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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Characteristics of the tropical tropopause inversion layer using high-resolution temperature profiles retrieved from COSMIC GNSS Radio Occultation" *by* Noersomadi Noersomadi et al.

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Reply to the comments by the Reviewer #1

This is a welcome study about the tropical TIL (a region where TIL literature is relatively sparse) and how ENSO and the MJO influence it. The manuscript is well organized and well written, presenting several novel results. I only see one important weakness before it can be published (see major comments 1-3), related to the amount of detail when the authors discuss their results, and how they fit/compare to previous works.

Once this has been overcome, it will definitely be worthy of publication in ACP. I hope the comments included below are helpful for this purpose.

We deeply appreciate the reviewer for providing constructive comments and suggestions to our manuscript. We show below our responses to the individual comments.

Major comments ### ## 1 # Amount of detail in the result sections. The text within your first result sections (3.1, 3.2, 3.3) could be shortened. Most of the results presented there basically agree with previous findings by Grise et al. (2010), Son et al. (2011), Kim and Son (2012), Pilch Kedzierski et al. (2016) or Randel et al. (2007) in their latitude or zonal structures and their seasonality. There are very little main results in these subsections that are really new, so one can move on quicker. Things get way more interesting in sections 3.4 and 3.5, I see lots of novel material. However all is discussed in a hurry compared to the previous result sections. The discussion of the results in sections 3.4 and 3.5 should be extended, because this is the most important and novel part of your study. Related to this, see Major comment 2.

We agree with the reviewer. We have shortened the text particularly section 3.1 by focusing on the N2 distribution in the tropics. We show latitude-height cross section of N2 during the two seasons both in the MC and PO and longitude-height cross section relative to CPT. We have modified sections 3.2 and 3.3 by following the suggestions by the reviewer (see below for the details). We have extended discussion in sections 3.4 and 3.5, adding the diagram of S-ab versus OLR in section 3.5 (see also below for the details).

2 # Referencing and highlighting what's new. Throughout the results sections I too often don't see what exactly is new and what agrees with previous studies. I'll go section by section here.

-Introduction: p.2 l.11: more appropriate references are Birner (2006) and Grise et al. (2010), in the sense that they look at the TIL in a global sense, including the tropics. Perhaps also keep Birner et al. (2002) as the first one about the TIL, but the most relevant to introduce your study are the two from above. We add the following statements in P2 L12-16: "Using routine radiosonde sounding data, a strong mean inversion at the tropopause in the midlatitude was analyzed (Birner et al., 2002; Birner, 2006). Grise et al. (2010) conducted a global survey of the TIL characteristics, including annual cycle, horizontal distribution and interannual variations related to the stratospheric Quasi Biennial Oscillation (QBO) using the Global Positioning System Radio Occultation (GPS-RO) data." We also add the statements citing Birner (2006) and Grise et al. (2010) in P2 L23-26. "Birner (2006) found that the mean N2 shows enhanced values near the extratropical tropopause compared to the extratropical lower stratosphere. Furthermore, Grise et al. (2010) found the largest magnitudes of N2 between $10^{\circ}-15^{\circ}$ latitude in both hemisphere during northern hemisphere (NH) winter season."

p.2 l.15-20: Randel and Wu (2005) studied Kelvin waves from GPS-RO and how they affect the zonal structures of tropopause height and the surrounding T structures. Should be included among Tsuda et al. (1994). We follow suggestion by the reviewer and add the following statement in P2 L32-33: "Randel and Wu (2005) demonstrated eastward phase tilt with height of Kelvin waves that modulate the climatological cold tropopause over Indonesia with the maximum amplitude near the tropical tropopause ($\sim$17 km)."

p.2 l.40: I really miss references to Grise et al. (2010) within this paragraph. We add Grise et al. (2010) following suggestion by the reviewer in P3 L17.

-Paragraph in p.4 l.30, and paragraph in p.6 l.30: Grise et al. (2010) did a comparison of LRT and CPT - relative N2 profiles (Their Fig. 2). You should discuss and compare your results to theirs. We add the following sentences in P6 L23-26: "We found the maxN2 at range $11-12.0 \times 10-4$ s-2 above CPT height in the two longitude regions. Note that Grise et al. (2010) reported that the zonal mean maxN2 value above the LRT and CPT heights was $\sim 8.0 \times 10-4$ s-2 using the CHAMP dataset (see fig.2 in Grise et al., 2010). The different larger values found in this study are probably due to the use of data of higher effective vertical resolution."

-Paragraph in p.6 l.40: I miss a discussion with Randel and Wu (2005), Kim and Son (2012) and Pilch Kedzierski et al. (2016) comparing your results to the modulation of the tropopause by Kelvin waves, MJO and other equatorial waves presented in those studies. We add the following sentences in P6 L30-34: “The results shown in Fig. 3 uncover the detail structure of N2 above CPT in the specific longitude regions compared to the results by Grise et al. (2010) that showed the mean N2 over 0−1 km layer above LRT. The vertical propagation of equatorial waves (Kelvin waves and/or gravity waves), as the results of convective forcing, modulates the tropopause (Tsuda et al., 1994; Randel and Wu, 2005; Kim and Alexander, 2015; Kim et al., 2018). The MJO activity was also found to control the tropopause variability (Kim and Son, 2012; Pilch Kedzierski et al., 2016).”

-p.7 l.30: you should compare your S-ab histograms to the ones of TP sharpness in Pilch Kedzierski et al. (2016). Although they use N2max there, this measure is comparable to yours since N2min below TP is always very low and N2max would dominate your distribution of S-ab. We add the following sentences in P7 L16-19: “The positive skewness distribution of S-ab is found to be similar to the results by Pilch Kedzierski et al. (2016) for maxN2+1 above LRT for both easterly and westerly QBO periods. This is reasonable since maxN2+1 above CPT would dominate the relatively low values of minN2−1 below CPT, showing similar features to those of S-ab.”

-Section 3.3: discussion with Grise et al. (2010), Pilch Kedzierski et al. (2016), Son et al. (2011), Kim and Son (2012)... is completely missing. These studies show horizontal structures of TP sharpness and its seasonality. Also, note that S-ab is centered around the Equator, while your convective activity by OLR is not, so how can you leave out modulation by equatorial waves out of the discussion? (convectively coupled or not, the amplitudes of eq. waves by definition maximize there) We add the following statements in P7 L41 – P8 L6: “Large S-ab values are found along in the equator region, while low OLR regions show latitudinal variation with season. Local and seasonal variability of horizontal structure of tropopause sharpness presented in this work is consistent with previous studies which attributed it to equatorial waves activity (e.g. Grise et al., 2010; Son et al., 2011; Kim and Son, 2012). However, we found different quantitative results in particular over the Western Pacific because of the use of maxN2+1 and minN2–1 instead of averaging N2 within ±1 km relative to CPT by Kim and Son (2012), and also because of the use of data of higher effective vertical resolution. Maximum static stability just above the tropical tropopause could also be associated with divergence flow as demonstrated by Pilch Kedzierski et al. (2016)."

-Section 3.5: discuss your results comparing to Zeng et al. (2012), Kim and Son (2012) and Pilch Kedzierski et al. (2016), who all showed how MJO modulates the tropopause zonal structures, sharpness or T structure within the TTL with the use of COSMIC GPS-RO. We add the following sentences in P10 L30-36: "Zeng et al. (2012) demonstrated cold temperature anomaly observed with COSMIC near the tropopause associated with rainfall anomaly during MJO active phase propagation. Kim and Son (2012) and Pilch Kedzierski et al. (2016) also found MJO signal modulates the tropopause temperature and sharpness structure using COSMIC temperature data. We found that the MJO propagation in the tropics has an impact on the variability in tropopause sharpness, being consistent with the results by Pilch Kedzierski et al. (2016). Note that, we demonstrated time evolution of positive sharpness anomaly associated with negative OLR anomaly, which is not shown in the previous studies (Kim and Son, 2012; Pilch Kedzierski et al., 2016)."

3

TIL sharpening by convection. Throughout the manuscript I find that discussions could be improved about how convection may sharpen the TIL. See Holloway and Neelin (2007), Paulik and Birner (2012) and Kim et al. (2018) for a detailed mechanism for tropopause cooling/sharpening by convection. A reference to these should be included in your manuscript. We add the sentences in P11 L2 – 7: It is well known that vertical structure of temperature perturbations associated with deep convection indicate warm anomaly in the middle and upper troposphere and cold anomaly near the tropopause (e.g. Holloway and Neelin, 2007; Paulik and Birner, 2012). Adiabatic cooling near the tropopause is a natural response to the diabatic warming due to convection as a result of hydrostatic adjustment (Holloway and Neelin, 2007). Kim et al. (2018) hypothesized that cold anomaly near the tropopause associated with organized deep convection during the MJO active phase is due to dehydration processes.

We also add some statements in the introduction referring to the paper suggested by the reviewer in P2 L42 – P3 L4: "Holloway and Neelin (2007) found negative correlation of temperature perturbations between the free troposphere (about 800 – 200 hPa) and the convective cold top (about 100 – 50 hPa). The cooling in the convective cold top is due to a hydrostatic adjustment to the deep convective heating (Holloway and Neelin, 2007). Paulik and Birner (2012) identified typical temperature perturbations in the deep convective cloud associated with reduced ozone event, warm anomaly in the mid and upper troposphere, and cold anomaly in the tropical tropopause layer (TTL). We are also interested in the characteristics of static stability in the TTL associated with the convective activity."

Also, I suggest to make a plot, for both PO and MC regions, showing a diagram of OLR versus S-ab of individual collocated RO profiles (e.g. in the same grid and day), similar to the diagram of Randel and Wu (2007) with rel. vorticity -vs- TP sharpness. In principle it should show increased S-ab with lower OLR values, at any region. With this you could link the convective influence on the TIL across different timescales (seasonal, MJO, ENSO) and it would be a great complement to figures 10-15 which are climatologies or monthly means. Thank you very much for your suggestion. We have created the following diagrams of OLR versus S-ab as Fig.14 for the revised manuscript, and add the following sentences in P11 L10-17.

Figure 14 Diagrams of S-ab versus OLR (top), and of the number of samples for S-ab and OLR (middle and bottom, respectively) in the MC (left) and PO (right) regions.

The added text: "To show the relationship between the convective activity and tropopause sharpness in the MC and PO regions at intra-seasonal through to inter-annual time scales, we provide the diagrams in Fig. 14 which are analogous to fig. 3 of Pilch Kedzierski et al. (2016) that showed sharpness versus divergence near the tropopause, and to fig. 5 of Randel et al. (2007) that showed sharpness versus vorticity in the extratropics. Fig. 14 displays the scatter plot of S-ab versus OLR in all seasons. As expected, large S-ab values at range 9−18 $\times$10−4 s−2 are associated with OLR values of 250−150 W m−2 for the number of samples > 180. We have also investigated the slope of relationship between S-ab and OLR in the top panel of Fig. 14 for the number of samples $\geq$ 500. Both slopes show only slight difference between the MC and PO regions, indicating that the variability of deep convection is the major cause of tropopause sharpness variability."

Minor and technical corrections ## ## ##

Use of 'GNSS' throughout the manuscript: The term 'GNSS' is being used for recent satellite missions such as Metop (A, B and C), and for planning future missions. GNSS is the more general term which includes navigation satellites from all countries, while GPS is the American part. The idea is that GNSS receivers are able to capture signals from more satellites and yield more occultation profiles. Now, the Metop/GRAS instrument stands for 'GNSS Receiver for Atmospheric Sounding' while the IGOR instruments onboard COSMIC stand for 'Integrated GPS Occultation Receiver'. In Anthes et al. (2008) it is always referred to as GPS, the same in subsequent publications. So, for consistency, I see no reason not to use GPS in your manuscript. We agree with the reviewer and use the term GPS in the revised manuscript.

Title: It's too general and needs to be more specific. I suggest to somehow highlight zonal structures and the influence of ENSO and the MJO in the title already. This is not the first manuscript to study the tropical TIL globally. We appreciate your suggestion and modify the title as: Influence of ENSO and MJO on the zonal structure of tropical tropopause inversion layer using high-resolution temperature profiles retrieved from COSMIC GPS Radio Occultation

Abstract: First paragraph can be shortened: details about the resolution of your RO profiles or the definitions (S-ab, dH and so on) belong to the Data and Methods section. You can elaborate some more within the second paragraph, and simply use TIL sharpness and thickness instead of the acronyms there. We would like to keep the details about the resolution because that is very important information of our COSMIC retrieval. Grise et al. (2010) used CHAMP dataset which freely available from the UCAR. On the other hand, Noersomadi and Tsuda (2017) discussed two GPS-RO products by the UCAR (i.e. COSMIC version 2010 and re-processed data version 2013). Noersomadi and Tsuda (2017) showed that COSMIC version 2010 indicated mixture of vertical resolution (0.1 – 1 km), while COSMIC version 2013 fixed the resolution at 0.5 km in the UTLS (see their result in fig. 3). Details explanation about the retrieval of COSMIC re-processed data version 2013 can be found in Zeng et al (2016).

p.2

l. 12: I think you mean '... very low temperature in the TTL...' We have revised as suggested.

l. 23-25: This sentence is vague and difficult to follow. I suggest to formulate it this way: how ENSO modulates TTL temperature anomalies or wave activity. We have modified the sentence in P2 L35-37 as: “The El Niño and La Niña events, known as the El Niño Southern Oscillation (ENSO), considerably influence the equatorial wave activity and the TTL structure (Trenberth, 1997; Nishimoto and Shiotani, 2012, Scherllin-Pirscher et al., 2012).”

l. 30: '(i.e. the sharpness)' doesn't fit there in the sentence. Rewrite. We refer to Fig. 2 (right panel) for clarity (P3 L6-8).

p.3

l. 4: also mention the MJO and QBO in this sentence, their influence on the tropical TIL was analyzed in this study as well. We have revised as suggested in P3 L23.

l. 6: also mention in this sentence that the real resolution of RO measurements increases in regions of increased refractivity gradients (such as inversion layers above the boundary layer or the tropopause), where it's most needed. We have revised as suggested in P3 L28-29.

l.27: in 2015 and 2016 the number of profiles is significantly less than that. We add the following statement in P4 L10-11: "Nevertheless, the number of profiles is significantly decreasing in 2015 and 2016 (60−100 profiles over 10°S–10°N)."

p.4 l.1: include a webpage here or within the Acknowledgements. We have added the webpage information in the Acknowledgements.

p.5

l. 6-10: is it a simple mean, or do you apply any kind of weighing to get the grid's value? We add the following statement in P6 L1: "... using simple arithmetic mean ..."

l. 38: I'm confused by this sentence, wasn't your dataset always 0.1 km vertically resolved? Then how can your LRT be sensitive to vertical resolution? We remove this statement because we do not show the N2 profile relative to LRT.

p.6 l. 16: I think you mean 'In agreement with previous studies'. Also, refer to those studies. We remove this statement because we do not show the N2 profile relative to LRT.

p.8 l.1-2: I'd erase this sentence, it's too vague. We have removed this as suggested.

p.10 l.10: this sentence is too speculative. Could as well be related to ENSO amplitudes within your study's time period, of only one decade. We add the following sentences in P10 L2 – 6: "We found that above the CPT the peak amplitude ΔN2 in the MC region is higher and larger (0.5 km above the CPT and 1.8 $\times$ 10−4 s−2) than in the PO region (0.2 km above CPT and 1.4 $\times$ 10−4 s−2). The difference in the thermal structure near tropopause over land and ocean may cause the difference in peak amplitude of ΔN2 above the CPT. One possibility is that the mountainous characteris-

tics of the MC region are favorable to generate convectively couple equatorial waves (Kubokawa et al., 2016).”

p.11

l. 21: I think statistics like ’x percent of values of this parameter are within y range’ are unnecessary in the Concluding remarks section, maybe even throughout the manuscript. I suggest instead to use a structure like: ’maxN2 is typically located within 0.5 km above the CPT’ or ’typical dH values range within...’ and refer to the corresponding figures, so that the important numbers are easier to digest for the reader. We have revised as suggested.

l. 39: what is meant with ’from the new definitions’? We reply to this comment together with the next comment.

l. 40: as it reads now, this paragraph fits better in the introduction section as motivation or for discussions within your result sections. I suggest to remove it. We agree with the reviewer and remove this paragraph. We add the following sentences referring to Fig. 14 in P12 L4-6: “The diagram of S-ab versus OLR both in the MC and PO regions during all seasons indicates that the variability of convective activity in the tropics is the major cause of that of the tropopause structure at various time scales.”

I also noticed some errors in your reference list: - First one is Andrews et al. (the ’s’ is currently missing throughout the manuscript) We have corrected this.

- The Anthes et al. reference for the COSMIC mission should rather be the one from 2008. We have corrected this.

- p.13 l.6: Kedzierski –> ’Pilch Kedzierski’ (also throughout the manuscript) We have corrected this.

Fig. 4: change colour of the blue line to something that contrasts more with the lower N2 values which are also blue. We do not include this figure in the revised manuscript and we focus on the N2 relative to CPT.

Figs. 5, 6, 7, and 8: I really need to zoom a lot to see the features you're describing in the text. I suggest keeping the lower boundary at -1 km instead of -3, and removing the contour lines to leave only the color shading for better visibility of the values reached within the TIL. We have modified the figures as suggested.

Figs. 12 and 13: why are two repeated seasonal cycles displayed instead of one? We keep these figures in Fig.8 after removing some figures, and then add the following statement in P8 L40: "We repeat two seasonal cycles in Fig. 8 to display seasonal cycle more clearly."

Fig. 14: could the authors provide a regression coefficient for these plots within the text? We have added correlation coefficient in the figure title following suggestion by the reviewer. The figure number changes into Fig. 9.

Thank you very much again for your very valuable comments and suggestions.

Reference Birner, T., Dörnbrack, A., and Schumann, U.: How sharp is the tropopause at midlatitudes?, Geophys. Res. Lett., 29, 1700, doi:10.1029/2002GL015142, 2002. Birner, T.: Fine-scale structure of the extratropical tropopause region, J. Geophys. Res., 111, D04104, doi:10.1029/2005JD006301, 2006. Gettelman, A., and Wang, T.: Structural diagnostics of the tropopause inversion layer and its evolution, J. Geophys. Res., 120, 46–62, doi:10.1002/2014JD021846, 2015. Grise, K. M., Thompson, D. W. J., and Birner, T.: A global survey of static stability in the stratosphere and upper troposphere, J. Clim., 23, 2275–2292, doi:10.1175/2009JCLI3369.1, 2010. Holloway, C. E., & Neelin, J. D.: The convective cold top and quasi equilibrium. Journal of the Atmospheric Sciences, 64(5),1467–1487, https://doi.org/10.1175/JAS3907.1, 2007. Kedzierski, R. P., Matthes, K. and Bumke, K.: The tropical tropopause inversion layer: Variability and modulation by equatorial waves, Atmos. Chem. Phys., 16, 11617–11633, doi:10.5194/acp-16-11617-2016, 2016. Kim, J.-E., and Alexander, M. J.: Direct impacts of waves on tropical cold point tropopause temperature, Geophys. Res. Lett., 42, 1584–1592, doi:10.1002/2014GL062737, 2015. Kim, J. and Son, S.

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Please also note the supplement to this comment:
https://www.atmos-chem-phys-discuss.net/acp-2018-1182/acp-2018-1182-AC1-supplement.pdf

Interactive comment on Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2018-1182, 2018.

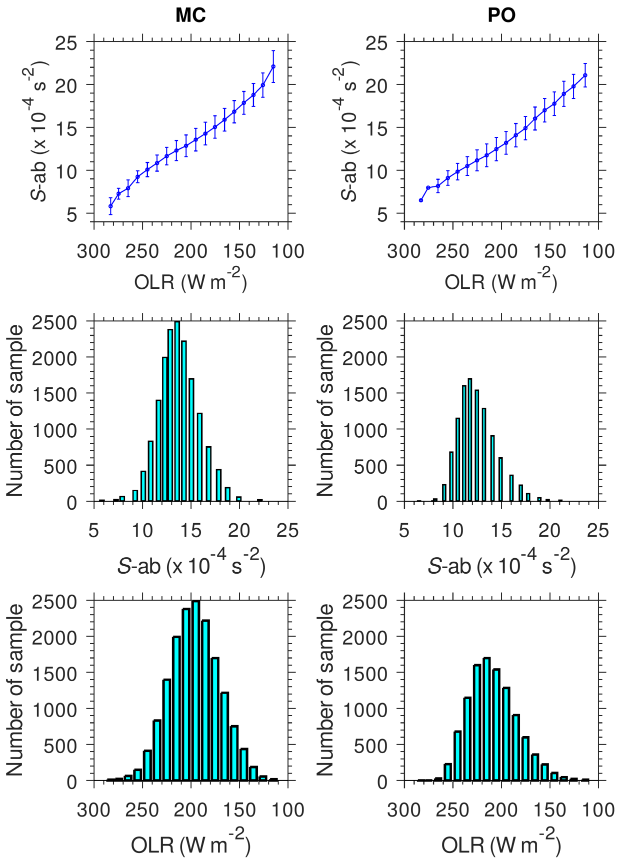

Fig. 1. Diagrams of S-ab versus OLR (top), and of the number of samples for S-ab and OLR (middle and bottom, respectively) in the MC (left) and PO (right) regions.

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Discussion paper