Dear Referee_2

Thank you very much for your valuable comments

We replied the comments one by one in its order: -

Major comments

Referee comment: -

1) The data of the atmospheric profiles came from very different GNSS-RO sources (Fig 1) and different time of missions. It means that accuracy, data time-rate, region of the atmosphere under RO-sounding very differ from one source (mission) to another. In turn, it may bring uncertainties and mistakes in the long lasting data interpreting. I would recommend to the authors to add correspondent explanation in Section 2 and in Conclusion section.

Answer: -

In several previous studies, multiple GNSS-RO missions were utilized together for the purpose of obtaining high spatial resolution. In addition, the assessment of using different GNSS-RO missions together showed high level of consistency (Hajj et al., 2004; Li et al., 2017; Tegtmeier et al., 2020; Xian et al., 2021).

We added clarification and explanation about the validity of using multi GNSS-RO missions together in our paper methodology, results and conclusion sections.

"In our study, the atmospheric profiles, from all used GNSS-RO missions, are compared to signify the high level of consistency and compatibility between RO missions available on the COSMIC Data Analysis and Archive Center (CDAAC) web, also the ability to merge them together in our study as a single dataset. COSMIC mission profiles are used as a fixed member in the intercomparison of all utilized RO missions as it is the most abundant regarding to profiles density and its time span make overlap with all other missions. Although the compared profiles are collocated within 3h time spacing and 230 km spatial spacing, the results of the conducted intercomparison show high agreement and consistency between profiles of collocated pairs. The following table and figure demonstrate the results of the collocated GNSS profile pairs. The correlation coefficient ranges from 0.97 to 0.99 and the mean of differences of temperature values between the collocated profile pairs ranges from 0.1 to 0.5 K."

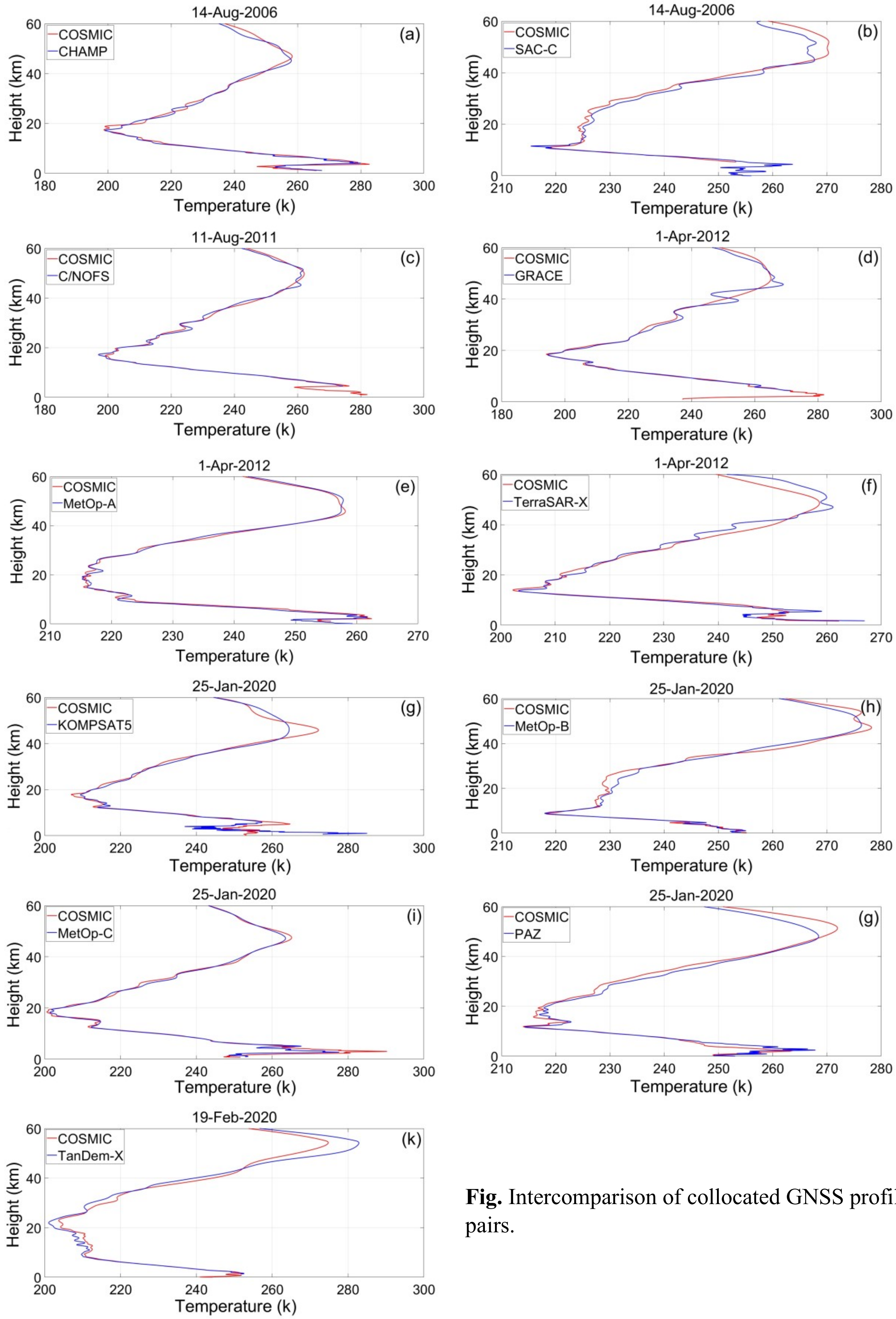

Fig. Intercomparison of collocated GNSS profile pairs.

Table. Results of the 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

Referee comment: -

2) In my opinion, there is luck of discussion of Fig 2-10. There is only list of facts with no even minimal comments. I suppose that minimal discussion for each figure is necessary, something like this: the results on Fig correspond (or contradict) to the physical model of the process (or the known results [Reference 1, Reference 2 et al.]). It can be explained by….. et al.

Answer: -

>>Done

We added more comments and detailed discussions for all figures to illustrate the results and draw a good conclusion about our study findings.

Referee comment: -

3) In my opinion Conclusion section should consist of more detailed explanation of the unfolded trends in the tropopause height increasing. This is the main results of the manuscript which is important in the global weather forecast.

Answer: -

We modified the conclusion to contain more in-depth details about our study results and findings.

Conclusions:

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

In most of the previous studies, the reported tropics widening rates range from 0.25° to 3.0° latitude/decade and their statistical significance vary by large amount based on the metrics used to estimate the TEL as well as the data sets utilized for its derivation (Davis and Rosenlof, 2012). In our study, TEL at each hemisphere is estimated using two tropopause height metrics. Applying the first method, subjective criterion, there are higher expansion and contraction rates than that from the second method, objective criterion. While using the objective criterion, the locations of TEL at both hemispheres are more poleward than that from the subjective criterion. Based on the subjective method, tropical width results from GNSS-RO have an expansive behavior in the NH with about 0.41°/decade, and a minor expansion trend in the SH with 0.08°/decade. ERA5 has non-significant contraction in both hemispheres. In case of the AIRS data, there is a clear expansion behavior in the NH with about 0.34°/decade, and a strong contraction in the SH with about -0.48°/decade. Based on the objective method, GNSS-RO has an expansion behavior in the NH with about 0.13°/decade, but there is no significant expansion or contraction in the SH. Results of several studies, based on different data sets and metrics, shown an expansive behavior of tropical belt in NH higher than that of SH and this broadly agree with our GNSS-RO based results (Hu and Fu, 2007; Archer and Caldeira, 2008; Hu et al., 2010; Zhou et al., 2011; Allen et al., 2012). For ERA5, there is no significant trend for the TEL results in the NH, while there is a minor contraction of about -

0.08°/decade in the SH. The AIRS data show an expansion in the NH with 0.13°/decade, and strong contraction in SH with -0.37°/decade. From all data sets, the TEL is located more poleward in the NH than in the SH. For both subjective and objective methods, the TELs reach the latitudes of 44.75°N and 46.75°N, respectively, at the NH. Meanwhile, at the SH the TELs reach the latitudes of 42°S and 44.75°S for subjective and objective methods, respectively. In both hemispheres, the variability of tropopause parameters (temperature and height) is maximum around the TEL locations.

The TCO shows increasing rates globally. The rate in the SH is higher than that of the NH. The ozone variability agrees well with the spatial and temporal modes of TEL estimated from GNSS-RO LRT height and this supports GNSS-RO TEL estimates over that of ERA5 and AIRS. In addition, CO2 and CH4, as the main GHGs responsible for global warming, concentrations increase cause a tropopause height rise (Meng et al., 2021; Pisoft et al., 2021). In our analysis, both CO2 and CH4 show a global increasing rate. Their upward trends at the NH and the SH are nearly the same. The patterns of TCO and CO2 display good agreement with the TELs locations at NH and SH. They show more poleward occurrence with time and their variability in NH is higher than that of SH. In addition, CH4 has signal at NH occurs more poleward than that at SH. The surface temperature and the precipitation both increase with time, and have strong correlation with LRT height. Both variables show an increasing rate at the NH higher than at the SH. The surface temperature shows strong spatial variability pattern that broadly agrees with the TEL locations from GNSS-RO. The spatial pattern of precipitation shows northward orientation. The SPEI meteorological drought index shows increasing rate globally. The NH shows increasing trend while SH shows decreasing trend. Since SPEI is multivariate, it has no direct response to the TEL behavior. In both hemispheres, the number of cells covered with drought decreased since 2001. It can be concluded 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 of SH. Furthermore, the variability of meteorological parameters agrees with GNSS TEL results more than with that of other data sets. The study results signify the importance of monitoring the tropopause and TEL parameters which can accurately indicate the climate variability and climate change globally.

Minor comments

Referee comment: -

1) Abstract: In my opinion Abstract is very long and difficult to catch the main idea of the research. All the numerical evaluations and its short discussion should be in the main text, but not in abstract. Abstract should be short and clear for readers. It should consists of following points: motivation; general list of means of data treatment (or theoretical analysis), experiment environment et al; main results and its novelty declaration comparing to the known results.

Answer: -

We modified the abstract to be short clear and more indicative about the study goal, data sets, methods, results and research conclusion.

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 increase of approximately 36 m/decade and 60 m/decade, respectively. The tropical edge latitudes (TELs) are estimated based on two tropopause height metrics, subjective and objective methods. Applying both metrics, the determined TELs 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 at both hemispheres. Moreover, the spatial and temporal patterns of total column ozone (TCO) have good agreement with the TELs 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 at 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 of SH. Furthermore, the variability of meteorological parameters agrees with GNSS TEL results more than with that of other data sets.

Referee comment: -

2) Line 72 and Line 74: What do these "…reanalyses trends…" and "…different reanalyses…" mean?

Answer: -

In our study, the type of the used reanalyses data are atmospheric reanalyses that are generated through the assimilation of the historical atmospheric observational data spanning an extended period, using a single consistent assimilation (analysis) scheme throughout.

Examples for the atmospheric reanalyses datasets:

- ECMWF Reanalysis v5 (ERA5)
- The Modern-Era Retrospective analysis for Research and Applications v2 (MERRA-2)
- National Centers for Environmental Prediction and the National Center for Atmospheric Research (NCEP/NCAR)
- Japanese 25-year ReAnalysis (JRA-25) & the Japanese 55-year Reanalysis (JRA-55)
- ECMWF re-analysis of meteorological observations from September 1957 to August 2002 (ERA-40)

- The reanalyses trends are the trends of any geophysical parameter from different reanalyses datasets. These trends can be biased to reflect changes in both the quality as well as the quantity of the underlying data (Schmidt et al., 2004; Ao and Hajj, 2013).

Referee comment: -

3) Line 236: Please check and correct it: "…is no significant correlation 0.21…".

Answer: -

>>Done

We modified it to be ["There is a correlation of about 0.66 between LRT and CPT height"].

Referee comment: -

4) Line 241: "global increasing trend of LRT height 241 of 36 m/decade". Looking at the Fig 2 I see this trend for CPT but not for LPT. Please check it.

Answer: -

>>Done

We checked it and found it to be correct:
Our analysis shows global increasing trend of LRT height of 36 m/decade since 2001 and global upward trend of CPT height of 60 m/decade since 2001.

Referee comment: -

5) Line 483: What do you mean here: "there is no significant signal in the…"?

Answer: -

We mean that there is no observed trend showing any expansion or contraction for the tropical belt using ERA5 data in the NH.

>>We modified it to be ["For ERA5, there is no significant trend for the TEL results in the NH,"]

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