lower occurrence of multiple tropopauses identified by the PTGT definition is due to its basis on the potential temperature gradient and the altitude dependence of its correspondence to temperature lapse rates (Tinney et al., 2022). Namely, greater extremes in temperature lapse rates are required to satisfy PTGT multiple tropopause criteria as altitude increases. This is especially true for triple tropopauses, which are 3–10 times more frequent using the LRT definition in areas where both the PTGT and LRT identify a triple tropopause.

Figures 15 and 16 show the time trends in double and triple tropopause occurrence, respectively, revealing that (regardless of tropopause definition) multiple tropopauses are predominantly (and significantly) increasing globally, as has been found in the aforementioned radiosonde and model-based studies for double tropopauses. The most substantial increases in double

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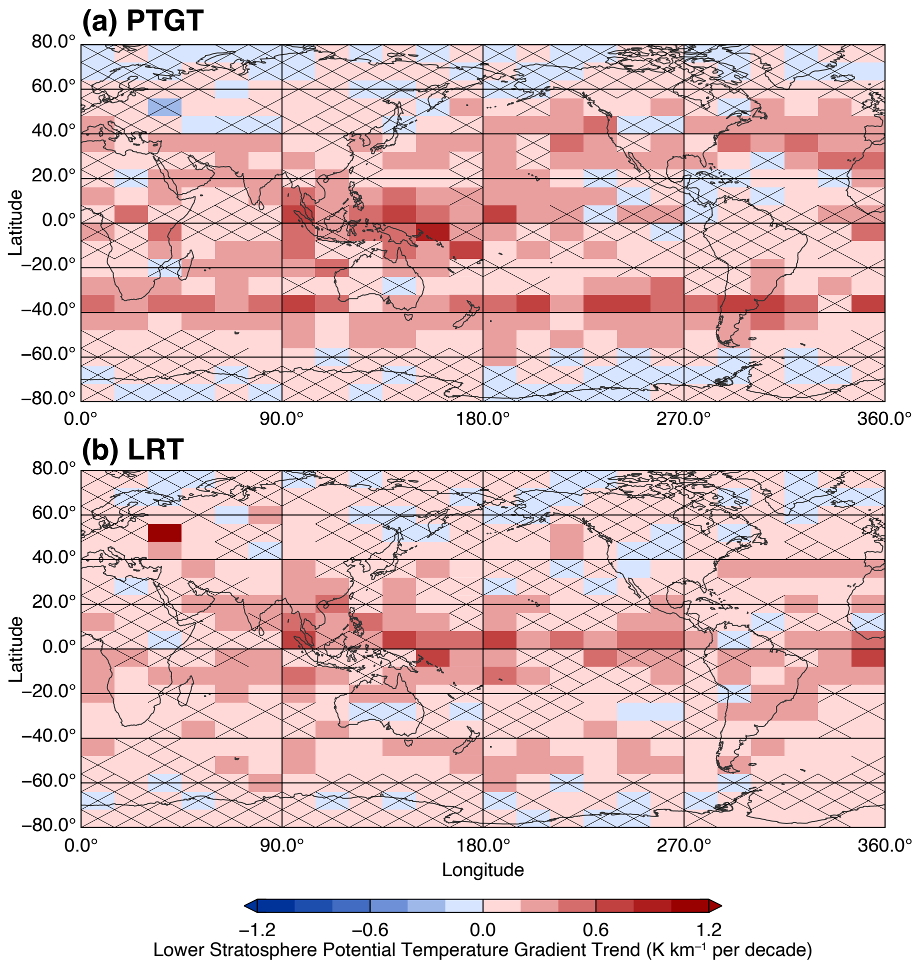

Figure 12. As in Fig. 4, but for the lower stratosphere potential temperature gradient.

tropopause frequency occur along the poleward edge of the high-frequency midlatitude belts (especially in the SH) and along the equator in the tropics. LRT double tropopauses at higher latitudes are also increasing significantly and doing so fastest in areas where double tropopauses are already frequent, especially in the NH. Significant increases in triple tropopauses, which have not been previously identified, are more confined to locations where they are climatologically more frequent. In each case, these increases in multiple tropopause occurrence imply that one or more of the mechanisms responsible is similarly increasing in frequency or significance.

4 Conclusions

This study utilized the most recent 23-year record of GNSS-RO data (2003–2025) to produce climatologies of and assess long-term changes (trends) in various tropopause characteristics. Two universal tropopause definitions which allowed investigation

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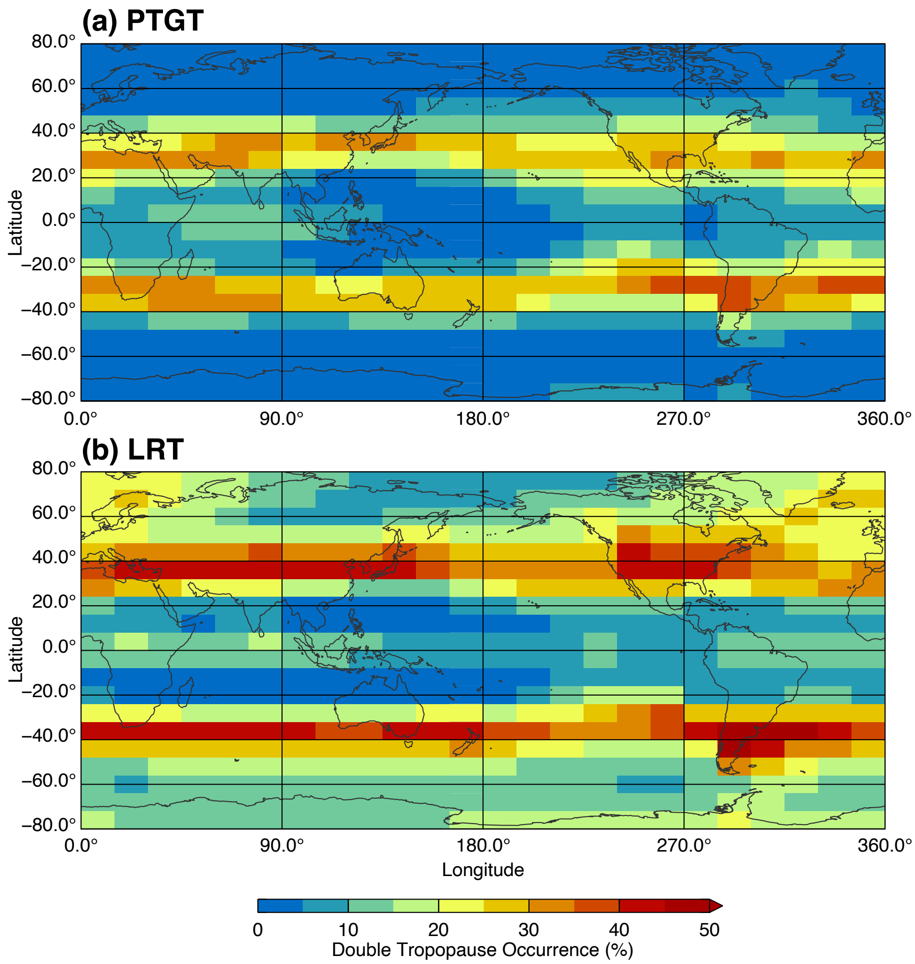

Figure 13. As in Fig. 2, but for double tropopause occurrence.

into all characteristics of interest were used: the PTGT (the first time it has been employed for this purpose) and LRT. Both tropopause definitions yielded the same general results, demonstrating that the diagnosed trends are largely insensitive to the choice of tropopause definition (except for multiple tropopauses at high latitudes). The tropopause characteristics investigated included primary tropopause altitude (Figs. 2 & 4), temperature (Figs. 3 & 5), and sharpness (Figs. 9–12), tropical tropopause frequency (Figs. 7 & 8), double tropopause frequency (Figs. 13 & 15), and triple tropopause frequency (Figs. 14 & 16).

Primary tropopause altitudes were found to be increasing globally, with the exception of a narrow region of decreasing tropopause altitudes over the SH east Pacific ocean basin. Primary tropopause temperatures were found to be increasing throughout the tropics and subtropics, with the greatest increases coinciding with the decreasing tropopause altitudes in the SH east Pacific region. These positive trends in tropopause temperatures in the deep tropics are of particular climactic importance due to the associated control on stratospheric water vapor concentrations (Randel and Park, 2019) and has implications for the

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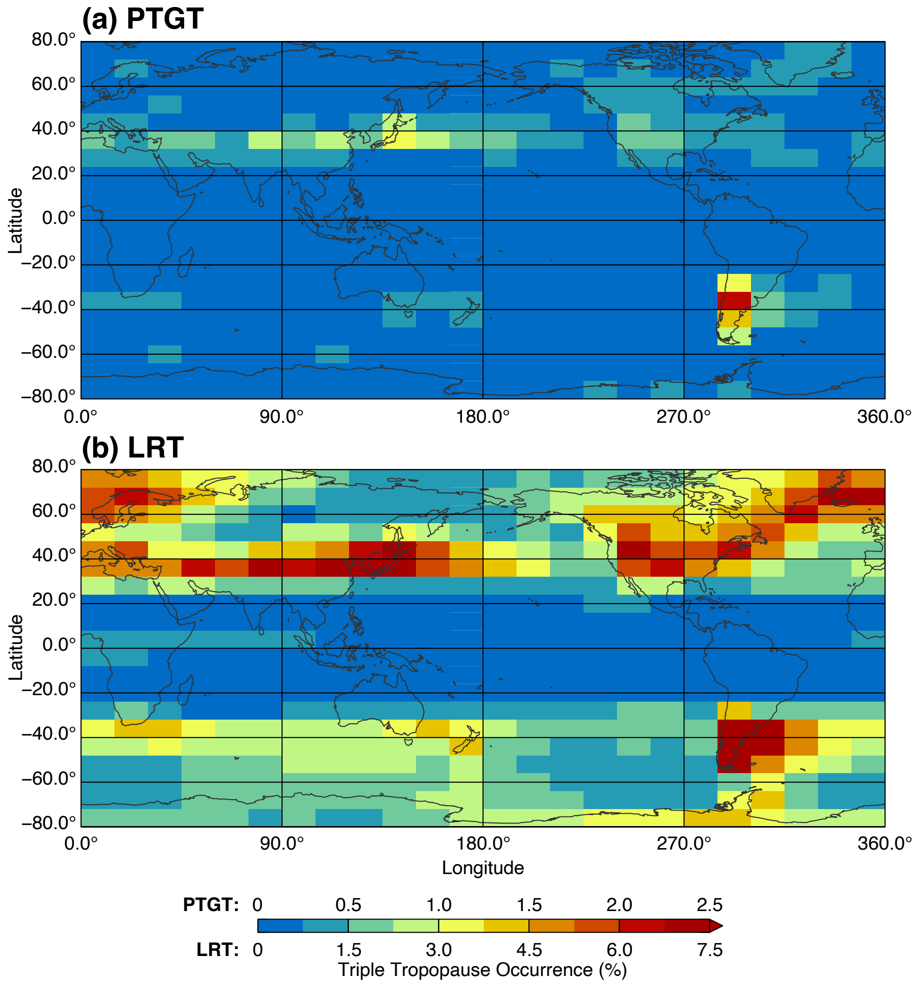

Figure 14. As in Fig. 2, but for triple tropopause occurrence. Note that the scale for LRT occurrence is 3 times greater than that for PTGT occurrence.

stratospheric water vapor climate feedback (Forster and Shine, 1999; Solomon et al., 2010). Analysis of tropical tropopause occurrence trends (primary tropopause altitudes ≥14 km) demonstrated that the SH east Pacific feature is driven by an observed narrowing of the tropics (tropopause break latitude) in this region. Tropical tropopause occurrence trends otherwise indicated a poleward-migrating tropopause break latitude (i.e., expansion of the tropics), especially across the NH. Tropopause sharpness trends were investigated for the first time in this study and revealed that the primary tropopause is becoming sharper, especially in the tropics and midlatitudes in regions where it is climatologically sharpest. In the tropics, increasing sharpness is driven by both decreasing stability in the upper troposphere and increasing stability in the lower stratosphere, while in the extratropics increasing sharpness is driven primarily by increasing lower stratosphere stability. Double tropopause and triple tropopause occurrence trends were investigated for the first time using GNSS-RO data, revealing increasing multiple tropopauses in most

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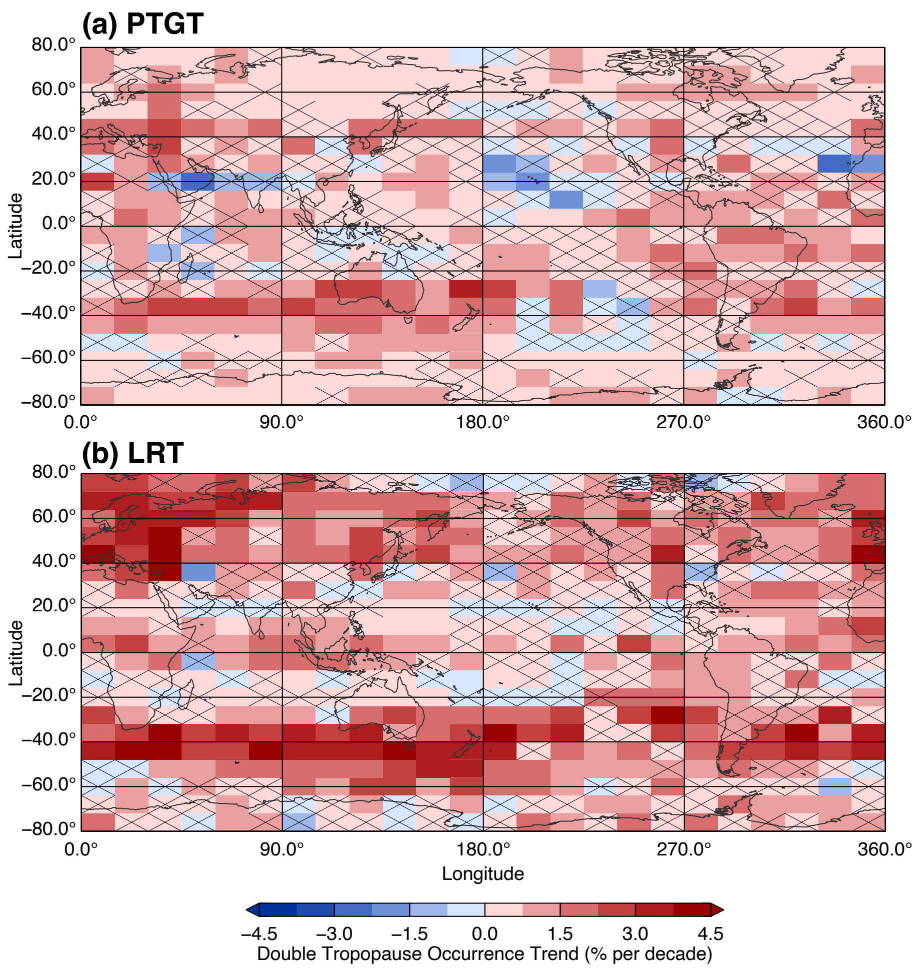

Figure 15. As in Fig. 4, but for double tropopause occurrence.

locations, which affirm similarly diagnosed trends in more limited datasets in prior studies. The triple tropopause trend analysis is particularly novel, as (to the authors' knowledge) this is the first such examination.

The primary tropopause altitude and temperature trends diagnosed in this study broadly mirror the results of prior work, especially those with similarly recent time periods. Ultimately, they indicate sustained increases in the depth of the troposphere in most locations, in alignment with observed long-term increases in tropospheric temperature. Consideration of the effect of migrating tropopause break latitudes (i.e., expansion/narrowing of the tropics) in this study helped to provide an explanation for the anomalous decreasing trends in tropopause altitude (and increasing trends in temperature) found over the SH east Pacific ocean basin - regional tropical narrowing. Furthermore, the regionally-resolved tropical tropopause frequencies also demonstrate that implied expansion of the tropics across the NH is a key driver of the locally-enhanced upward tropopause

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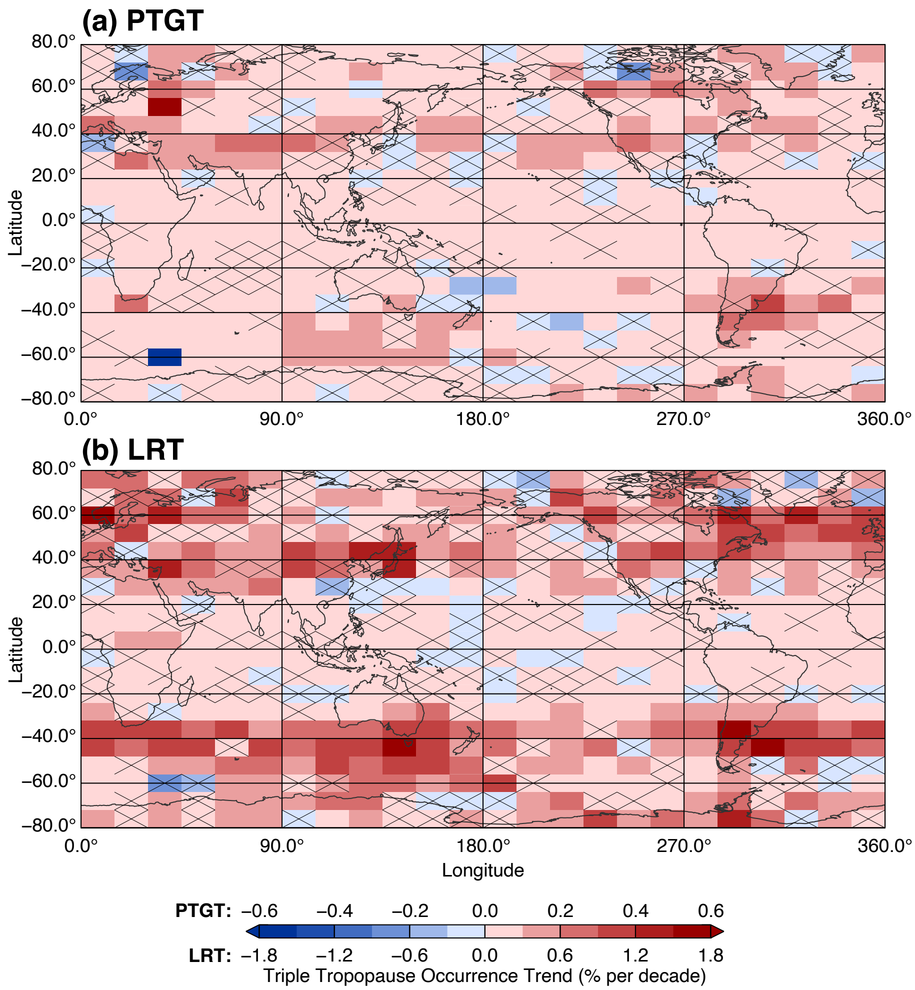

Figure 16. As in Fig. 4, but for triple tropopause occurrence. Note that the scale for the LRT occurrence trend is 3 times greater than that for the PTGT occurrence trend.

altitude trends there. Future work should separately explore changes in the altitude distributions of the tropical and extratropical modes to remove the impacts of a meandering tropopause break and thus better isolate prevailing height trends.

The primary tropopause sharpness trends revealed for the first time in this study imply that the tropopause is becoming more vertically rigid throughout the tropics, subtropics, and midlatitudes. The significance of both upper troposphere and lower stratosphere stability components to the observed increases in the tropics suggests multiple factors are at play there, potentially including changes in deep convection, radiation, and the stratospheric circulation. The leading term of increasing stratospheric stability driving the diagnosed increases in tropopause sharpness in the extratropics indicates that the TIL is becoming sharper there. Future efforts should examine TIL changes in greater detail, including assessing changes in its depth as well as magnitude, and diagnosing the factors responsible (e.g., circulation, radiation, etc.). Similar efforts should be undertaken

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to better understand the mechanisms responsible for increasing primary tropopause sharpness in the tropics, especially that responsible for the longitudinal variability in lower stratosphere stability increases. The authors plan to explore this further using alternative observations and model output.

The multiple tropopause trends in this study affirm similar trends diagnosed for double tropopauses using radiosondes and reanalyses in the only two prior studies to investigate such changes: Castanheira et al. (2009) and Xian and Homeyer (2019). Observed trends in triple tropopauses diagnosed for the first time in this study further reveal the globally-increasing complexity in tropopause structure, which has important implications for atmospheric dynamics and transport. Namely, because the leading mechanisms for multiple tropopause formation are dynamic, the increased frequency of double and triple tropopause occurrence likely indicates increased transport, STE, and/or wave dynamics. Thus, a detailed mechanism-based study is needed to understand the primary drivers of such long-term trends, which the authors plan to execute. Such a study will also help to better characterize the physical significance of multiple tropopauses identified by the LRT, PTGT, or both definitions.

The results in this study unequivocally indicate that, for the most recent 23-year period, tropopause characteristics are changing significantly across the globe. Studies which depend on a tropopause identification (e.g., STE) must consider this non-stationarity to ensure that similarly-inferred long-term changes in dependent variables are unbiased. As the GNSS-RO record continues to grow, these tropopause characteristic trend analyses should be extended to assess to what extent they exhibit climate-scale changes versus long-term variability. A longer record would also enable reliable seasonal assessment of long-term changes in tropopause characteristics which, due to the commensurately limited sample (23 seasons versus 276 months for the full monthly time series), were found to be almost entirely insignificant for the period in this study (not shown, though comparable to those in Ladstädter et al. (2025)). For reference, seasonal climatologies of all tropopause characteristics (which are robust) are provided in the appendix.

Appendix A

Seasonal PTGT and LRT climatologies of each tropopause characteristic from the 23-year study period are provided here for reference. These include primary tropopause altitude (Fig. A1), primary tropopause temperature (Fig. A2), primary tropopause sharpness (Fig. A3), tropical tropopause occurrence (Fig. A4), double tropopause occurrence (Fig. A5), and triple tropopause occurrence (Fig. A6).

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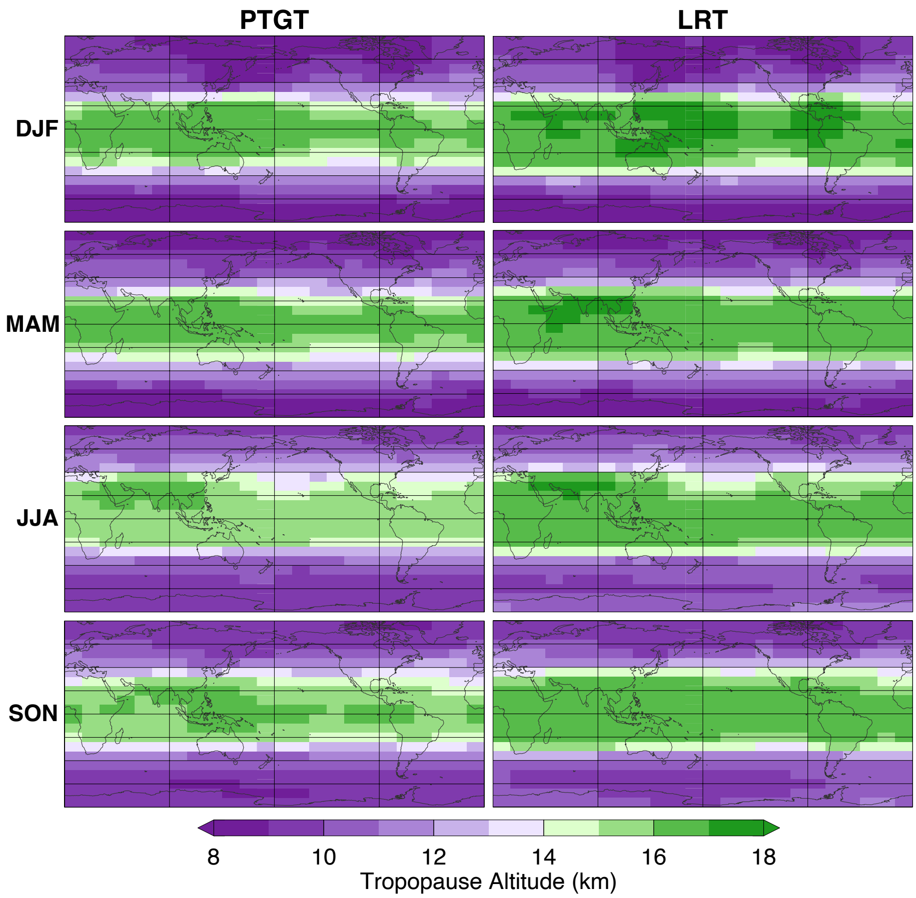

Figure A1. Maps of seasonal mean GNSS-RO primary tropopause altitude based on the (left) PTGT and (right) LRT tropopause definitions. From top to bottom, seasons are December-January-February (DJF), March-April-May (MAM), June-July-August (JJA), and September-October-November (SON).

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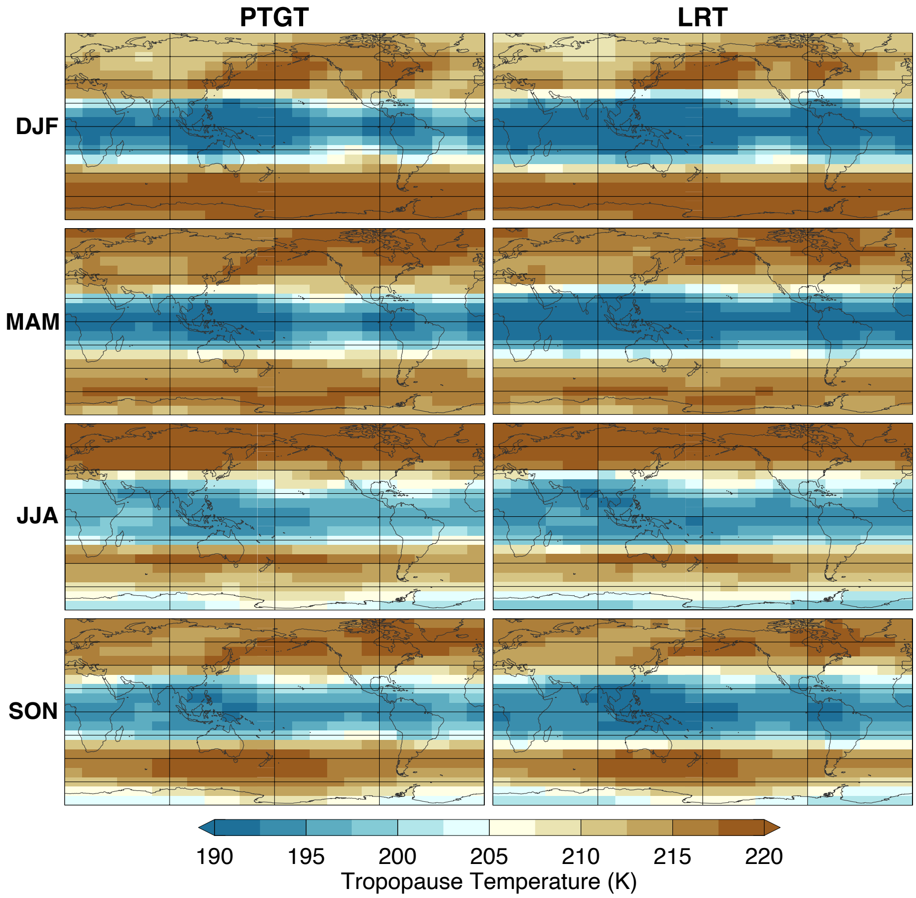

Figure A2. As in Fig. A1, but for primary tropopause temperature.

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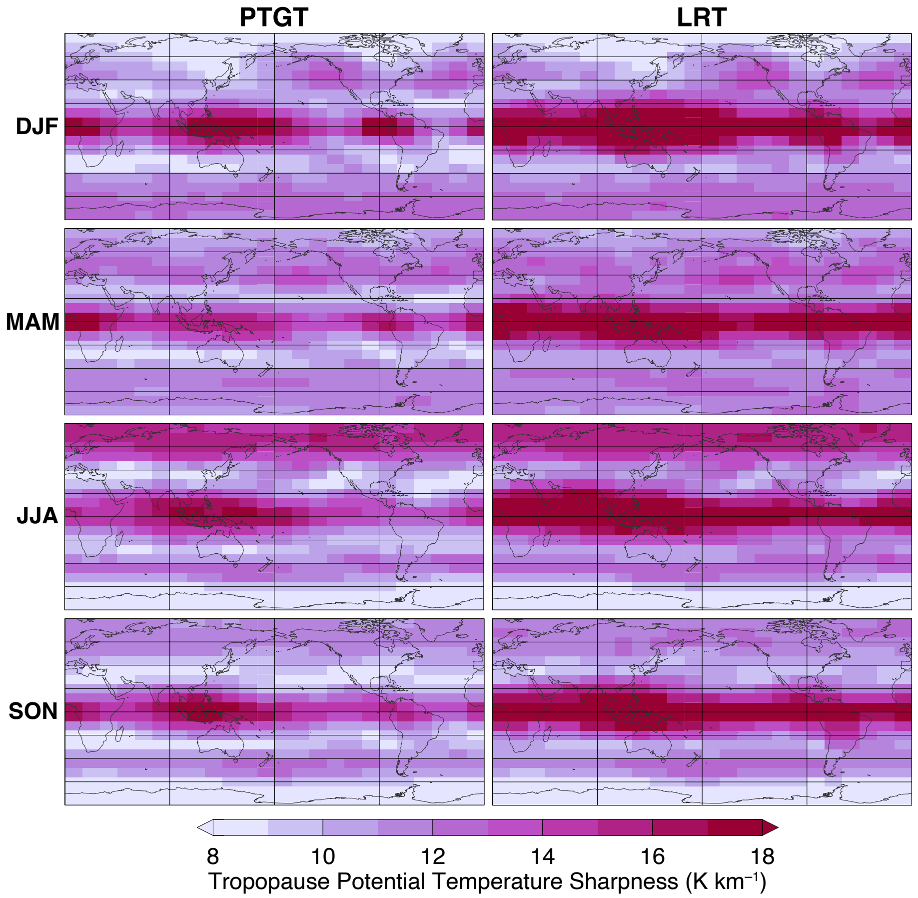

Figure A3. As in Fig. A1, but for primary tropopause sharpness.

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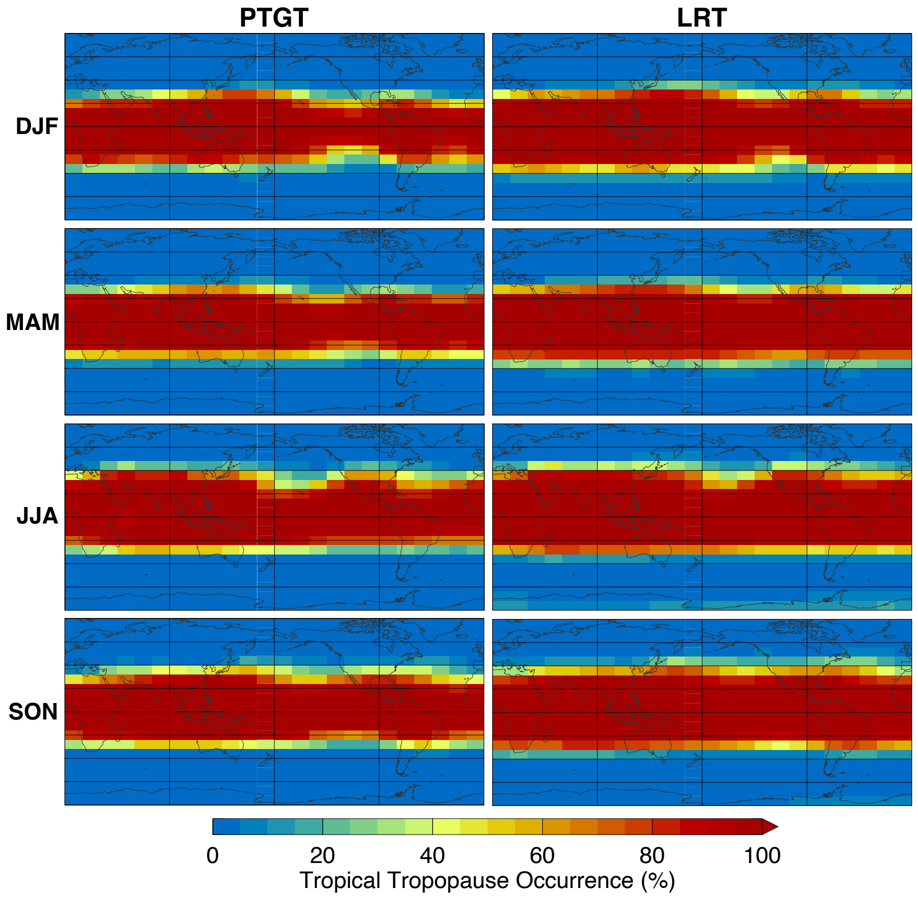

Figure A4. As in Fig. A1, but for tropical tropopause occurrence.

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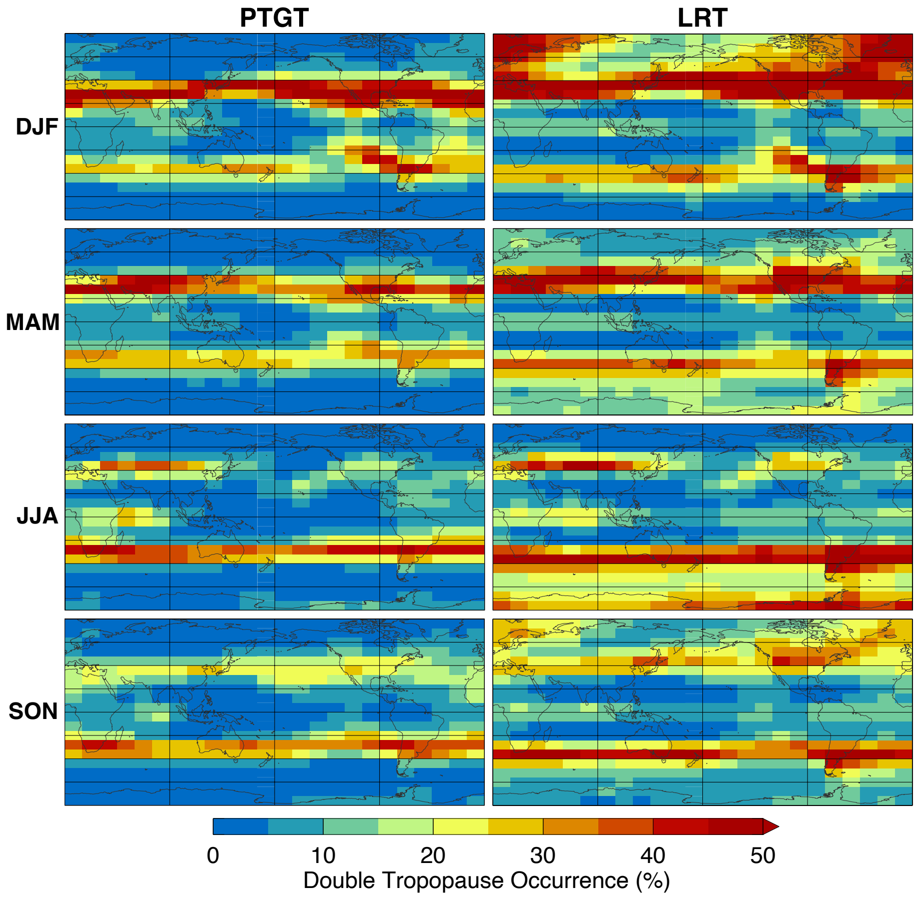

Figure A5. As in Fig. A1, but for double tropopause occurrence.

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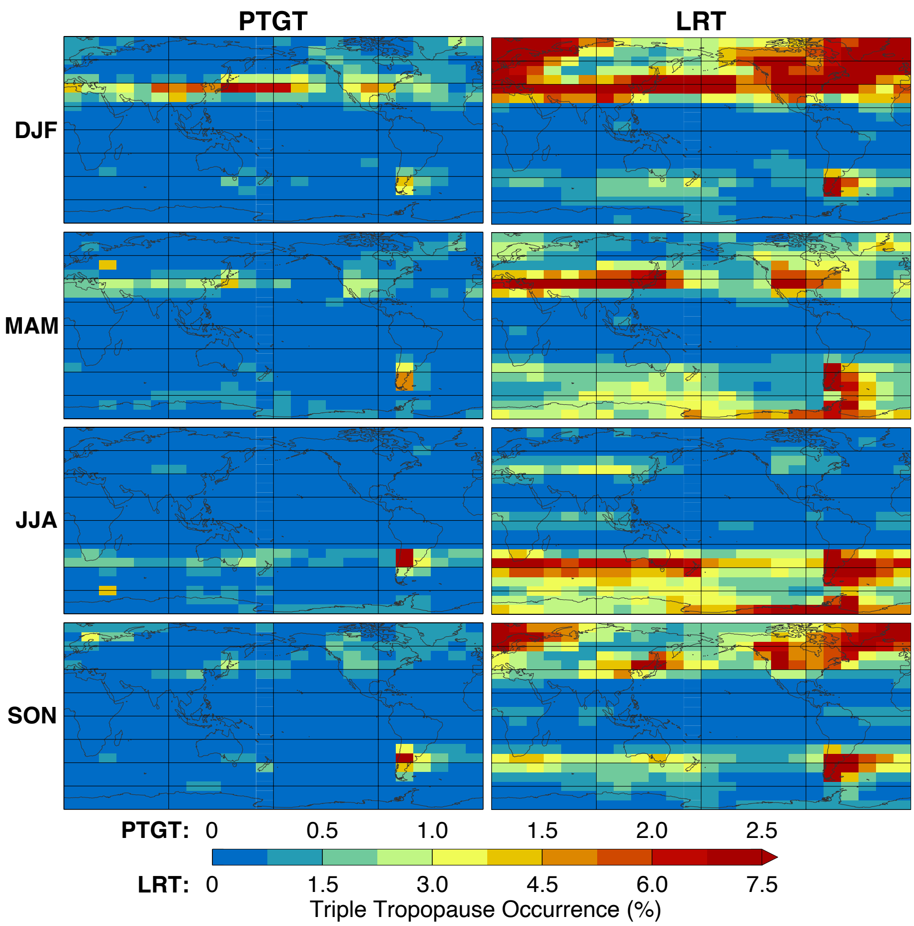

Figure A6. As in Fig. A1, but for triple tropopause occurrence. Note that the scale for LRT occurrence is 3 times greater than that for PTGT occurrence.

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Data availability. All data utilized in this study are publicly available. Earth Radio Occultation data was last accessed on 25 April 2026 from https://registry.opendata.aws/gnss-ro-opendata (Leroy et al., 2024). The multivariate ENSO index version 2 was last accessed on 01 June 2026 (NOAA PSL, 2026). The time series of Singapore radiosonde 50-hPa QBO zonal wind was last accessed on 01 June 2026 (NASA Goddard, 2026).

Author contributions. CRH and ENT contributed equally to the conceptualization of this work. CRH led the investigation, formal analysis, visualization, and drafting of the manuscript. ENT provided validation and review & editing of the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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