

Determination of Tropical Belt Widening Using Multiple GNSS Radio Occultation Measurements

Mohamed Darrag^{1,2}, Shuanggen Jin^{1,3,4*}, Andrés Calabia¹ and Aalaa Samy²

¹School of Remote Sensing and Geomatics Engineering, Nanjing University of Information Science and Technology, Nanjing 210044, China

²National Research Institute of Astronomy and Geophysics-NRIAG, 11421- Helwan, Cairo, Egypt

³Shanghai Astronomical Observatory, Chinese Academy of Science, Shanghai, China

⁴School of Surveying and Land Information Engineering, Henan Polytechnic University, Jiaozuo 454000, China

*Corresponding author: sgjin@nuist.edu.cn; sg.jin@yahoo.com

Abstract

In the last decades, several studies reported the tropics expansion but the rates of expansion are widely different. In this paper, data of 12 global navigation satellite systems radio occultation (GNSS-RO) missions from June 2001 to November 2020 with high resolution were used to investigate the possible widening of the tropical belt along with the probable drivers and impacts in both hemispheres. Applying both lapse rate tropopause (LRT) and cold point tropopause (CPT) definitions, the global tropopause height shows an increase of approximately 36 m/decade and 60 m/decade, respectively. The tropical edge latitudes (TEs) are estimated based on two tropopause height metrics, subjective and objective methods. Applying both metrics, the determined TEs using GNSS have expansive behavior in northern hemisphere (NH) while in southern hemisphere (SH) there are no significant trends. In case of ECMWF Reanalysis v5 (ERA5) there are no considerable trends in both hemispheres. For Atmospheric Infrared Sounder (AIRS), there is expansion in NH and observed contraction in SH. The variability of tropopause parameters (temperature and height) is maximum around the TEL locations in both hemispheres. Moreover, the spatial and temporal patterns of total column ozone (TCO) have good agreement with the TEs positions estimated using GNSS LRT height. Carbon dioxide (CO₂) and Methane (CH₄), the most important greenhouse gases (GHGs) and the main drivers of global warming, have spatial modes in the NH that are located more poleward than that in the SH. Both surface temperature and precipitation have strong correlation with GNSS LRT height. The surface temperature spatial pattern broadly agrees with the GNSS TEL positions. In contrast, Standardized Precipitation Evapotranspiration Index (SPEI) has no direct connection with the TEL behavior. The results illustrate that the tropics widening rates are different from data set to another and from metric to another. In addition, TEL behavior in NH is different from that in SH. Furthermore, the variability of meteorological parameters agrees with GNSS TEL results more than with that of other data sets.

Keywords: GNSS-RO, Tropopause, Tropical belt, Climate change.

1. Introduction

Several studies have reported a widening of the tropics in observations, model simulations and reanalyses. This expansion may lead to profound changes in the global climate system, even a minor expansion of the tropical belt would have significant implications because the shift of the jet streams and subtropical dry zones toward poles have direct effects on weather and precipitation patterns. The widening of the tropical belt is largely considered to be a response to global warming

40 caused by increased GHGs concentrations (Davis and Rosenlof, 2012; Davis and Birner, 2013;
41 Staten et al., 2018; Grise et al., 2019; Watt-Meyer et al., 2019; Meng et al., 2021; Pisoft et al.,
42 2021). The reported widening rates, in most of previous studies, range from 0.25° to 3.0°
43 latitude/decade and their statistical significance vary by large amount based on the metrics used to
44 estimate the tropical edge latitude (TEL) as well as the data sets utilized for its derivation. In
45 addition, the used metrics may respond in different ways to the force driving the widening because
46 of their differing physics (Davis and Rosenlof, 2012). Hudson et al. (2006), based on atmospheric
47 ozone concentrations, reported that northern hemisphere (NH) occupied by the tropical region
48 grew at a rate of 1°/per decade. Using independent set of satellite-based microwave observations
49 of atmospheric temperature, Fu et al. (2006) inferred tropical belt widening for the period 1979–
50 2005. They estimated a net widening of about 2° latitude. Based on radiosonde (RS) and reanalysis
51 data Seidel and Randel (2007) reported an expansion of 5 to 8 degrees latitude during the period
52 from 1979 to 2005. In addition, Hu and Fu (2007) found a widening of the tropical Hadley
53 circulation system, and estimated its magnitude as 2° to 4.5° latitude during period from 1979 to
54 2005. Ao and Hajj (2013) used GPS RO data over the period 2002 to 2011 and analyzed it to
55 examine the possible expansion of the tropical belt due to climate change. Their analysis showed
56 a statistically significant widening trend of 1°/decade in the NH while in Southern Hemisphere
57 (SH) no significant trend was found.

58 In astronomy and cartography, the edges of the tropical belt are the Tropics of Cancer and
59 Capricorn, at latitudes of ~23.5° north and south, where the Sun is directly overhead at solstice.
60 They are determined by the tilt of the Earth's axis of rotation relative to the planet's orbital plane,
61 and their location varies slowly, predictably and very slightly by about 2.5° latitude over 40,000
62 years (Gnanadesikan and Stouffer, 2006). In climatology, tropics edges vary seasonally,
63 interannually, and in response to climate forcing. They move poleward in the summer and
64 equatorward in the winter (Davis and Birner, 2013). There are several indicators that define the
65 boundaries of the tropical belt. Generally, three main classes of metrics are employed to estimate
66 the tropical belt borders: circulation-based metrics (e.g., based on the Hadley cells and the
67 subtropical jets), temperature-based metrics (e.g., based on tropopause characteristics), and surface
68 climate metrics (e.g., based on precipitation and surface winds) (Waliser et al., 1999). The common
69 metrics used for TEL determination are discussed in details in Staten et al. (2018) and Adam et al.
70 (2018). TELs estimated applying different metrics not all necessarily yield the same location. Their
71 positions vary by much larger amounts and much more rapidly and unpredictably than the
72 astronomically defined tropics (Lee and Kim, 2003).

73 Study of tropical belt widening is a challenging task due to the complexity and dynamics
74 of the Earth's atmospheric system and the data limitations. These limitations are the low spatial
75 resolution of RS data as it only covers land and its distribution is not symmetrical in both
76 hemispheres. For the satellite remote sensing technologies and model analyses both suffer from
77 low vertical resolution. Furthermore, reanalyses trends can be biased to reflect changes in both the
78 quality as well as the quantity of the underlying data and the expansion rates computed from
79 different reanalyses were considerably different (Schmidt et al., 2004; Ao and Hajj, 2013).
80 Nowadays, Global navigation satellite systems (GNSS) have provided an exceptional opportunity
81 to retrieve land surface and atmospheric parameters globally (e.g., Jin and Park, 2006; Jin and

82 Zhang, 2016; Wu and Jin, 2014; Jin et al., 2011, 2017), particularly space-borne GNSS Radio
83 Occultation (GNSS-RO) because GNSS-RO has long-term stability and works in all-weather-
84 conditions, which make it a powerful tool for studying climate variability. Since GNSS-RO has
85 uniform global coverage, it covers all locations even at the polar regions and oceans, which are
86 blind zones of other detection systems such as RS and radar. Moreover, GNSS-RO observations
87 vertically finer resolved than any of the existing satellite temperature measurements available for
88 the upper-troposphere lower-stratosphere (UTLS) thus GNSS-RO is well suited for this challenge.
89 Moreover, it is a key component for a broad range of other studies, including equatorial waves,
90 Kelvin waves, gravity waves, Rossby and mixed Rossby–gravity waves, and thermal tides (Bai et
91 al., 2020; Scherllin-Pirscher et al., 2021). A number of studies confirmed the feasibility and
92 excellent eligibility of GNSS-RO measurements for monitoring the atmosphere and for climate
93 change detection (Foelsche et al., 2009; Steiner et al., 2011).

94 Nowadays, GNSS-RO is a valuable remote sounding technique for the atmosphere. During
95 the GNSS-RO event, the GNSS satellite transmit signals that are received onboard a low earth
96 orbiting (LEO) satellite. Due to the atmospheric refractivity, these signals suffer time delay and
97 bending. The atmosphere excess propagation (AEP) is the main observable, and can be calculated
98 with millimeters accuracy, providing high quality and global observations (Wickert et al., 2001a).
99 For instance, the AEP estimate is the base to extract the profiles of bending angle, refractivity, and
100 temperature (Wickert et al., 2004; Xia et al., 2017). The GNSS-RO technique was firstly performed
101 within the US GPS/METEorology experiment for the period from 1995 to 1997 (Kursinski et al.,
102 1997). Also, it is continuously applied aboard various LEO satellite missions since 2001. “These
103 missions are Challenging Mini-satellite Payload (CHAMP) (Wickert et al., 2004; Wickert et al.,
104 2001b); Gravity Recovery and Climate Experiment (GRACE) also Gravity Recovery and Climate
105 Experiment Follow-on (GRACE-FO) (Wickert et al., 2009); Scientific Application Satellite-C/D
106 (SAC-C/D) (Hajj et al., 2004); TerraSAR-X; TanDEM-X; Constellation Observing System for
107 Meteorology, Ionosphere, and Climate (COSMIC/COSMIC-2, also known as FORMOSAT-3/FO
108 RMOSAT-7); the Meteorological Operational satellite Programme-A/B/C (MetOp-A/B/C);
109 FengYun-3C/D (FY-3C/D) (Sun, 2019); Communications/Navigation Outage Forecasting
110 System(C/NOFS); Korea Multi-Purpose Satellite-5 (KOMPSAT-5); the Indian Space Research
111 Organization spacecraft Ocean Satellite-2 (OceanSat-2); and Spanish PAZ (peace in Spanish). A
112 few missions were retired, such as COSMIC-1, GRACE, CHAMP, and SAC-C/D, and some
113 missions are completed by the end of 2020, such as FY-3C, TanDEM-X/TerraSAR-X,
114 KOMPSAT-5, OceanSat-2, and C/NOFS. More missions are planned for the future like MetOp
115 Second Generation (MetOp-SG), FengYun-3E/F/G/H (FY-3E/F/G/H), TerraSAR-X Next
116 Generation (TSX-NG), Jason Continuity of Service-A/B (JASON-CS-A/B”, also known as
117 Sentinel 6A/6B), and Meteor-MP N1/N2. By 2025, the planned missions will provide around
118 14,700 RO profiles daily (Jin et al., 2013; Oscar, 2020)”.

119 In recent years, monitoring the tropopause has received an increased attention for climate
120 change studies. Many studies signified the tropopause rise as a result of the troposphere warming
121 caused by the increase of the GHGs emissions in the atmosphere (Davis and Rosenlof, 2012; Davis
122 and Birner, 2013; Staten et al., 2018; Grise et al., 2019; Watt-Meyer et al., 2019; Meng et al.,
123 2021; Pisoft et al., 2021). The tropopause characteristics are important for the understanding of

124 the exchange of troposphere-stratosphere (Holton et al., 1995). In addition, the chemical,
 125 dynamical, and radiative connections between the troposphere and stratosphere are crucial to
 126 understand and predict climate change worldwide. Exchanges of water, mass, and gases between
 127 the troposphere and stratosphere occurs through the tropopause. Several studies have investigated
 128 the tropopause over the tropics using different data types, and have revealed the problem of the
 129 TEL shift (Ao and Hajj, 2013; Tegtmeier et al., 2020; Kedzierski et al., 2020). GNSS-RO provided
 130 high accuracy remote sensing observations of the thermal structure of the tropopause and was used
 131 to investigate the trend and variability of the tropopause (Son et al., 2011). Among the most
 132 outstanding advantages of GNSS-RO are their high accuracy of 0.2–0.5 K in estimating
 133 temperature in the UTLS region and vertical resolution of 200 m. These advantages make GNSS-
 134 RO especially appropriate to detect the possible tropical belt widening based on the height metrics
 135 of the tropopause (Kursinski et al., 1997; Ho et al., 2012). Using tropopause metrics for TEL
 136 determination have many advantages because it can be accurately estimated from remotely sensed
 137 temperature profiles with sufficient vertical resolution, such as GNSS-RO profiles (Davis and
 138 Birner, 2013; Seidel and Randel, 2006).

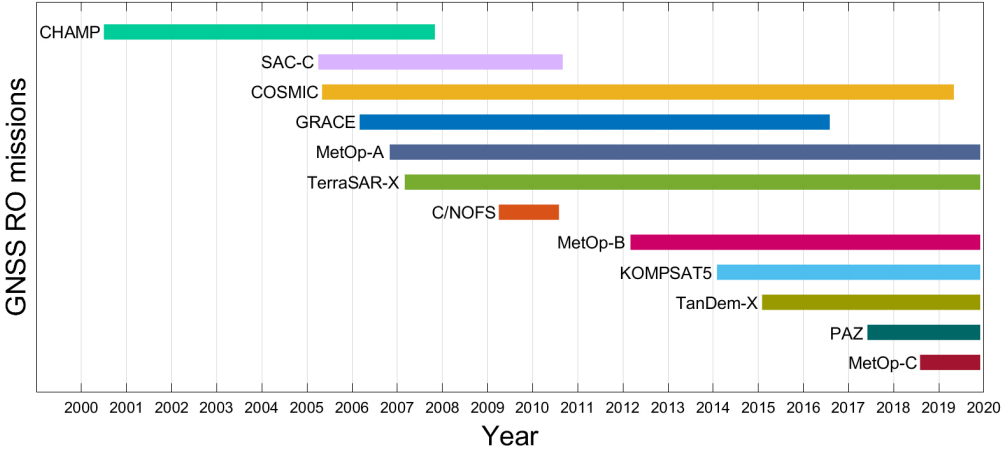
139 In this study, we investigate the TEL variability from different sources, mainly GNSS-RO data. In
 140 Section 2, a description of the GNSS-RO data and other data sets used in our study is presented.
 141 In addition, the methods to derive TEL and the data analysis are presented. Section 3 describes
 142 and discusses the results of the analysis, and our conclusion and summary are given in Section 4.

143 **2. Data and Methods**

144 *2.1. Data*

145 In this study we employ the following data sets:

- 146 • The main data used in this study is GNSS-RO atmospheric profiles data from 12 LEO
 147 missions from June 2001 to November 2020. The data (CDAAC, 2021) is available at the
 148 COSMIC Data Analysis and Archive Center (CDAAC). The GNSS-RO data availability
 149 and its time span are shown in Figure 1.



158 **Fig. 1** GNSS-RO data used in this study.

- 159
- 160
- 161
- 162
- 163
- 164
- 165
- 166
- 167
- 168
- 169
- 170
- 171
- 172
- 173
- 174
- 175
- 176
- 177
- 178
- 179
- 180
- 181
- 182
- 183
- 184
- 185
- 186
- 187
- 188
- 189
- 190
- 191
- 192
- 193
- 194
- 195
- 196
- 197
- 198
- 199
- 200
- ERA5 is the fifth generation ECMWF reanalysis for the global climate and weather. Monthly averaged temperature data on pressure levels from ERA5 that provides global coverage for the period from Jun.2001 to Nov.2020 are used to calculate the LRT tropopause height and temperature. The horizontal resolution of the ERA5 data is $0.25^\circ \times 0.25^\circ$, while the vertical coverage covers from 1000 hPa to 1 hPa, with a vertical resolution of 37 pressure levels (Hersbach et al., 2019a).
 - The Atmospheric Infrared Sounder (AIRS) is the spectrometer onboard the second Earth Observing System (EOS) polar-orbiting platform, Aqua. In combination with the Advanced Microwave Sounding Unit (AMSU), AIRS constitutes an innovative atmospheric sounding instrument with infrared and microwave sensors. LRT height and temperature data provided by AIRS (AIRX3STM v7.0) are provided monthly and have global coverage, with horizontal resolution of $1^\circ \times 1^\circ$ (Aumann et al., 2003; AIRS, 2019a). In this study we use data for the period from September 2002 to November 2020. The data is available at AIRS (2019a).
 - The Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA-2) provides total column ozone (TCO) at a global scale, monthly, and with a spatial resolution of $0.5^\circ \times 0.625^\circ$. In this work, we use data from June 2001 to November 2020. The data is to be compared with the LRT height from GNSS-RO. In addition, TCO can provide information about the tropics behavior and can help in emphasizing the GNSS-RO outputs (GMAO, 2015).
 - CarbonTracker is a Carbon dioxide (CO_2) measurement and modeling system developed by NOAA Earth System Research Laboratories (ESRL) to keep track of CO_2 sources and sinks throughout the world. Monthly column average CO_2 data with a global coverage from June 2001 to March 2019 is used in this study (Jacobson et al., 2020). The data has spatial resolution of $2^\circ \times 3^\circ$. Here we use this data to study the behavior and trend of CO_2 which is the most important GHG and the largest forcing component in climate change.
 - AIRS provides monthly measurements of Methane (CH_4) at 24 pressure levels and spatial resolution of $1^\circ \times 1^\circ$ (AIRS, 2019b). We employ data from September 2002 to November 2020. CH_4 plays a crucial role in global warming as it is one of the main GHGs that drives long-term climate change.
 - Global monthly average surface temperature data from ERA5 reanalysis has horizontal resolution of $0.25^\circ \times 0.25^\circ$ (Hersbach et al., 2019b). In this study we utilize data from June 2001 to November 2020. The purpose of using this data is to study the impacts of the variability in the tropics on the global climatological parameters.
 - Monthly average precipitation data is available from the Global Precipitation Climatology Project (GPCP) at horizontal resolution of $2.5^\circ \times 2.5^\circ$ (Adler et al., 2016). We use data from June 2001 to November 2020. The purpose of this data is to investigate the relation between the tropical belt width and the corresponding precipitation pattern.
 - Precipitation and Potential Evapotranspiration (PET): Global monthly average precipitation and PET at horizontal resolution of $0.5^\circ \times 0.5^\circ$ are available from the Climatic Research Unit (CRU) Time-Series (TS). This data is employed to compute the SPEI, meteorological drought index. We utilize data from June 2001 to November 2020. The data

201 is available at Harris et al. (2020). The SPEI drought index was calculated following the
202 indications of Vicente-Serrano et al. (2010) and Beguería et al. (2013).

203 *2.2. Methods*

204 Due to the use of 12 GNSS-RO missions together in our analysis, we compared the different
205 missions' profiles to investigate the consistency between data from different sources. After that,
206 the GNSS-RO temperature profiles with a uniform coverage worldwide have been used to
207 calculate the tropopause height and the tropopause temperature based on both tropopause
208 definitions LRT and CPT. According to the definition of World Meteorological Organization
209 (WMO) "The thermal LRT is defined as the lowest level at which the lapse rate decreases to
210 2°C/km or less, provided also the average lapse rate between this level and all higher levels within
211 2 km does not exceed 2°C/km" (WMO, 1957). While, the CPT is indicated by the minimum
212 temperature in a vertical profile of temperature (Holton et al., 1995). Here, in order to avoid
213 outliers, the tropopause height values of both definitions are limited between 6-20 km. The results
214 of LRT and CPT are subsequently gridded into 5° x 5°. Finally, the spatial and temporal variability
215 of all climatic parameters are investigated using the Principal Component Analysis (PCA)
216 technique (Calabia and Jin, 2016; Calabia and Jin, 2020). This technique provides a new set of
217 modes that provide the variance through a linear combination of the original variables, based on
218 Eigen Decomposition. The solution is a couple of matrices containing the eigenvalues and
219 corresponding eigenvectors of the initial dataset. Each eigenvector is regarded as a map, the
220 eigenvalues provide the percentage of the contribution to the total variability, and the temporal
221 coefficients are used to represent the maps at a given epoch. The first PCA mode has the largest
222 variance, and the following modes represent the next level of variance, which usually are a residual
223 variability. For this reason, since the variability of the variables used in this study are mainly driven
224 by the annual variation, we only employ the first PCA component for each case.

225 The locations of TEL are estimated from monthly zonal average of LRT height derived
226 from GNSS-RO, ERA5, and AIRS data. The ERA5 and AIRS tropopause parameters are
227 resampled at the same resolution of GNSS-RO. The zonal average LRT height is spline
228 interpolated as a function of latitude (Ao and Hajj, 2013), and the TEL is determined at each
229 hemisphere using two tropopause height metrics. The first method relies on subjective criterion,
230 according to the first method TEL defined as the latitude at which the LRT height falls 1.5 km
231 under the tropical average (15°S–15°N) LRT height (Davis and Rosenlof, 2012). The second
232 method is an objective criterion, in which the TEL is defined as the latitude of maximum LRT
233 height meridional poleward gradient (Davis and Rosenlof, 2012). Moreover, the rate of expansion
234 and/or contraction of the tropical belt is estimated from both calculation methods, at each
235 hemisphere, independently. In addition, the trend and spatial-temporal variability of CO₂ and CH₄,
236 as important drivers of global warming, are investigated. Furthermore, the trend and spatial-
237 temporal pattern of TCO that give information about the tropical belt width are investigated.
238 Finally, we broadly examine the surface temperature, precipitation, and drought trends as
239 meteorological parameters which may have a changing behavior as a response to tropics
240 expansion.

241

242 **3. Results and Analysis**

243 *3.1- Assessment of GNSS-RO Temperature Profiles*

244 In several previous studies, multiple GNSS-RO missions were utilized together for the purpose of
245 obtaining high spatial resolution. In addition, the assessment of using different GNSS-RO missions
246 together showed high level of consistency (Hajj et al., 2004; Li et al., 2017; Tegtmeier et al., 2020;
247 Xian et al., 2021). In our study, the atmospheric profiles, from all used GNSS-RO missions, are
248 compared together to signify the high level of consistency and compatibility between RO missions
249 available on CDAAC web, also the ability to merge them together in our study as a single dataset.
250 COSMIC mission profiles are used as a fixed member in the intercomparison of all utilized RO
251 missions as it is the most abundant regarding to profiles density and its time span make overlap
252 with all other missions. The results of the conducted intercomparison show high agreement and
253 consistency between profiles of collocated pairs (Fig. 2). Table 1 demonstrates the results of the
254 collocated GNSS profile pairs. The correlation coefficient between the collocated profile pairs
255 ranges from 0.97 to 0.99 and the temperature mean difference ranges from 0.1 to 0.5 K.

256

257 **Table.1** Intercomparison of collocated GNSS profile pairs.

Mission	Correlation coefficient	Mean difference (k)
(a) COSMIC – CHAMP	0.99	0.5
(b) COSMIC – SAC-C	0.99	0.2
(c) COSMIC – C/NOFS	0.99	0.32
(d) COSMIC – GRACE	0.99	0.1
(e) COSMIC – MetOp-A	0.99	0.28
(f) COSMIC – TerraSAR-X	0.98	0.22
(g) COSMIC – KOMPSAT5	0.97	0.13
(h) COSMIC – MetOp-B	0.99	0.14
(i) COSMIC – MetOp-C	0.99	0.47
(j) COSMIC – PAZ	0.98	0.33
(k) COSMIC – TanDem-X	0.99	0.47

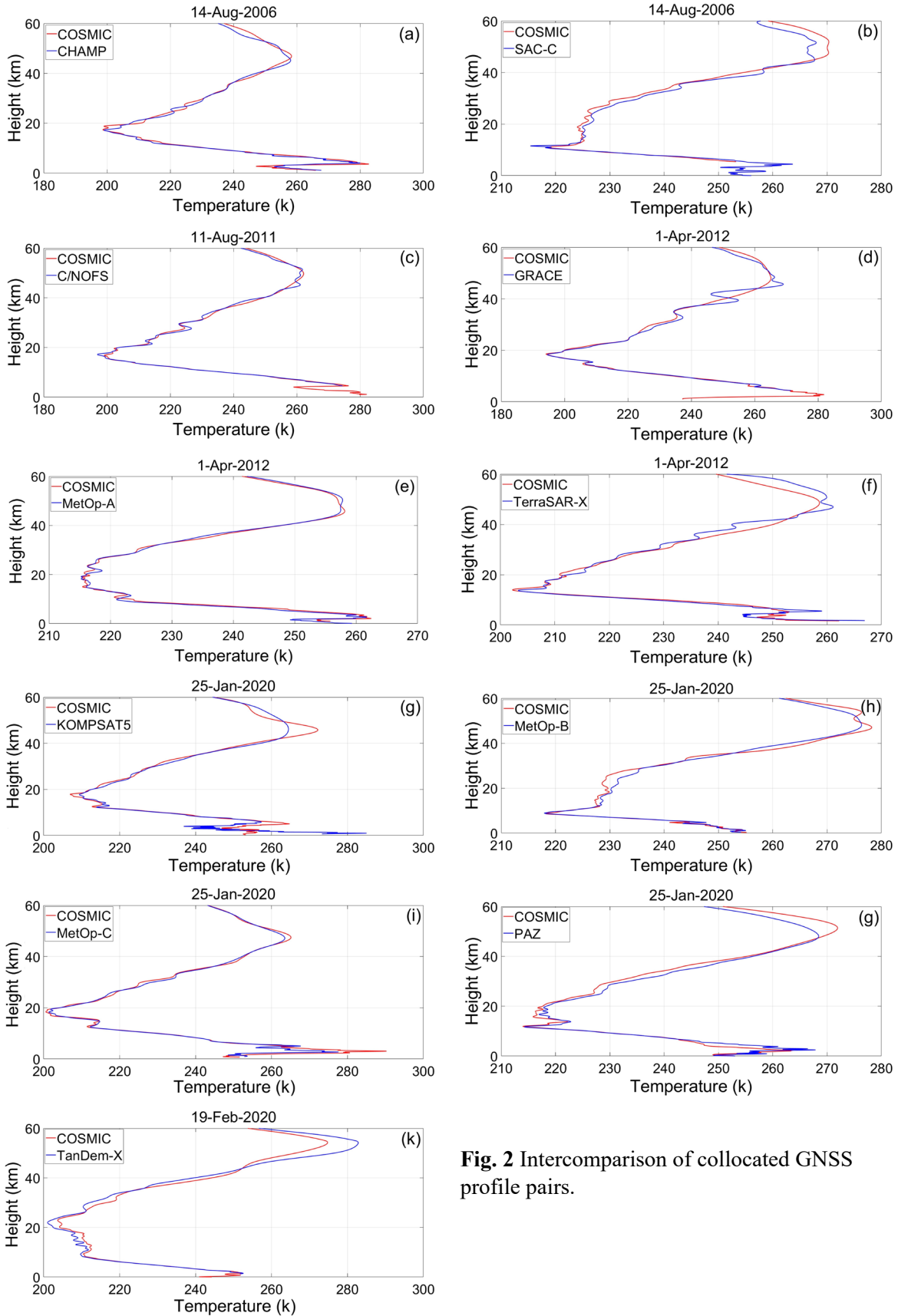
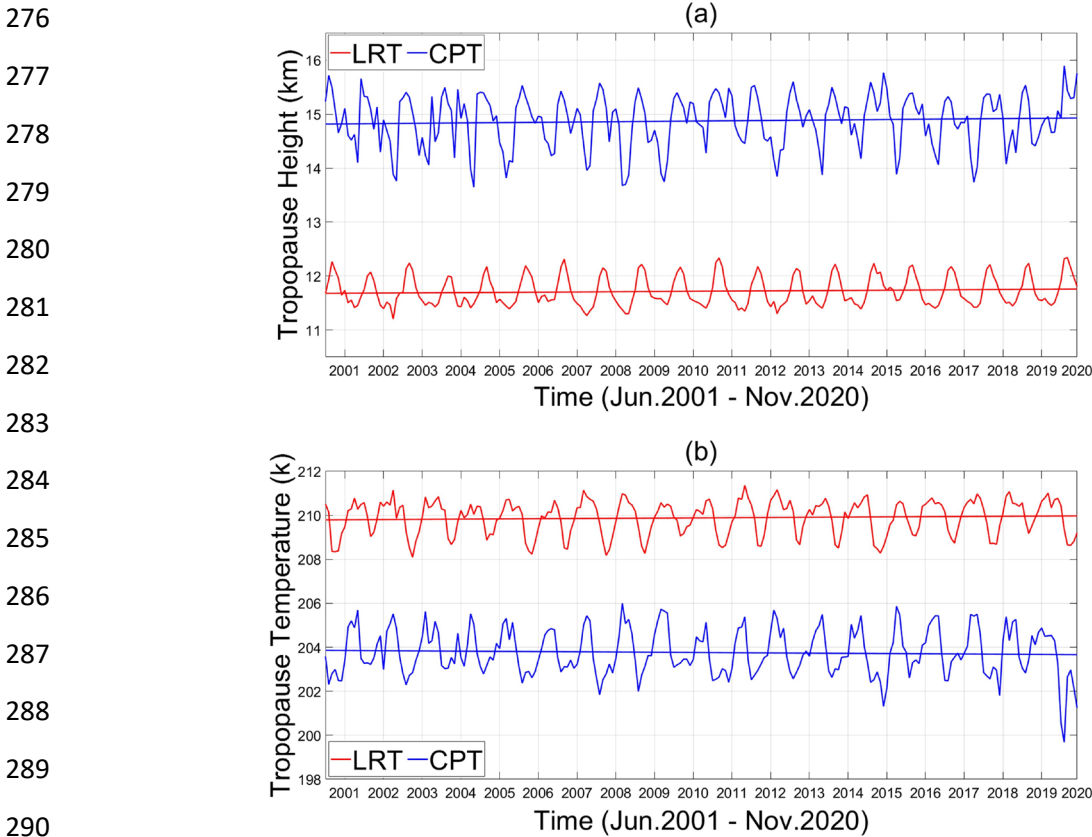


Fig. 2 Intercomparison of collocated GNSS profile pairs.

259 3.2. Tropopause Characteristics from GNSS-RO

260 Figure 3 shows the global parameters of GNSS LRT and CPT from June 2001 to November 2020.
261 As clear in Figure 3, the CPT height is always higher than that of LRT. The mean difference
262 between them is about 2.62 km, and there is a correlation of about 0.66 between LRT and CPT
263 height. Previous studies have reported that the average of CPT height is between 0.5 and 1 km
264 higher than the LRT height average (Munchak and Pan, 2014). The LRT temperature is higher
265 than that of the CPT. The mean difference between them is about 4.02 k, and the correlation
266 coefficient between them is 0.61. Our results are consistent with previous studies that displayed a
267 global increase of the tropopause height from radiosonde observations (Seidel and Randel, 2006)
268 and reanalysis (Santer et al., 2004).

269 Our analysis shows global increasing trend of LRT height of 36 m/decade since 2001 and
270 this has good agreement with that of Schmidt et al. (2008) which shown upward trend of global
271 LRT height of 39–66 m/decade. The LRT temperature show an increase of 0.09 k/decade. For the
272 LRT definition, the correlation coefficient between the LRT height and temperature is -0.78. In
273 case of CPT definition, the global trend of CPT height has increased 60 m/decade since 2001, but
274 that of CPT temperature has decreased 0.09 k/decade. The correlation coefficient between the CPT
275 height and temperature is -0.82.



291 **Fig.3** The LRT and CPT (a) height and (b) temperature is shown from 2001 to 2020.

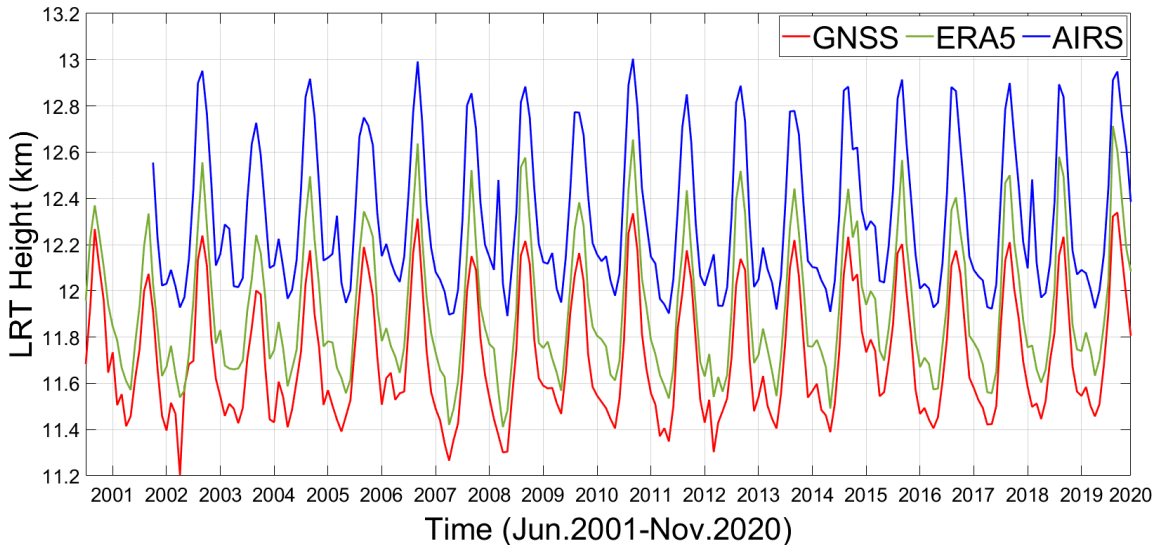
292

293 3.3. Comparison between GNSS, ERA5, and AIRS

294 In this study, TEL at each hemisphere is estimated from the monthly zonal average tropopause
295 height retrieved from the LRT definition. This is done because the LRT represents the location of
296 the point of thermal transition between troposphere and stratosphere. Furthermore, it reacts to both
297 tropospheric and stratospheric temperature changes. Many studies (Seidel and Randel, 2006;
298 Santer et al., 2004) have shown that LRT height is a good climate change indicator. Figure 4 shows
299 the LRT height values derived from GNSS, ERA5, and AIRS. In general, AIRS shows the highest
300 values of LRT height, while GNSS shows the lowest values. The trends show that ERA5 data has
301 the highest increasing rate of LRT height, being 48 m/decade since June, 2001. In contrast, AIRS
302 has the lowest rates for LRT height, showing an increase of 12 m/decade since September, 2002.

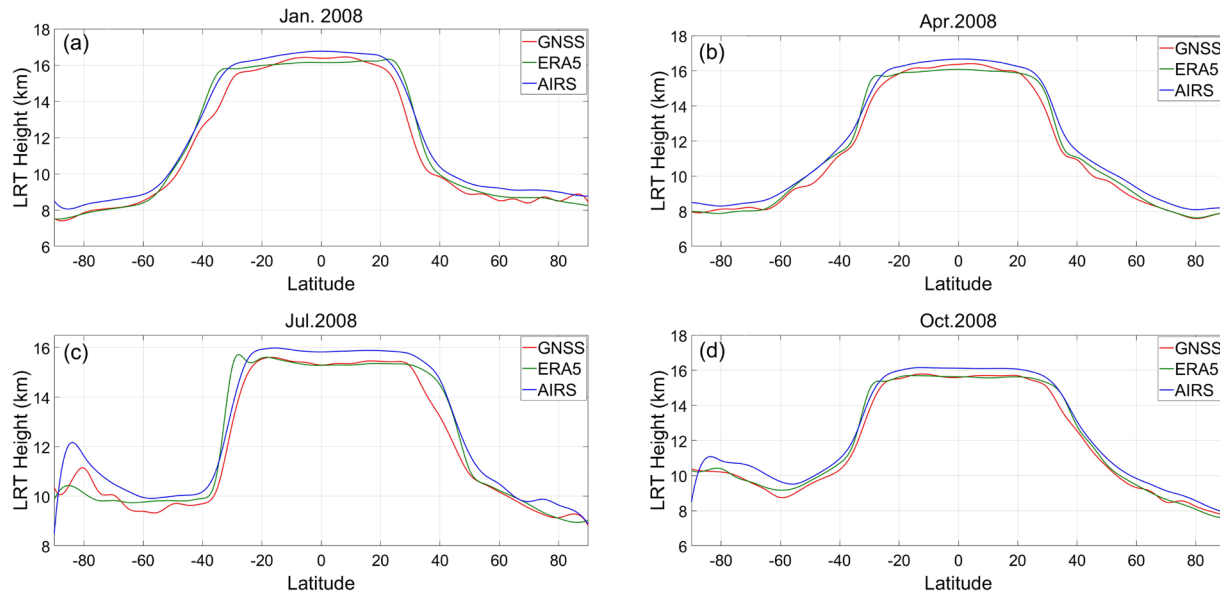
303 The zonal mean of LRT height for the 3 data sets during January, April, July, and October
304 of 2008 are shown in Figure 5. In January 2008, the high LRT covered higher latitudes in SH than
305 in the NH. The opposite occurs in July. In April 2008, the high LRT covered similarly in both
306 hemispheres. In October, the area covered with high tropopause in NH is larger than that of SH,
307 but not as wide as the coverage in July. This suggest that the warmer the air the wider the area
308 covered with high tropopause. As stated in section 2, the TEL in NH and SH have been estimated
309 applying 2 tropopause height metrics. The results are discussed in detail in the followings.

310



311 **Fig. 4** LRT height from GNSS, ERA5, and AIRS.

312



313 **Fig. 5** Monthly zonal average LRT height from GNSS, ERA5 and AIRS.

314 *3.3.1. Subjective Criterion for TEL*

315 According to subjective criterion (Davis and Rosenlof, 2012), the TEL at each hemisphere is the
 316 latitude at which the tropopause height is 1.5 km under the tropical average tropopause height
 317 (15°S-15°N). As shown in Figure 6 and Table 2, the tropical belt based on GNSS has expanded
 318 0.41°/decade in the NH, and 0.08°/decade in the SH, since 2001. Using GNSS-RO data the tropical
 319 belt expansion trends in NH and SH agree with the results of Ao and Hajj (2013). According to
 320 Meng et al. (2021) the highest trend of LRT height is covering latitudinal band 30°N to 40°N and
 321 this possibly caused by the tropical widening and subtropical jet poleward shift over the past four
 322 decades (Staten et al., 2018) and this corresponds with our study findings. In case of ERA5, there
 323 is no significant expansion or contraction in both hemispheres. While AIRS has expansion of about
 324 0.34°/decade at the NH and strong contraction of about -0.48°/decade at the SH.

325 **Table.2** Tropical belt expansion and contraction rates based on subjective criterion.

Source	Duration	NH		SH	
GNSS	Jun.2001-Nov.2020	0.41	± 0.09	0.08	± 0.04
ERA5	Jun.2001-Nov.2020	-0.01	± 0.1	-0.04	± 0.05
AIRS	Sep.2002-Nov.2020	0.34	± 0.11	-0.48	± 0.05

326
 327
 328
 329
 330
 331
 332
 333
 334
 335
 336
 337
 338
 339
 340
 341
 342
 343
 344
 345
 346
 347
 348
 349
 350
 351
 352
 353
 354
 355

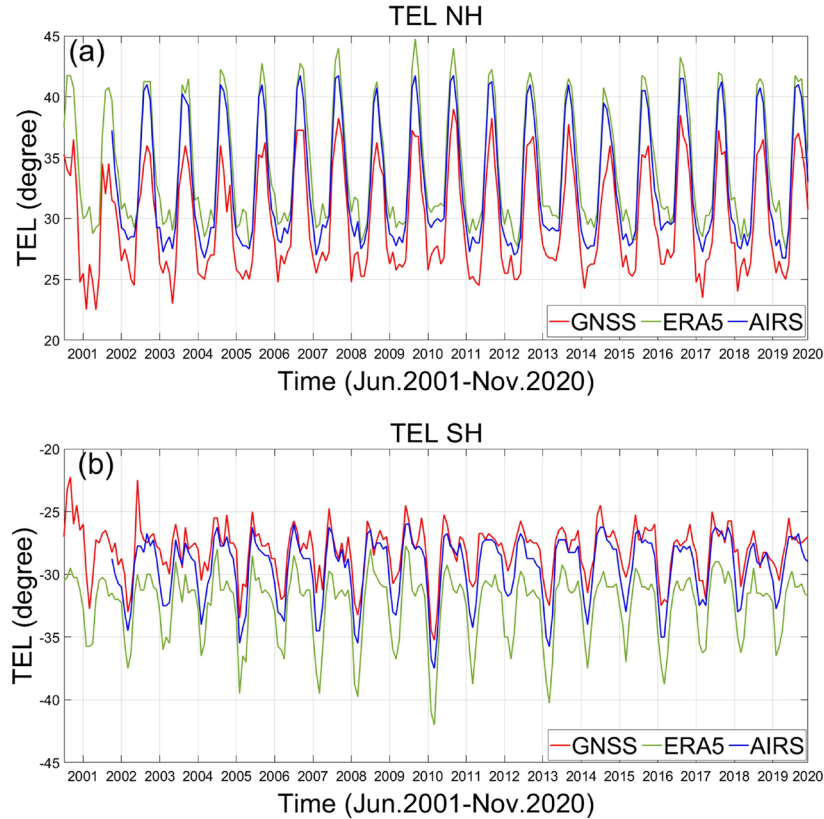


Fig. 6 TEL using subjective criterion (a) NH and (b) SH.

3.3.2. *Objective Criterion for TEL*

According to objective criterion (Davis and Rosenlof, 2012), TEL at each hemisphere is the latitude of maximum poleward gradient of tropopause height. As shown in Figure 7 and Table 3, the tropical belt based on GNSS has expanded about 0.13°/decade in the NH since 2001, but there is no significant expansion or contraction in the SH. In case of ERA5, there is no significant trend in NH, while SH has a minor contraction of approximately -0.08°/decade. AIRS has an expansion of 0.13°/decade in NH, and strong contraction in SH of -0.37°/decade. It is clear from these results, that the rates of expansion and contraction using the objective criterion are less than that of the subjective criterion. While in case of the objective method, TEL are located more poleward than that of the subjective method.

Table.3 Tropical belt expansion and contraction rates based on objective criterion.

Source	Duration	NH		SH	
GNSS	Jun.2001-Nov.2020	0.13	± 0.1	-0.03	± 0.06
ERA5	Jun.2001-Nov.2020	-0.06	± 0.1	-0.08	± 0.06
AIRS	Sep.2002-Nov.2020	0.13	± 0.04	-0.37	± 0.06

356
357
358
359
360
361
362
363
364
365
366
367
368
369
370
371

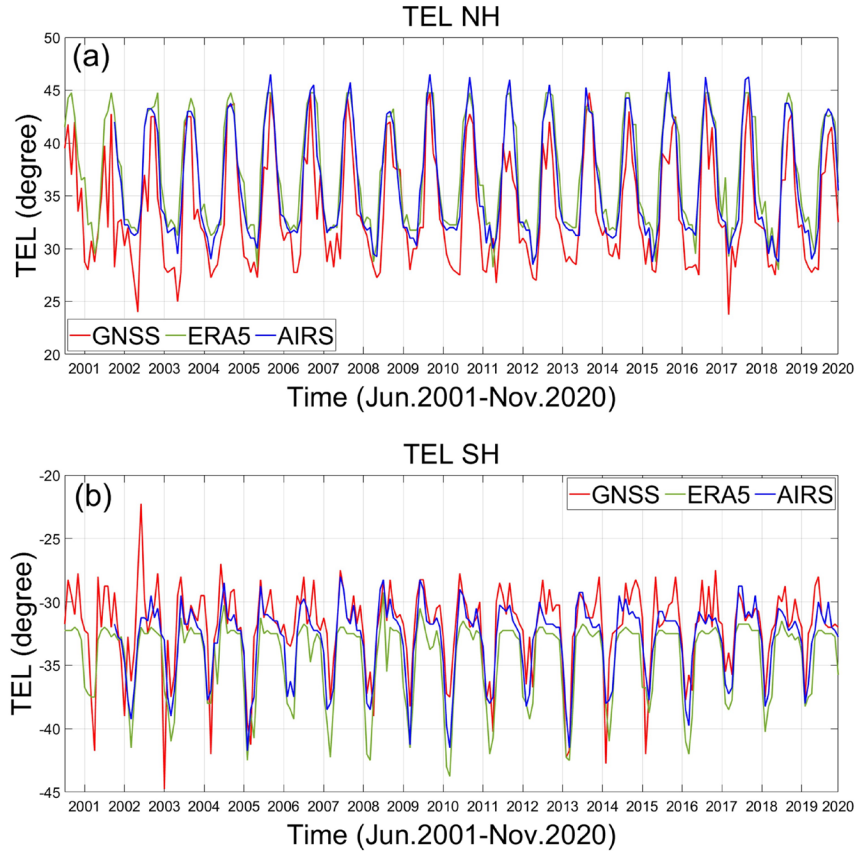
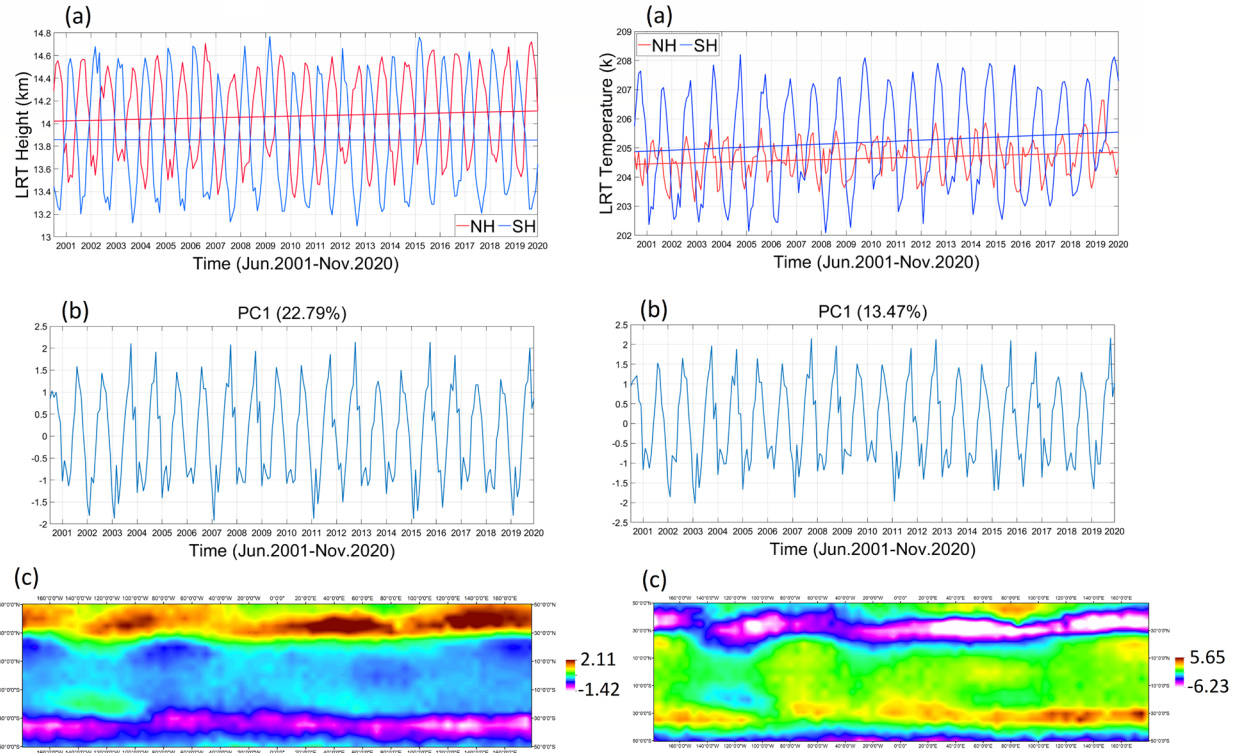


Fig.7 TEL using objective criterion, (a) NH and (b) SH.

3.4. Spatial and Temporal Variability of LRT

In this section, the GNSS LRT height and temperature between 50°N to 50°S are investigated (Fig. 8). In the NH, the LRT height has increased about 48 m/decade since 2001 and this is consistent with the results of Meng et al. (2021) which shown increase of LRT height around 44.4 m/decade over 20°N to 80°N for the period from 2001 to 2020. In contrast, LRT height in the SH shows a slight decrease of -2.4 m/decade. Regarding to LRT temperature, it has increased about 0.21 k/decade in NH and 0.34 k/decade in SH. Both hemispheres LRT temperature time series show increasing rates higher than the global one 0.09 k/decade. Figure 8 also shows the temporal and spatial variability given by the 1st PCA. The temporal variability for LRT Height captures 22.79% of the total variance. For the LRT temperature, PCA1 captures 13.47% of the total variability. These values are relatively small, showing that the variability spreads along lower degree PCA modes. We can clearly see the annual forcing. The spatial variability shows similar patterns for LRT height and temperature. The signal at the NH is stronger and wider than that at the SH.



385 **Fig.8** GNSS-RO based LRT height (left) and temperature (right). In (a) temporal time series (b) temporal
 386 variability given by PCA1, and (c) spatial variability map given by PCA1.

387

388 3.5. Total Column Ozone (TCO), Carbon dioxide (CO₂), and Methane (CH₄)

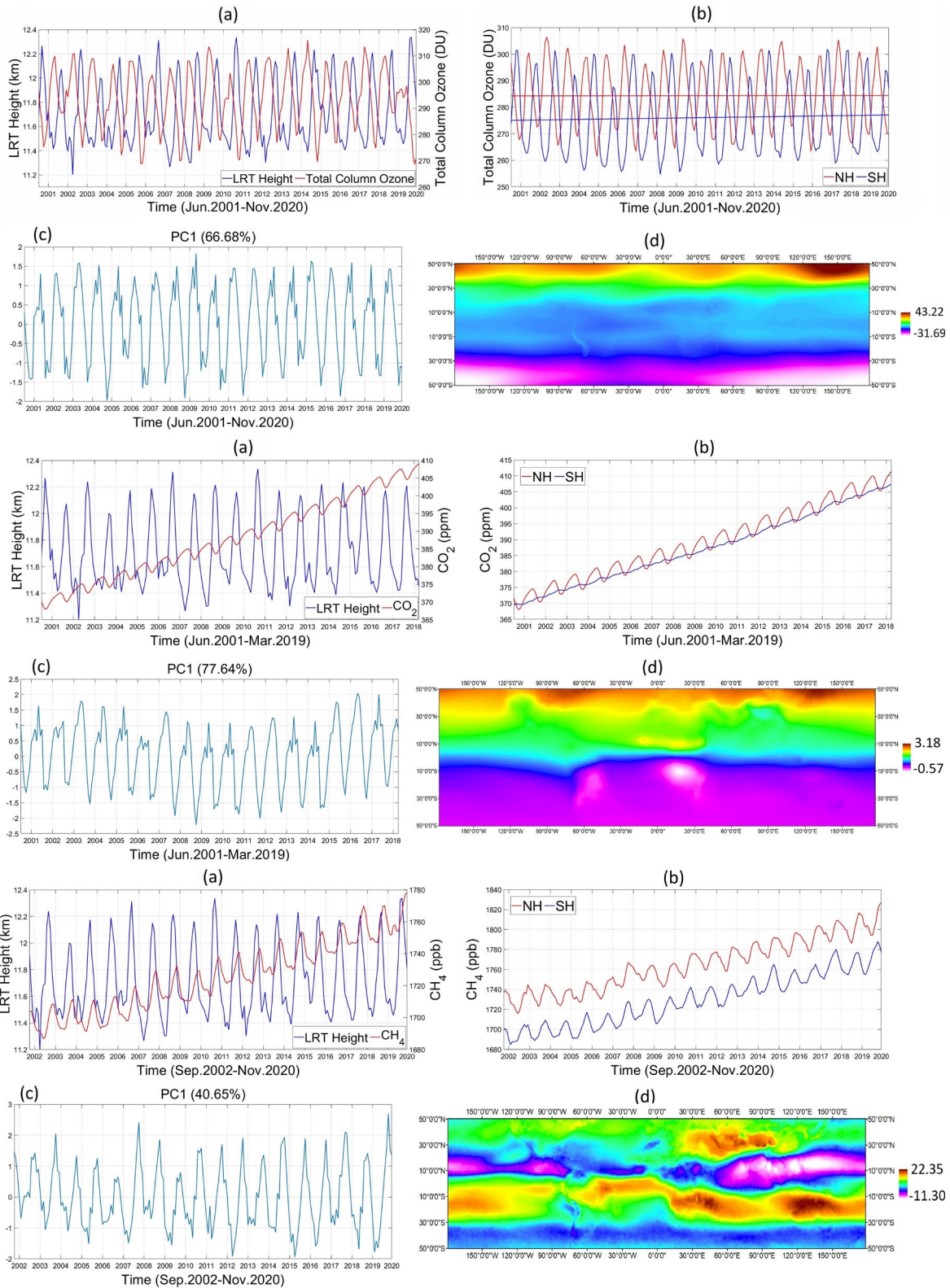
389 Figure 9 shows that since 2001, TCO has a global increase of 0.7 DU/decade. TCO has a strong
 390 negative correlation of -0.64 with the LRT height. This corresponds with the results of previous
 391 work which clarified that TCO pattern is inversely proportion with tropopause height and can give
 392 indication about the tropical belt width (Hudson et al., 2003; Hudson et al., 2006; Hudson, 2012;
 393 Davis et al., 2018). TCO has increased 0.06 DU/decade and 1.05 DU/decade in the NH and the
 394 SH, respectively. Shangguan et al. (2019) reported to asymmetric trends of ozone in the
 395 midlatitudes of both hemispheres in the middle stratosphere, with considerable ozone decrease in
 396 NH and ozone increase in SH. In our results, the PCA1 of TCO represents 66.68% of the total
 397 variability. The spatial map of PCA1 shows stronger signal in the NH than that in the SH. The NH
 398 signal is located more poleward than that of the SH. Comparisons with GNSS-RO LRT height
 399 spatial and temporal pattern suggest the TCO expansion in the NH, and a weak expansion or non-
 400 significant contraction in the SH.

401 Several studies signified to an increase in the tropopause height as a result of the
 402 troposphere warming caused by the rise of the GHGs concentrations in the atmosphere (Meng et
 403 al., 2021; Pisoft et al., 2021). CO₂ is the most important GHG and it is considered a main driver
 404 of global warming. The time series of the CO₂ is shown in Figure 9. In this figure, we can see that
 405 CO₂ has an increase of 21.38 ppm/decade since 2001. It has a correlation of -0.05 with GNSS LRT
 406 height. CO₂ column average in both NH and SH has the same increasing rate of 21.6 ppm/decade.

407 This is higher than the global rate. The CO₂ standard deviation (STD) in NH is 11.38 which is
408 higher than that of SH 10.90. The temporal variability given by the PCA1 capture 77.64% of the
409 total variability. PCA1 shows increasing trend and large variability with time. The map of PCA1
410 variability shows a shift toward the north pole. This seems to be related to the coverage of the
411 tropical belt i.e., the TEL occurrence at the NH is more poleward than that of the SH.

412 CH₄ is one of the main GHGs, and it is considered a long-term driver of climate change.
413 The global time series of CH₄ column average (Fig. 9a) shows increasing trend of 39 ppb/decade
414 since 2001. This variable has a correlation of 0.23 with GNSS-RO LRT height. CH₄ column
415 average in both NH and SH show equal increasing trends of 46.8 ppb/decade. This is higher than
416 the global rate. The CH₄ STD in the NH is similar to that in the SH 25.91. The temporal variability
417 of PCA1 capture 40.65% of the total variability. It shows non-significant trend but its range
418 increases with time. The map of PCA1 shows more poleward signal in the NH than its equivalent
419 in the SH. The NH signal reaches 30°N while the SH signal does not reach the limit of 30°S. This
420 is clearly in with the GNSS TEL results, showing that the tropical condition in the NH covers a
421 wider area than that in the SH.

422



423 **Fig.9** TCO (top), CO₂ (middle), and CH₄ (bottom) results. In (a) global time series against GNSS LRT
 424 height (b) temporal time series in NH and SH (c) temporal variability given by PCA1 and (d) spatial
 425 variability map given by PCA1.

426 *3.6. Surface Temperature and GPCP Precipitation*

427 Many studies revealed the relation of the surface temperature with the tropopause height and
428 tropical belt expansion. Thurn and Craig (1997, 2000) found the simulated tropopause height to
429 be sensitive to the surface temperature. Figure 10 shows that the global surface temperature has
430 increased 0.3 k/decade since 2001. A clear correlation between the surface temperature and the
431 GNSS-RO LRT height is seen, with a value of 0.81. The surface temperature in both NH and SH
432 shows increasing trends of 0.23 k/decade and 0.18 k/decade, respectively. The surface temperature
433 in the NH has STD of 3.5 while that of the SH has STD of 1.5. The PCA1 capture 84.41% of the
434 total variance. The PCA1 shows an increasing trend and amplitude with time. The PCA1 map has
435 a signal in SH weaker than that in NH. The results of surface temperature agree with that of GNSS-
436 RO TEL. For instance, the NH show expansive behavior more than that in the SH which shows a
437 minor expansion using subjective criterion and non-significant contraction applying objective
438 criterion. Gao et al. (2015) signified that the correlation coefficient between global tropopause
439 height anomalies and the Niño 3.4 sea surface temperature index is 0.53, with a maximum
440 correlation coefficient of 0.8 at a lag of three months. Fomichev et al. (2007) also found that an
441 increase in sea surface temperature resulted in a tropopause height increase in a coupled chemistry
442 climate model simulation. Hu and Fu (2007) suggested that an increase in sea surface temperatures
443 in the tropics could result in an increase in the tropopause height and a wider Hadley Circulation
444 (tropics width). In addition, our results support surface temperature as a proposed driver for tropics
445 expansion (Allen et al., 2012a; Adam et al., 2014).

446 The precipitation spatial and temporal variability is investigated to examine the impacts of
447 the TEL variability on the precipitation behavior. The GPCP precipitation has a global decrease of
448 -0.04 mm/decade since 2001. The precipitation behavior has strong correlation of 0.61 with the
449 GNSS LRT height. The GPCP precipitation in the NH show a minor decreasing trend of -0.02
450 mm/decade meanwhile the SH shows a significant decreasing trend of -1.3 mm/decade. The
451 precipitation in the NH has STD of 15.84 and the SH has STD of 16.47. The PCA1 capture 29.30%
452 of the total variability. PCA1 has upward trend and amplitude with time. The PCA1 map shows a
453 pattern in NH that is stronger and more poleward than that in SH. The precipitation can be used as
454 an independent metric in signifying the TELs locations. Many studies, rely upon surface-based
455 variables to investigate tropical widening, used the GPCP monthly dataset to examine shifts in the
456 positions and boundaries of the subtropical dry zones (Hu et al., 2010; Zhou et al., 2011; Allen et
457 al., 2012b).

458

459

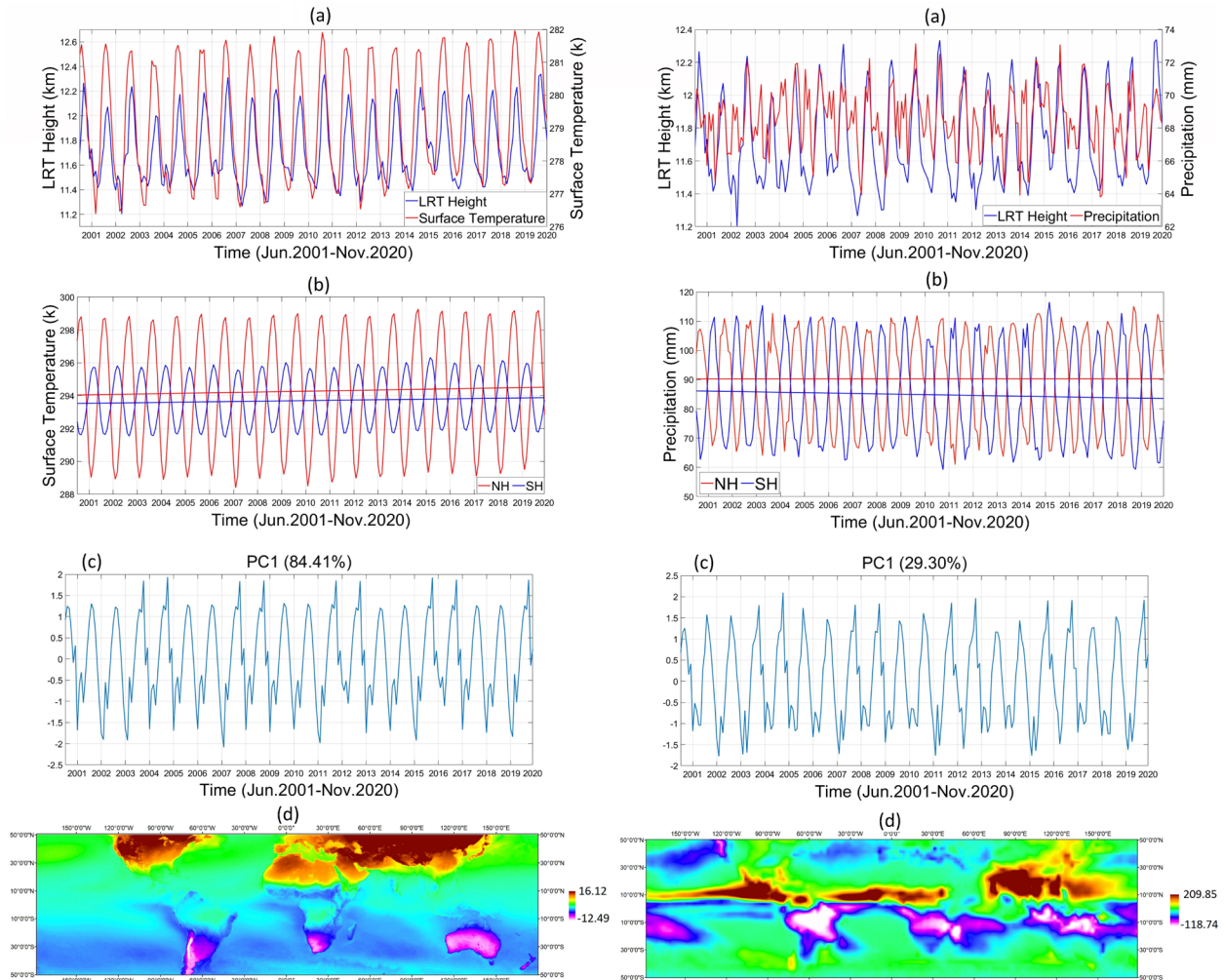
460

461

462

463

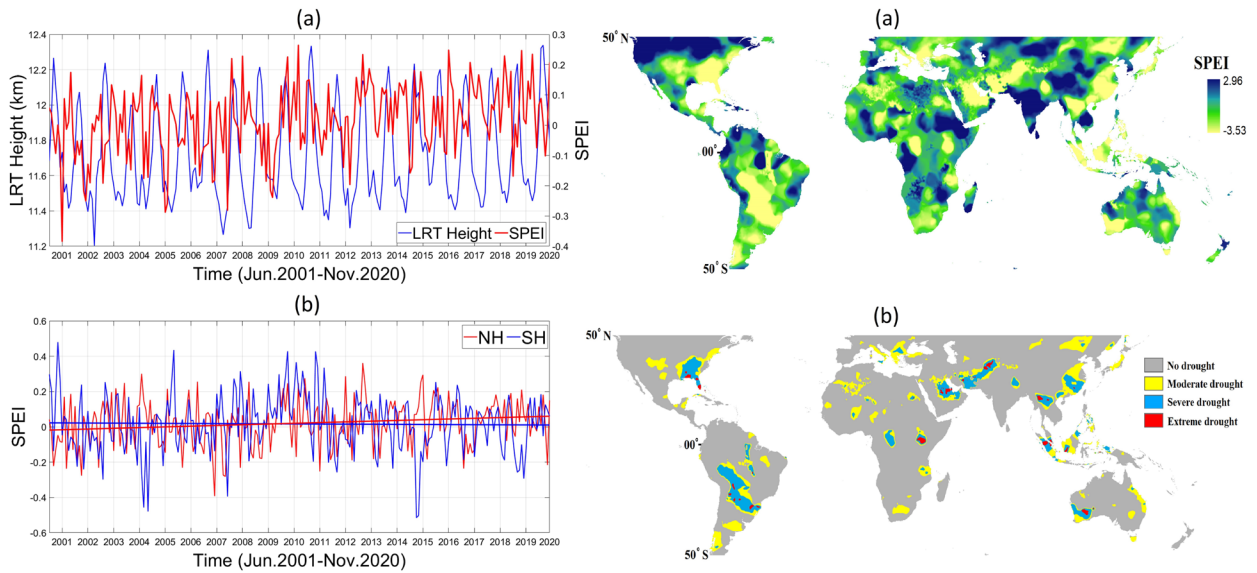
464



465 **Fig.10** Surface Temperature (left) and GPCP precipitation (right). In (a) global time series against LRT
 466 height (b) temporal time series in NH and SH (c) temporal variability given by PCA1 and (d) spatial
 467 variability map given by PCA1.

468 **3.7. Standardized Precipitation Evapotranspiration Index (SPEI)**

469 The tropical belt widening would contribute in increasing the midlatitude droughts frequency in
 470 both hemispheres (Hu and Fu, 2007; Fu et al., 2006; Seidel et al., 2007). The SPEI is usually
 471 employed to monitor the meteorological drought status. As clear in Figure 11, the SPEI has a
 472 global increase of 0.056 per decade since 2001. The NH shows an increase of 0.035 per decade,
 473 and the SH has a decrease of -0.005 per decade. The SPEI has no correlation with GNSS LRT
 474 height -0.002. Because the study area is wide and extends through many continents, the SPEI, in
 475 our study, only provides information about the dry and wet condition. Figure 11 shows the spatial
 476 pattern of SPEI in September 2019, and the areas by category of no-drought, moderate, severe,
 477 and extreme. Figure 12 shows the number of cells covered with drought, and its corresponding
 478 classification from Figure 11. The total number of cells covered with drought at the NH nearly
 479 double its value at the SH. Both hemispheres have a decreasing trend of the number of cells
 480 covered with drought. The decrease rate is 510 cell/decade in the NH and 373 cell/decade in the
 481 SH. The drought does not show any spatial pattern associated with the locations of TELs.



482 **Fig.11** On the left, SPEI drought index (a) global SPEI time series in comparison with LRT height and (b)
 483 SPEI for two latitudinal bands 0°-50°N & 0°-50°S. On the right, (a) SPEI drought index in September 2019
 484 and (b) SPEI drought categories in September 2019.

485

486

487

488

489

490

491

492

493

494

495

496

497

498

499

500

501

502

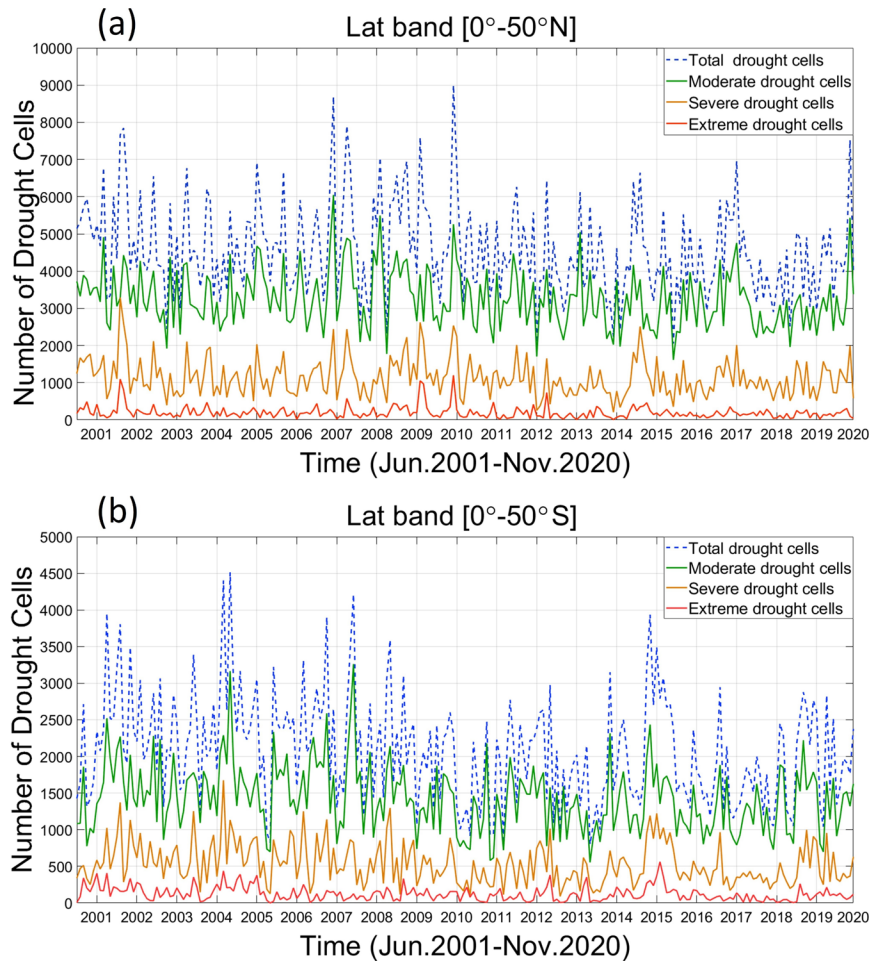


Fig.12 Number of cells covered with drought at (a) NH and (b) SH.

503 4. Conclusions

504 The GNSS-RO is a well-established technique to derive atmospheric temperature structure in the
505 UTLS region. In this study, GNSS-RO data of 12 RO missions are combined together to examine
506 the possible tropical belt expansion. The intercomparison of GNSS-RO profiles of the different
507 utilized RO missions show high level of consistency to be employed together in our analysis.
508 GNSS-RO profiles are employed to derive tropopause height and temperature based on LRT and
509 CPT definitions. The tropopause height is a key element in climate change research because its
510 variability has a correlation with the global warming phenomena (Santer et al., 2003; Sausen and
511 Santer, 2003; Seidel and Randel, 2006; Mohd Zali and Mandeep, 2019). Our analyses show that
512 GNSS LRT and CPT height have increased 36 m/decade and 60 m/decade, respectively, since
513 June, 2001. There is high correlation between the tropopause height and temperature, being -0.78
514 and -0.82 for LRT and CPT, respectively. The LRT height from ERA5 shows an increase of 48
515 m/decade since June, 2001 and that derived from AIRS has a smaller increasing rate of 12
516 m/decade since September, 2002.

517 In most of the previous studies, the reported tropics widening rates range from 0.25° to
518 3.0° latitude/decade and their statistical significance vary by large amount based on the metrics
519 used to estimate the TEL as well as the data sets utilized for its derivation (Davis and Rosenlof,
520 2012). In our study, TEL at each hemisphere is estimated using two tropopause height metrics.
521 Applying the first method, subjective criterion, there are higher expansion and contraction rates
522 than that from the second method, objective criterion. While using the objective criterion, the
523 locations of TELs in both hemispheres are more poleward than that from the subjective criterion.
524 Based on the subjective method, tropical width results from GNSS-RO have an expansive behavior
525 in the NH with about 0.41° /decade, and a minor expansion trend in the SH with 0.08° /decade.
526 ERA5 has non-significant contraction in both hemispheres. In case of the AIRS data, there is a
527 clear expansion behavior in the NH with about 0.34° /decade, and a strong contraction in the SH
528 with about -0.48° /decade. Based on the objective method, GNSS-RO has an expansive behavior
529 in the NH with about 0.13° /decade, but there is no significant expansion or contraction in the SH.
530 For ERA5, there is no significant trend for the TEL results in the NH, while there is a minor
531 contraction of about -0.08° /decade in the SH. The AIRS data show an expansion in the NH with
532 0.13° /decade, and strong contraction in SH with -0.37° /decade. Results of several studies, based
533 on different data sets and metrics, shown an expansive behavior of tropical belt in NH higher than
534 that of SH and this broadly agree with our GNSS-RO based results (Hu and Fu, 2007; Archer and
535 Caldeira, 2008; Hu et al., 2010; Zhou et al., 2011; Allen et al., 2012b). From all data sets, the TEL
536 is located more poleward in the NH than in the SH. For both subjective and objective methods, the
537 TELs reach the latitudes of 44.75°N and 46.75°N , respectively, at the NH. Meanwhile, at the SH
538 the TELs reach the latitudes of 42°S and 44.75°S for subjective and objective methods,
539 respectively. In both hemispheres, the variability of tropopause parameters (temperature and
540 height) is maximum around the TEL locations.

541 The TCO shows increasing rates globally. The rate in the SH is higher than that of the
542 NH. The ozone variability agrees well with the spatial and temporal modes of TEL estimated from
543 GNSS-RO LRT height and this supports GNSS-RO TEL estimates over that of ERA5 and AIRS.

544 In addition, CO₂ and CH₄, as the main GHGs responsible for global warming, concentrations
545 increase cause a tropopause height rise (Meng et al., 2021; Pisoft et al., 2021). In our analysis, both
546 CO₂ and CH₄ show a global increasing rate. Their upward trends at the NH and the SH are nearly
547 the same. The patterns of TCO and CO₂ display good agreement with the TELs locations in NH
548 and SH. They show more poleward occurrence with time and their variability in NH is higher than
549 that of SH. In addition, CH₄ has signal in NH occurs more poleward than that in SH. The surface
550 temperature and precipitation both increase with time, and have strong correlation with LRT
551 height. Both variables show an increasing rate at the NH higher than at the SH. The surface
552 temperature shows strong spatial variability pattern that broadly agrees with the TEL locations
553 from GNSS-RO. The spatial pattern of precipitation shows northward orientation. The SPEI
554 meteorological drought index shows increasing rate globally. It has upward trend in NH while
555 having decreasing trend in SH. Since SPEI is multivariate, it has no direct response to the TEL
556 behavior. In both hemispheres, the number of cells covered with drought decreased since 2001. It
557 can be concluded that the tropical belt widening rates are different from data set to another and
558 from metric to another. In addition, TEL behavior in NH is different from that of SH. Furthermore,
559 the variability of meteorological parameters agrees with GNSS TEL results more than with that of
560 other data sets. The study results signify the importance of monitoring the tropopause and TEL
561 parameters which can accurately indicate the climate variability and climate change globally.

562 **Funding:** This study was supported by the National Natural Science Foundation of China (NSFC)
563 Project (Grant No. 12073012), National Natural Science Foundation of China-German Science
564 Foundation (NSFC-DFG) Project (Grant No. 41761134092), China Scholarship Council (CSC)
565 and Ministry of Higher Education of the Arab Republic of Egypt.

566 **Author contributions**

567 M.D. provided the main ideas, developed the methodology, conceived and performed the
568 experiments, and analyzed the results; S.G. provided supervision, mentorship, and funding
569 support; A.C. provided manuscript edition and revision tasks; A.S. helped in manuscript writing
570 and editing.

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

572 **Acknowledgements**

573 The authors thanks to the CDAAC for providing GNSS-RO data, NOAA ESRL for providing
574 CarbonTracker CT2019B, and Copernicus Climate Change Service Information for MERRA-2
575 and ERA5 data. We are grateful to the Climate Research Unit (CRU), the University of Delaware
576 (UDEL), and Global Precipitation Climatology Project (GPCP) for granting access to datasets.
577 The first author especially thanks to National Research Institute of Astronomy and Geophysics,
578 Egypt, and to Nanjing University of Information Science and Technology, China, for granting the
579 scholarship for pursuing his Ph.D.

580 **References**

581 Adam, O., Grise, K. M., Staten, P., Simpson, I. R., Davis, S. M., Davis, N. A., Waugh, D. W., Birner, T.,
582 and Ming, A.: The TropD software package (v1): standardized methods for calculating tropical-width

583 diagnostics. *Geoscientific Model Development*, 11(10), 4339–4357. [https://doi.org/10.5194/gmd-11-4339-](https://doi.org/10.5194/gmd-11-4339-2018)
584 2018, 2018.

585 Adam, O., Schneider, T., and Harnik, N.: Role of Changes in Mean Temperatures versus Temperature
586 Gradients in the Recent Widening of the Hadley Circulation. *Journal of Climate*, 27(19), 7450–7461.
587 <https://doi.org/10.1>, 2014.

588 Adler, R., Wang, J., Sapiano, M., Huffman, G., Chiu, L., Xie, P., Ferraro, R., Schneider, U., Becker, A.,
589 Bolvin, D., Nelkin, E., Gu, G., and NOAA CDR Program.: Global Precipitation Climatology Project
590 (GPCP) Climate Data Record (CDR), Version 2.3 (Monthly). National Centers for Environmental
591 Information. doi:10.7289/V56971M6, 2016.

592 AIRS project: Aqua/AIRS L3 Monthly Standard Physical Retrieval (AIRS-only) 1 degree x 1 degree V7.0,
593 Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC),
594 10.5067/UBENJB9D3T2H, 2019a.

595 AIRS project: Aqua/AIRS L3 Monthly Standard Physical Retrieval (AIRS+AMSU) 1 degree x 1 degree
596 V7.0, Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC),
597 10.5067/KUC55JEVO1SR, 2019b.

598 Allen, R. J., Sherwood, S. C., Norris, J. R., and Zender, C. S.: The equilibrium response to idealized thermal
599 forcings in a comprehensive GCM: implications for recent tropical expansion. *Atmospheric Chemistry and*
600 *Physics*, 12(10), 4795–4816. <https://doi.org/10.5194/acp-12-4795-2012>, 2012a.

601 Allen, R. J., Sherwood, S. C., Norris, J. R., and Zender, C. S.: Recent Northern Hemisphere tropical
602 expansion primarily driven by black carbon and tropospheric ozone. *Nature*, 485(7398), 350–354.
603 <https://doi.org/10.1038/nature11097>, 2012b.

604 Ao, C. O., and Hajj, J. A.: Monitoring the width of the tropical belt with GPS radio occultation
605 measurements, *Geophys. Res. Lett.*, 40, 6236–6241, doi: 10.1002/2013GL058203, 2013.

606 Archer, C. L., and Caldeira, K.: Historical trends in the jet streams. *Geophysical Research Letters*, 35(8).
607 <https://doi.org/10.1029/2008gl033614>, 2008.

608 Aumann, H., Chahine, M., Gautier, C., Goldberg, M., Kalnay, E., McMillin, L., Revercomb, H.,
609 Rosenkranz, P., Smith, W., Staelin, D., Strow, L., and Susskind, J.: AIRS/AMSU/HSB on the aqua mission:
610 design, science objectives, data products, and processing systems. *IEEE Transactions on Geoscience and*
611 *Remote Sensing*, 41(2), 253–264. <https://doi.org/10.1109/tgrs.2002.808356>, 2003.

612 Bai, W., Deng, N., Sun, Y., Du, Q., Xia, J., Wang, X., Meng, X., Zhao, D., Liu, C., Tan, G., Liu, Z., and
613 Liu, X.: Applications of GNSS-RO to Numerical Weather Prediction and Tropical Cyclone Forecast.
614 *Atmosphere*, 11(11), 1204. <https://doi.org/10.3390/atmos11111204>, 2020.

615 Beguería, S., Vicente-Serrano, S. M., Reig, F., and Latorre, B.: Standardized precipitation
616 evapotranspiration index (SPEI) revisited: parameter fitting, evapotranspiration models, tools, datasets and
617 drought monitoring. *International Journal of Climatology*, 34(10), 3001–3023.
618 <https://doi.org/10.1002/joc.3887>, 2013.

619 Calabia, A., and Jin, S.: New Modes and Mechanisms of Long-Term Ionospheric TEC Variations From
620 Global Ionosphere Maps. *Journal of Geophysical Research: Space Physics*, 125(6).
621 <https://doi.org/10.1029/2019ja027703>, 2020.

622 Calabia, A., and Jin, S.: New modes and mechanisms of thermospheric mass density variations from
623 GRACE accelerometers. *Journal of Geophysical Research: Space Physics*, 121(11), 11,191–11,212.
624 <https://doi.org/10.1002/2016ja022594>, 2016.

625 CDAAC: <https://cdaac-ww.cosmic.ucar.edu/cdaac/products.html>, last access: 20 March 2021.

626 Davis, N. A., and Birner, T.: Seasonal to multidecadal variability of the width of the tropical belt. *Journal*
627 *of Geophysical Research: Atmospheres*, 118(14), 7773–7787. <https://doi.org/10.1002/jgrd.50610>, 2013.

628 Davis, S. M., and Rosenlof, K. H.: A Multidiagnostic Intercomparison of Tropical-Width Time Series Using
629 Reanalyses and Satellite Observations. *Journal of Climate*, 25(4), 1061–1078. [https://doi.org/10.1175/jcli-](https://doi.org/10.1175/jcli-d-11-00127.1)
630 [d-11-00127.1](https://doi.org/10.1175/jcli-d-11-00127.1), 2012.

631 Davis, S. M., Hassler, B., and Rosenlof, K. H.: Revisiting ozone measurements as an indicator of tropical
632 width. *Progress in Earth and Planetary Science*, 5(1). <https://doi.org/10.1186/s40645-018-0214-5>, 2018.

633 Foelsche, U., Pirscher, B., Borsche, M., Kirchengast, G., and Wickert, J.: Assessing the Climate Monitoring
634 Utility of Radio Occultation Data: From CHAMP to FORMOSAT-3/COSMIC. *Terrestrial, Atmospheric*
635 *and Oceanic Sciences*, 20(1), 155. [https://doi.org/10.3319/tao.2008.01.14.01\(f3c\)](https://doi.org/10.3319/tao.2008.01.14.01(f3c)), 2009.

636 Fomichev, V. I., Johnson, A. I., de Grandpre', J., Beagley, S. R., McLandress, C., Semeniuk, K., and
637 Shepherd, T. G.: Response of the middle atmosphere to CO₂ doubling: Results from the Canadian middle
638 atmosphere model, *J. Clim.*, 20, 1121– 1144, 2007.

639 Fu, Q., Johanson, C. M., Wallace, J. M., and Reichler, T.: Enhanced mid-latitude tropospheric warming in
640 satellite measurements. *Science* 312, 1179, 2006.

641 Gao, P., Xu, X., and Zhang, X.: Characteristics of the Trends in the Global Tropopause Estimated From
642 COSMIC Radio Occultation Data. *IEEE Transactions on Geoscience and Remote Sensing*, 53(12), 6813–
643 6822. <https://doi.org/10.1109/tgrs.2015.2449338>, 2015.

644 GMAO (Global Modeling and Assimilation Office), MERRA-2 instM_2d_asm_Nx: 2d,Monthly
645 mean,Single-Level,Assimilation,Single-Level Diagnostics V5.12.4, Greenbelt, MD, USA, Goddard Earth
646 Sciences Data and Information Services Center (GES DISC), 10.5067/5ESKGQTZG7FO, 2015.

647 Gnanadesikan, A., and Stouffer, R. J.: Diagnosing atmosphere-ocean general circulation model errors
648 relevant to the terrestrial biosphere using the Köppen climate classification. *Geophysical Research Letters*,
649 33(22). <https://doi.org/10.1029/2006gl028098>, 2006.

650 Grise, K. M., Davis, S. M., Simpson, I. R., Waugh, D. W., Fu, Q., Allen, R. J., Rosenlof, K. H.,
651 Ummenhofer, C. C., Karnauskas, K. B., Maycock, A. C., Quan, X. W., Birner, T., and Staten, P. W.: Recent
652 Tropical Expansion: Natural Variability or Forced Response? *Journal of Climate*, 32(5), 1551–1571.
653 <https://doi.org/10.1175/jcli-d-18-0444.1>, 2019.

654 Hajj, G. A., Ao, C. O., Iijima, B. A., Kuang, D., Kursinski, E. R., Mannucci, A. J., Meehan, T. K., Romans,
655 L. J., de la Torre Juarez, M., and Yunck, T. P.: CHAMP and SAC-C atmospheric occultation results and
656 intercomparisons. *Journal of Geophysical Research: Atmospheres*, 109(D6), n/a.
657 <https://doi.org/10.1029/2003jd003909>, 2004.

658 Harris, I., Osborn, T. J., Jones, P. et al.: Version 4 of the CRU TS monthly high-resolution gridded
659 multivariate climate dataset. *Sci Data* 7, 109: <https://doi.org/10.1038/s41597-020-0453-3>, 2020.

660 Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C.,
661 Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., and Thépaut, J-N.: ERA5 monthly
662 averaged data on pressure levels from 1979 to present. Copernicus Climate Change Service (C3S) Climate
663 Data Store (CDS). 10.24381/cds.6860a573, 2019a.

664 Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C.,
665 Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., and Thépaut, J-N.: ERA5 monthly
666 averaged data on single levels from 1979 to present. Copernicus Climate Change Service (C3S) Climate
667 Data Store (CDS). 10.24381/cds.f17050d7, 2019b.

668 Ho, S. P., Hunt, D., Steiner, A. K., Mannucci, A. J., Kirchengast, G., Gleisner, H., Heise, S., von Engeln,
669 A., Marquardt, C., Sokolovskiy, S., Schreiner, W., Scherllin-Pirscher, B., Ao, C., Wickert, J., Syndergaard,
670 S., Lauritsen, K. B., Leroy, S., Kursinski, E. R., Kuo, Y. H., and Gorbunov, M.: Reproducibility of GPS
671 radio occultation data for climate monitoring: Profile-to-profile inter-comparison of CHAMP climate
672 records 2002 to 2008 from six data centers. *Journal of Geophysical Research: Atmospheres*, 117(D18), n/a.
673 <https://doi.org/10.1029/2012jd017665>, 2012.

674 Holton, J. R., Haynes, P. H., McIntyre, M. E., Douglass, A. R., Rood, R. B., and Pfister, L.: Stratosphere-
675 troposphere exchange, *Rev. Geophys.*, 33(4), 403-439, doi:10.1029/95RG02097, 1995.

676 Hu, Y., and Fu, Q.: Observed poleward expansion of the Hadley circulation since 1979. *Atmospheric
677 Chemistry and Physics*, 7(19), 5229–5236. <https://doi.org/10.5194/acp-7-5229-2007>, 2007.

678 Hu, Y., Zhou, C., and Liu, J.: Observational evidence for poleward expansion of the Hadley circulation.
679 *Advances in Atmospheric Sciences*, 28(1), 33–44. <https://doi.org/10.1007/s00376-010-0032-1>, 2010.

680 Hudson, R. D., Andrade, M. F., Follette, M. B., and Frolov, A. D.: The total ozone field separated into
681 meteorological regimes – Part II: Northern Hemisphere mid-latitude total ozone trends. *Atmospheric
682 Chemistry and Physics*, 6(12), 5183–5191. <https://doi.org/10.5194/acp-6-5183-2006>, 2006.

683 Hudson, R. D., Frolov, A. D., Andrade, M. F., and Follette, M. B.: The Total Ozone Field Separated into
684 Meteorological Regimes. Part I: Defining the Regimes. *Journal of the Atmospheric Sciences*, 60(14), 1669–
685 1677, 2003.

686 Hudson, R. D.: Measurements of the movement of the jet streams at mid-latitudes, in the Northern and
687 Southern Hemispheres, 1979 to 2010. *Atmospheric Chemistry and Physics*, 12(16), 7797–7808.
688 <https://doi.org/10.5194/acp-12-7797-2012>, 2012.

689 Jacobson, A. R., Schuldt, K. N., Miller, J. B., Oda, T., Tans, P., Arlyn Andrews, Mund, J., Ott, L., Collatz,
690 G. J., Aalto, T., Afshar, S., Aikin, K., Aoki, S., Apadula, F., Baier, B., Bergamaschi, P., Beyersdorf, A.,
691 Biraud, S. C., Bollenbacher, A., ... Miroslaw Zimnoch.: CarbonTracker CT2019B. NOAA Global
692 Monitoring Laboratory. <https://doi.org/10.25925/20201008>, 2020.

693 Jin, S., Cardellach, E., and Xie, F.: *GNSS Remote Sensing: Theory, Methods and Applications (Remote
694 Sensing and Digital Image Processing, 19) (2014th ed.)*. Springer, 2013.

695 Jin, S.G., and Park, P.: Strain accumulation in South Korea inferred from GPS measurements, *Earth Planets
696 Space*, 58(5), 529-534, doi: 10.1186/BF03351950, 2006.

697 Jin, S.G., and Zhang, T.: Terrestrial water storage anomalies associated with drought in Southwestern USA
698 derived from GPS observations. *Surv. Geophys.*, 37(6), 1139-1156, doi: 10.1007/s10712-016-9385-z,
699 2016.

700 Jin, S.G., Han, L., and Cho, J.: Lower atmospheric anomalies following the 2008 Wenchuan Earthquake
701 observed by GPS measurements. *J. Atmos. Sol.-Terr. Phys.*, 73(7-8), 810-814, doi:
702 10.1016/j.jastp.2011.01.023, 2011.

703 Jin, S.G., Jin,R., and Kutoglu, H.: Positive and negative ionospheric responses to the March 2015
704 geomagnetic storm from BDS observations. *J. Geodesy*, 91(6), 613-626, doi: 10.1007/s00190-016-0988-4,
705 2017.

706 Kedzierski, R., Matthes, K., and Bumke, K.: New insights into Rossby wave packet properties in the
707 extratropical UTLS using GNSS radio occultations. 10.5194/acp-2020-124, 2020.

708 Kursinski, E. R., Hajj, A. G., Hardy, R. K., Schofield, T. J., and Linfield, R.: Observing the Earth's
709 atmosphere with radio occultation measurements using the Global Positioning System, *J. Geophys. Res.*,
710 102, 23,429–23,465, doi: 10.1029/97JD01569, 1997.

711 Lee, S., and Kim, H.: The Dynamical Relationship between Subtropical and Eddy-Driven Jets. *Journal of*
712 *the Atmospheric Sciences*, 60, 1490-1503, 2003.

713 Li, W., Yuan, Y. B., Chai, Y. J., Liou, Y. A., Ou, J. K., and Zhong, S. M.: Characteristics of the global
714 thermal tropopause derived from multiple radio occultation measurements. *Atmospheric Research*, 185,
715 142–157. <https://doi.org/10.1016/j.atmosres.2016.09.013>, 2017.

716 Meng, L., Liu, J., Tarasick, D. W., Randel, W. J., Steiner, A. K., Wilhelmson, H., Wang, L., and
717 Haimberger, L.: Continuous rise of the tropopause in the Northern Hemisphere over 1980–2020. *Science*
718 *Advances*, 7(45). <https://doi.org/10.1126/sciadv.abi8065>, 2021.

719 Mohd Zali, R., and Mandeep, J. S.: The tropopause height analysis in equatorial region through the GPS-
720 RO. *E3S Web of Conferences*, 76, 04002. <https://doi.org/10.1051/e3sconf/20197604002>, 2019.

721 Munchak, L. A., and Pan, L. L.: Separation of the lapse rate and the cold point tropopauses in the tropics
722 and the resulting impact on cloud top-tropopause relationships. *Journal of Geophysical Research:*
723 *Atmospheres*, 119(13), 7963–7978. <https://doi.org/10.1002/2013jd021189>, 2014.

724 Oscar: <https://www.wmo-sat.info/oscar/gapanalyses?mission=9>, last accessed on 15 August 2020.

725 Pisoft, P., Sacha, P., Polvani, L. M., Añel, J. A., de la Torre, L., Eichinger, R., Foelsche, U., Huszar, P.,
726 Jacobi, C., Karlicky, J., Kuchar, A., Miksovsky, J., Zak, M., and Rieder, H. E.: Stratospheric contraction
727 caused by increasing greenhouse gases. *Environmental Research Letters*, 16(6), 064038.
728 <https://doi.org/10.1088/1748-9326/abfe2b>, 2021.

729 Santer, B. D., Sausen, R., Wigley, T. M. L., Boyle, J. S., AchutaRao, K., Doutriaux, C., Hansen, J. E.,
730 Meehl, G. A., Roeckner, E., Ruedy, R., Schmidt, G., and Taylor, K. E.: Behavior of tropopause height and
731 atmospheric temperature in models, reanalyses, and observations: Decadal changes, *J. Geophys. Res.*, 108,
732 D14002, doi:10.1029/2002JD002258, 2003.

733 Santer, B. D., Wigley, T. M. L., Simmons, A. J., Källberg, P. W., Kelly, G. A., Uppala, S. M., Ammann,
734 C., Boyle, J. S., Brüggemann, W., Doutriaux, C., Fiorino, M., Mears, C., Meehl, G. A., Sausen, R., Taylor,
735 K. E., Washington, W. M., Wehner, M. F., and Wentz, F. J.: Identification of anthropogenic climate change
736 using a second-generation reanalysis. *Journal of Geophysical Research: Atmospheres*, 109(D21), n/a.
737 <https://doi.org/10.1029/2004jd005075>, 2004.

738 Sausen, R., and Santer, B. D.: Use of changes in tropopause height to detect human influences on climate,
739 Meteorol. Z., 12, 131–136, doi:10.1127/0941-2948/2003/0012-0131, 2003.

740 Scherllin-Pirscher, B., Steiner, A. K., Anthes, R. A., Alexander, M. J., Alexander, S. P., Biondi, R., Birner,
741 T., Kim, J., Randel, W. J., Son, S. W., Tsuda, T., and Zeng, Z.: Tropical Temperature Variability in the
742 UTLS: New Insights from GPS Radio Occultation Observations. Journal of Climate, 34(8), 2813–2838.
743 <https://doi.org/10.1175/jcli-d-20-0385.1>, 2021.

744 Schmidt, T., Wickert, J., Beyerle, G., and Heise, S.: Global tropopause height trends estimated from GPS
745 radio occultation data. Geophysical Research Letters, 35(11). <https://doi.org/10.1029/2008gl034012>, 2008.

746 Schmidt, T., Wickert, J., Beyerle, G., and Reigber, C.: Tropical tropopause parameters derived from GPS
747 radio occultation measurements with CHAMP. Journal of Geophysical Research: Atmospheres, 109(D13),
748 n/a. <https://doi.org/10.1029/2004jd004566>, 2004.

749 Seidel, D. J., and Randel, W. J.: Variability and trends in the global tropopause estimated from radiosonde
750 data. Journal of Geophysical Research, 111(D21). <https://doi.org/10.1029/2006jd007363>, 2006.

751 Seidel, D. J., Fu, Q., Randel, W. J., and Reichler, T. J.: Widening of the tropical belt in a changing climate.
752 Nature Geoscience, 1(1), 21–24. <https://doi.org/10.1038/ngeo.2007.38>, 2007.

753 Shangguan, M., Wang, W., and Jin, S.: Variability of temperature and ozone in the upper troposphere and
754 lower stratosphere from multi-satellite observations and reanalysis data. Atmospheric Chemistry and
755 Physics, 19(10), 6659–6679. <https://doi.org/10.5194/acp-19-6659-2019>, 2019.

756 Son, S. W., Tandon, N. F., and Polvani, L. M.: The fine-scale structure of the global tropopause derived
757 from COSMIC GPS radio occultation measurements. Journal of Geophysical Research, 116(D20).
758 <https://doi.org/10.1029/2011jd016030>, 2011.

759 Staten, P. W., Lu, J., Grise, K. M., Davis, S. M., and Birner, T.: Re-examining tropical expansion. Nature
760 Climate Change, 8(9), 768–775. <https://doi.org/10.1038/s41558-018-0246-2>, 2018.

761 Steiner, A. K., Lackner, B. C., Ladstädter, F., Scherllin-Pirscher, B., Foelsche, U., and Kirchengast, G.:
762 GPS radio occultation for climate monitoring and change detection. Radio Science, 46(6).
763 <https://doi.org/10.1029/2010rs004614>, 2011.

764 Sun, Y., Liu, C., Tian, Y., Liu, C., Li, W., Zhao, D., Li, F., Qiao, H., Wang, X., Du, Q., Bai, W., Xia, J.,
765 Cai, Y., Wang, D., Wu, C., and Meng, X.: The Status and Progress of Fengyun-3e GNOS II Mission for
766 GNSS Remote Sensing. 5181-5184. 10.1109/IGARSS.2019.8899319, 2019.

767 Tegtmeier, S., Anstey, J., Davis, S., Dragani, R., Harada, Y., Ivanciu, L., Kedzierski, R., Krüger, K., Legras,
768 B., Long, C., Wang, J., Wargan, K., and Wright, J.: Temperature and tropopause characteristics from
769 reanalyses data in the tropical tropopause layer. Atmospheric Chemistry and Physics. 20. 753-770.
770 10.5194/acp-20-753-2020, 2020.

771 Thuburn, J., and Craig, G. C.: GCM tests of theories for the height of the tropopause, J. Atmos. Sci., 54,
772 869– 882, 1997.

773 Thuburn, J., and Craig, G. C.: Stratospheric influence on tropopause height: The radiative constraint, J.
774 Atmos. Sci., 57, 17– 28, 2000.

775 Vicente-Serrano, S. M., Beguería, S., and López-Moreno, J. I.: A Multiscalar Drought Index Sensitive to
776 Global Warming: The Standardized Precipitation Evapotranspiration Index. *Journal of Climate*, 23(7),
777 1696–1718. <https://doi.org/10.1175/2009jcli2909.1>, 2010.

778 Waliser, D. E., Shi, Z., Lanzante, J. R., and Oort, A. H.: The Hadley circulation: assessing NCEP/NCAR
779 reanalysis and sparse in-situ estimates. *Climate Dynamics*, 15(10), 719–735.
780 <https://doi.org/10.1007/s003820050312>, 1999.

781 Watt-Meyer, O., Frierson, D. M. W., and Fu, Q.: Hemispheric Asymmetry of Tropical Expansion Under
782 CO₂ Forcing. *Geophysical Research Letters*, 46(15), 9231–9240. <https://doi.org/10.1029/2019gl083695>,
783 2019.

784 Wickert, J., Galas, R., Beyerle, G., König, R., and Reigber, C.: GPS ground station data for CHAMP radio
785 occultation measurements. *Physics and Chemistry of the Earth, Part A: Solid Earth and Geodesy*, 26(6–8),
786 503–511. [https://doi.org/10.1016/s1464-1895\(01\)00092-8](https://doi.org/10.1016/s1464-1895(01)00092-8), 2001a.

787 Wickert, J., Michalak, G., Schmidt, T., Beyerle, G., Cheng, C. Z., Healy, S. B., Heise, S., Huang, C. Y.,
788 Jakowski, N., Köhler, W., Mayer, C., Offiler, D., Ozawa, E., Pavelyev, A. G., Rothacher, M., Tapley, B.,
789 and Köhler, C.: GPS Radio Occultation: Results from CHAMP, GRACE and FORMOSAT-3/COSMIC.
790 *Terrestrial, Atmospheric and Oceanic Sciences*, 20(1), 35. [https://doi.org/10.3319/tao.2007.12.26.01\(f3c\)](https://doi.org/10.3319/tao.2007.12.26.01(f3c)),
791 2009.

792 Wickert, J., Reigber, C., Beyerle, G., König, R., Marquardt, C., Schmidt, T., Grunwaldt, L., Galas, R.,
793 Meehan, T. K., Melbourne, W. G., and Hocke, K.: Atmosphere sounding by GPS radio occultation: First
794 results from CHAMP. *Geophysical Research Letters*, 28(17), 3263–3266.
795 <https://doi.org/10.1029/2001gl013117>, 2001b.

796 Wickert, J., Schmidt, T., Beyerle, G., König, R., Reigber, C., and Jakowski, N.: The Radio Occultation
797 Experiment aboard CHAMP: Operational Data Analysis and Validation of Vertical Atmospheric Profiles.
798 *Journal of the Meteorological Society of Japan. Ser. II*, 82(1B), 381–395.
799 <https://doi.org/10.2151/jmsj.2004.381>, 2004.

800 WMO: Meteorology—A three dimensional science: Second session of the commission for aerology.
801 Geneva: World Meteorological Organization (WMO). (WMO Bull. No. 4), 1957.

802 Wu, X. R., and Jin, S.G.: GNSS-Reflectometry: Forest canopies polarization scattering properties and
803 modeling, *Adv. Space Res.*, 54(5), 863-870, doi: 10.1016/j.asr.2014.02.007, 2014.

804 Xia, P., Ye, S., Jiang, K., and Chen, D.: Estimation and evaluation of COSMIC radio occultation excess
805 phase using undifferenced measurements. *Atmospheric Measurement Techniques*, 10(5), 1813–1821.
806 <https://doi.org/10.5194/amt-10-1813-2017>, 2017.

807 Xian, T., Lu, G., Zhang, H., Wang, Y., Xiong, S., Yi, Q., Yang, J., and Lyu, F.: Implications of GNSS-
808 Inferred Tropopause Altitude Associated with Terrestrial Gamma-ray Flashes. *Remote Sensing*, 13(10),
809 1939. <https://doi.org/10.3390/rs13101939>, 2021.

810 Zhou, Y. P., Xu, K. M., Sud, Y. C., and Betts, A. K.: Recent trends of the tropical hydrological cycle
811 inferred from Global Precipitation Climatology Project and International Satellite Cloud Climatology
812 Project data. *Journal of Geophysical Research*, 116(D9). <https://doi.org/10.1029/2010jd015197>, 2011.