Dear Referee_1

Thank you very much for your valuable comments

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

Referee comment: -

The authors did a good job in the first part. However, the second part is not well done. The authors may just focus on the first part. If they are also interested in exploring the underlying mechanisms for the tropical belt widening, a much in-depth study is required.

Answer: -

Our study main objective is the determination of tropical belt possible expansion using multiple GNSS Radio Occultation (GNSS-RO) measurements. So, we widely focused on the widening rates and their spatial and temporal patterns as the main point of our research. For the purpose of deep understanding of our work results, we investigated the modes and trends of Carbon dioxide (CO2) and Methane (CH4) as the main greenhouse gases (GHGs) responsible for global warming and climate variability. In addition, we studied the total column ozone (TCO) pattern which inversely proportion with tropopause height and can give indication about the tropical belt width (Hudson et al., 2003; Hudson et al., 2006; Hudson, 2012; Davis et al., 2018). Moreover, surface temperature, precipitation and meteorological drought are investigated as meteorological parameters that their spatial and temporal patterns may change as a result of the expanding or contracting tropics.

In our next papers, we are planning to extend our research about tropical belt to include the mechanisms and drivers of tropical belt width variability. Moreover, the implications of tropics widening and/or contraction on many subtropical regions will be clarified. Finally, the future projection of the tropical edge latitude locations and trends until 2100 will be widely studied.

Referee comment: -

In the first part, the authors only presented the results from GNSS RO satellite, AIRS, and ERA5. There is lack of in-depth discussion on these results. For example, **(a)** why the results are different, **(b)** which one is more reliable, **(c)** what the advantages and limitations for each dataset is, **(d)** how your results compare with literature…

Answer: -

(a)

In most of 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 tropical edge latitude (TEL) as well as the data sets utilized for its derivation. In addition, the used metrics may respond in different ways to the force driving the widening because of their differing physics (Davis and Rosenlof, 2012) ***[L48-L52]***. There are several indicators that define the boundaries of the tropical belt. Generally, three main classes of metrics are employed to estimate the tropical belt borders: circulation-based metrics (e.g., based on the Hadley cells and the subtropical jets), temperature-based metrics (e.g., based on tropopause characteristics), and surface climate metrics (e.g., based on precipitation and surface winds) (Waliser et al., 1999). The common metrics used for TEL determination are discussed in details in (Staten et al., 2018; Adam et al., 2018). TELs estimated applying different metrics not all necessarily yield the same location. Their positions vary by much larger amounts and much more rapidly and unpredictably than the astronomically defined tropics (Lee and Kim, 2003) ***[L59-L67]***.

(b)

In our analysis the most reliable TEL results are that based on GNSS-RO data because, in this study, the TELs were determined based on two tropopause height metrics and GNSS-RO can provide high accuracy remote sensing observations of the thermal structure of the tropopause and was used to investigate the trend and variability of the tropopause (Son et al., 2011). Among the most outstanding advantages of GNSS-RO are their high accuracy of 0.2–0.5 K in estimating temperature in the UTLS region and vertical resolution of 200 m. These advantages make GNSS-RO especially appropriate to detect the possible tropical belt widening based on the height metrics of the tropopause (Kursinski et al., 1997; Ho et al., 2012). Using tropopause metrics for TEL determination have many advantages because they can be accurately estimated from remotely sensed temperature profiles with sufficient vertical resolution, such as GNSS-RO profiles (Davis and Birner, 2013; Seidel and Randel, 2006) ***[L122-L130]***. A number of studies confirmed the feasibility and excellent eligibility of GNSS-RO measurements for monitoring the atmosphere and for climate change detection (Foelsche et al., 2009; Steiner et al., 2011) ***[L86-L88]***.

(c)

The advantages of the using AIRS and ERA5 data are the good global spatial resolution and being gridded in regular spatial grid over fixed time span. But they suffer from low vertical resolution. Furthermore, reanalyses trends can be biased to reflect changes in both the quality as well as the quantity of the underlying data and the expansion rates computed from different reanalyses were considerably different (Schmidt et al., 2004; Ao and Hajj, 2013). Nowadays, Global navigation satellite systems (GNSS) have provided an exceptional opportunity to retrieve land surface and atmospheric parameters globally (e.g., Jin and Park, 2006; Jin and Zhang, 2016; Wu and Jin, 2014; Jin et al., 2011, 2017), particularly space-borne GNSS Radio Occultation (GNSS-RO) because GNSS-RO has long-term stability and works in all-weather-conditions, which make it a powerful tool for studying climate variability. Since GNSS-RO has uniform global coverage, it covers all locations even at the polar regions and oceans, which are blind zones of other detection systems such as radiosonde (RS) and radar. Moreover, GNSS-RO observations vertically finer resolved than any of the existing satellite temperature measurements available for the upper-troposphere lower-stratosphere (UTLS) thus GNSS-RO is well suited for this challenge. Moreover, it is a key component for a broad range of other studies, including equatorial waves, Kelvin waves, gravity waves, Rossby and mixed Rossby–gravity waves, and thermal tides (Bai et al., 2020; Scherllin-Pirscher et al., 2021) ***[L71-L86]***.

(d)

There is no universal definition of the TEL that is applicable across all datasets; each sees the transition zone between tropics and subtropics in a different way. So, the responses of the used metrics show different sensitivities. Regarding to previous studies about the tropical belt widening most of them showed widening rates ranging from 0.25°/decade to 3°/decade. It is not clear to what extent this range reflects inherent differences in differing aspects of the circulation and its drivers, versus the use of different reanalyses, datasets, time periods, and details of tropical edge definitions.

Hudson et al. (2006) analyzed satellite observations of atmospheric ozone concentrations, focusing on the well-known distinction between the tropical regions, where total column ozone concentration is relatively low, and extratropical regions, where it is higher. Their analysis indicates that the area of the northern hemisphere occupied by the tropical region grew during the 25-year period at a rate of 1°/per decade. Using independent set of satellite-based microwave observations of atmospheric temperature, Fu et al. (2006) inferred tropical-belt widening for the period 1979–2005. Noting that stratospheric cooling and tropospheric warming trends are stronger in the 15–45-degree latitude belts of both hemispheres, they estimate a net widening of the tropical belt of about 2° latitude. A third approach, by Seidel and Randel (2007), based on RS and reanalysis data using tropopause height changes in the subtropics to estimate changes in the width of the tropics. they report an expansion of 5 to 8 degrees latitude during 1979–2005. Using two other types of observations, atmospheric reanalysis and satellite observations of outgoing longwave radiation emitted by the Earth, Hu and Fu (2007) also found a widening of the tropical Hadley circulation system, and estimate its magnitude as 2° to 4.5° latitude during period from 1979 to 2005. Ao and Hajj (2013) used GPS RO data over the period 2002 to 2011 and analyzed it to examine the possible expansion of the tropical belt due to climate change. Analysis showed that a statistically significant widening trend 1°/decade was found in the Northern Hemisphere (NH) while in Southern Hemisphere (SH) no statistically significant trends were found.

The different used metrics for determination of tropical belt width and the results of expansion and/or contraction of most of previous work are discussed in details in Davis and Rosenlof (2012); Lucas et al. (2014); Staten et al. (2018) & Adam et al. (2018).

Referee comment: -

In the second part, **(a)** the authors presented time series for a variable of interested, and its PC1 time series and spatial distribution. They also calculated correlation coefficients between tropopause height and that variable. However, it is unclear how these analyses related to the tropical belt widening. The discussion is rather superficial. **(b)** It is hard to understand what the authors' points. For example, how precipitation is connected to the tropical belt widening?

Answer: -

(a)

We studied the trends, spatial modes and temporal patterns for many parameters [*Carbon dioxide (CO_2), Methane (CH_4), total column ozone (TCO), surface temperature, precipitation and meteorological drought*]. In addition, we calculated the correlation coefficient between lapse rate tropopause (LRT) height and these meteorological variables and these analyses have a strong relation with the tropical belt widening as the tropical edge latitudes (TELs) are determined based on two tropopause height metrics.

In our analyses the pattern of Carbon dioxide (CO_2) and Methane (CH_4) as the main greenhouse gases (GHGs) responsible for global warming were investigated as proposed drivers for the tropical edge latitudes (TELs) poleward or equatorward shift. Total column ozone (TCO) was utilized to emphasize the tropopause height results and ensure the TELs locations as it can be used as independent metric for TEL calculation. Moreover, surface temperature, precipitation and meteorological drought were used to clarify the implications of the tropical belt width variability along the study period.

(b)

As clear from our paper title, our main interest is the determination of the tropical belt possible expansion using multiple GNSS-RO missions. As we stated before, the precipitation spatial and temporal variability is investigated to examine the impacts of the tropical belt expansion/contraction on the precipitation behavior. is this expansion/contraction associated with a change of the precipitation amount and/or behavior?

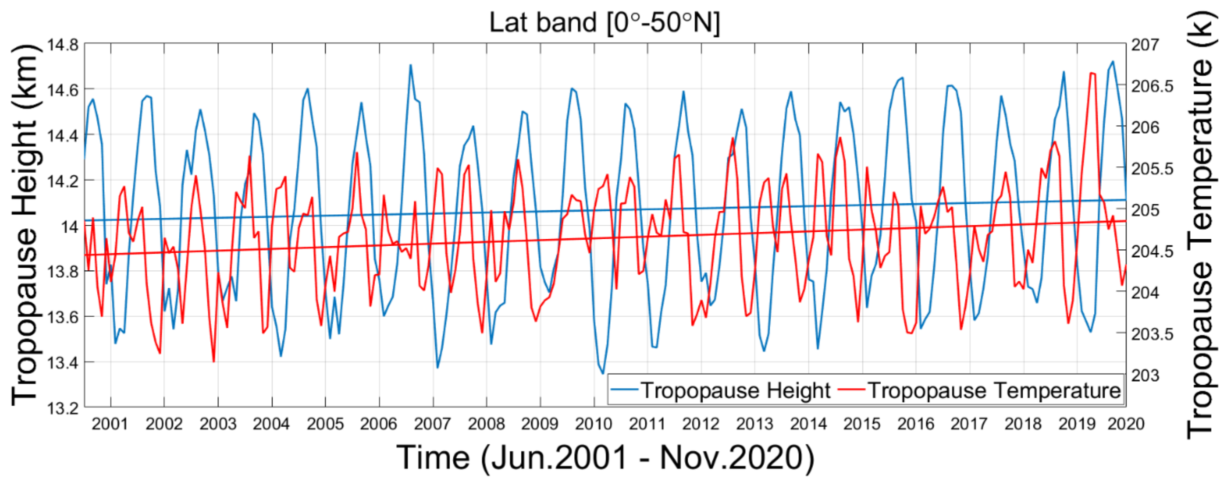
Furthermore, the precipitation can be used as an independent metric in signifying the TELs locations. Many studies, rely upon surface-based variables to investigate tropical widening, used the Global Precipitation Climatology Project (GPCP) monthly dataset to examine shifts in the positions and boundaries of the subtropical dry zones (Hu et al., 2010; Zhou et al., 2011; Allen et al., 2012).

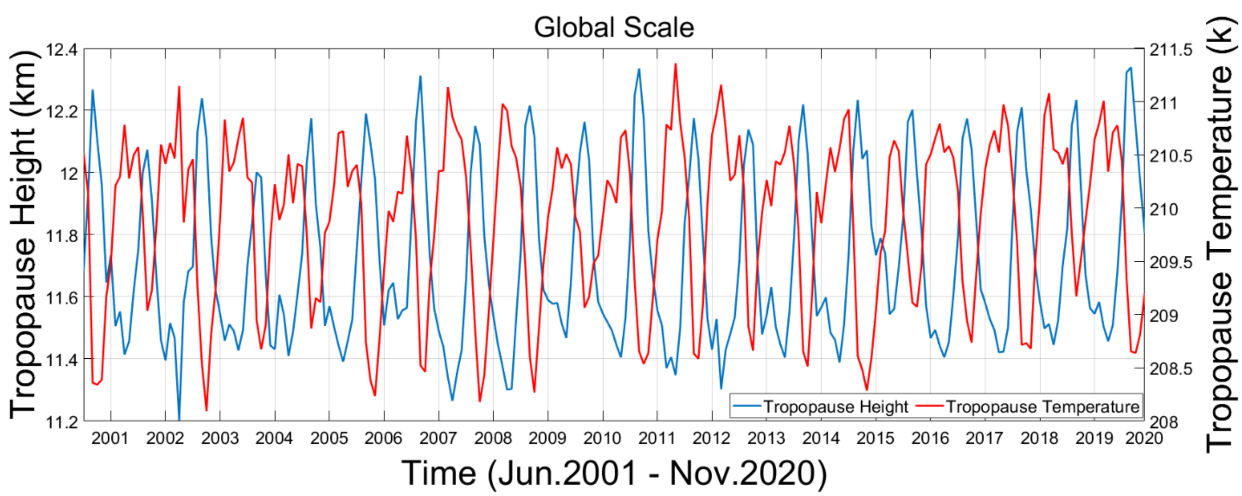
Referee comment: -

In section 3.3, the authors stated that LRT temperature shows an increasing trend in both hemisphere during the study period. This is strange for the northern hemisphere where tropopause height shows an increasing trend. As known, if tropopause height increases, tropopause temperature generally decreases.

Answer: -

In section 3.3, for northern hemisphere (NH), both LRT height and temperature have increasing trends along the study period and such results do not contradict with the fact that tropopause height and temperature inversely proportion. The following figures show that there is no conflict in having upward trends for both LRT height and temperature at NH and globally. As clear from the following figures especially that of the whole globe, when the LRT height is high (peak) the LRT temperature is low (trough) and vice versa. The inverse proportion between both can be indicated by the high negative correlation of about -0.78 ***[L241-L244]***.





Referee comment: -

In section 3.5, the authors stated that the correlation coefficient between the surface temperature and the GNSS RO LRT tropopause height is 0.81. **(a)** Is this high correlation possible? **(b)** How is this value calculated? **(c)** How is this value compared with that in the literature?

Answer: -

(a)

Yes, this high correlation between surface temperature and the GNSS RO LRT height is possible. The results of surface temperature have good accordance with the LRT height results and, as a result, with TEL patterns. Hence, these findings support surface temperature as a proposed driver for tropics expansion (Allen et al., 2012; Adam et al., 2014).

(b)

The correlation coefficient between the surface temperature and the GNSS RO LRT tropopause height is calculated using global monthly average time series of both variables.

(c)

Several studies revealed the relation of the surface temperature with the tropopause height and tropical belt expansion. Thuburn and Craig (1997, 2000) used an atmospheric General Circulation Model (GCM) to examine different theories regarding the key factors determining tropopause height. They found the simulated tropopause height to be sensitive to surface temperature. Gao et al. (2015) signified that the correlation coefficient between global tropopause height anomalies and the Niño 3.4 sea surface temperature index is 0.53, with a maximum correlation coefficient of 0.8 at a lag of three months. Fomichev et al. (2007) also found that an increase in sea surface temperature resulted in a tropopause height increase in a coupled chemistry climate model simulation. Hu and Fu (2006) suggested that an increase in sea surface temperatures in the tropics could result in an increase in the tropopause height and a wider Hadley Circulation (tropics width). In addition, our results support surface temperature as a proposed driver for tropics expansion (Allen et al., 2012; Adam et al., 2014).

Specific

L33, replace “pole ward” to “poleward”, the same as for the remaining manuscript.

>>Done

L37-38, please add a statement on what this means to TEL.

>>Done

L50, TEL first appears in the text.

>>Done

L64, it should be in Staten et al. (2018) and Adm et al. (2018). The same format applies for the remaining text.

>>Done

L70, RS first appears in the text

>>Done

L90, LEO first appears here and is defined in L97

>>Done

L98 and L113, remove “, and ”, respectively.

>>Done

L218-219, what is this function? Is it an area weighted average?

>> The zonal average LRT height was spline interpolated as a function of latitude.

L275, “figure 4” should be “Figure 4”. The same applies for the text throughout. For example, in L318, it should be Figure 6 and Table 2

>>Done

L321, “On the other side”? this is used a few times, it may not be a correct expression.

>>Done

L322, “capture” is not a suitable word to use here.

>>Done

L408, “Precipitation” should be “precipitation”, the same for L410

>>Done

L473, L476, L478, “For the subjective method”, “for the AIRS data,”, “In case of objective method”, … These are not good expressions. The authors may use different expressions; for example, “based on the subjective method” is better.

>>Done

Fig. 7, use different letters for the subplots. Two figures (c) are too small.

>>The subplots are arranged in two columns; the left is LRT height and the right is LRT temperature. Done.

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