RC3: 'Comment on egusphere-2024-345', Anonymous Referee #2

We feel great thanks for your professional review work on our manuscript. As you are concerned, there are several problems that need to be addressed. According to your nice suggestions, we have made extensive corrections to our previous draft, the detailed corrections are listed below. In addition, we have written a Supplement, listing the definitions of the two methods (Bi-Gaussian and lapse rate tropopause (LRT)) and a wide variety of scenarios that may be encountered in the process of identifying the tropopause structure in details, in order to demonstrate the differences of two different methods. We hope the Supplement will help you understand the results in the main text.

General Comments:

This paper is an interesting study and methodology of the definition and computation of single and multiple tropopauses (TPs). Although the authors have made intensive investigation with the excellent radiosonde measuring net in China, however, the results of the bi-Gaussian fitting method (BGF) are not convincing for me and with respect to the publication requirements of ACP.

I have listed below various items regarding the analysis and especially the form of the presentation of the study, which needs further improvements. If the authors consider most of the comments in a revised version, the article may be acceptable for publication in ACP.

In general, I have concerns about the quality of the BGF method. The study misses a validation of the tropopause results with respect to frequency (double TP events) and especially height of the tropopause (TPH) with independent measurements (e.g. GPS occultation) and methods. Although, this is partly done in Fig. 6, I was a bit puzzled that later, differences of >1km between the tropical TPH of lapse rate TP and BGF are described with ‘small’. It is already obvious from former studies that the LRT is usually placed below the cold point in the tropics. So, why do you compare apples and oranges? Consequently, I was a bit surprised that Fig.6 shows no clear indication for a positive

bias (are most of the profiles not really in the tropics?), but many TPHs are quite high (>17 km), which looks very tropics-like. However, a closer look seems to show such a 'positive' bias in Fig. 6 for STH/DTH1 compared to LRTH1. This fact is not discussed properly in the manuscript with respect to different definitions of both TP methods.

Reply:

1) Spatial distribution characteristics of DT occurrence frequency in China based on bi-Gaussian method are shown in the Fig.9 in the revised manuscript. The maximum of annual mean occurrence frequency (thickness) is about 47.19 % (5.42 km), and the minimum is about 1.07 % (1.96 km) in the latitude range of [16 ºN, 50 ºN]. And, DT occurs most frequently in mid-latitude regions in winter. The meridian distribution of the tropopause based on the bi-Gaussian method is qualitatively and quantitatively consistent with the previously reported results (Randel et al., 2007; Peevey et al., 2012; Xu et al., 2014), including a research based on GPS radio occultation.

2) In order to avoid ambiguity, "local coldest point (LCP)" was replaced to "possible tropopause height (PTH)" in the revised manuscript. There are relatively strong peaks at PTHs, and these PTHs actually contain the height layers that satisfy the LRT definition. Firstly, find all the PTHs in the search range, which can reduce the missed detect rate, and then the fitting optimal solution is obtained by bi-Gaussian function fitting. The recognition process is similar to LRT. And, the bi-Gaussian function has a good ability to express the temperature profiles in the UTLS. Therefore, bi-Gaussian is not a substitute for CPT, but has a more reasonable identification result than CPT, and can capture a more complete evolution process.

3) The CPT altitude is on average 400 m higher than the LRT with values varying between 300 m in July and 500 m in September (Schmidt et al., 2004), the CPT and LRT height definitions are inconsistent, with a difference of 2 km considered to be the boundary value (Pan et al., 2018; Xia et al., 2021). On the one hand, this difference is caused by the inherent properties of the two definitions (see the Fig. 1 below), because CPT is the transition point at which temperature lapse rate changes from negative to positive, which is common in the tropics. On the other hand, CPT defines the higher and colder inversion layer (if exist) as the tropopause, so that the two methods can't

identify the same temperature inversion layer (see Fig. 3(a) in the revised manuscript). This situation mostly occurs in the middle and high latitudes, which may be one of the reasons for the large deviation between CPT and LRT in the middle and high latitudes.

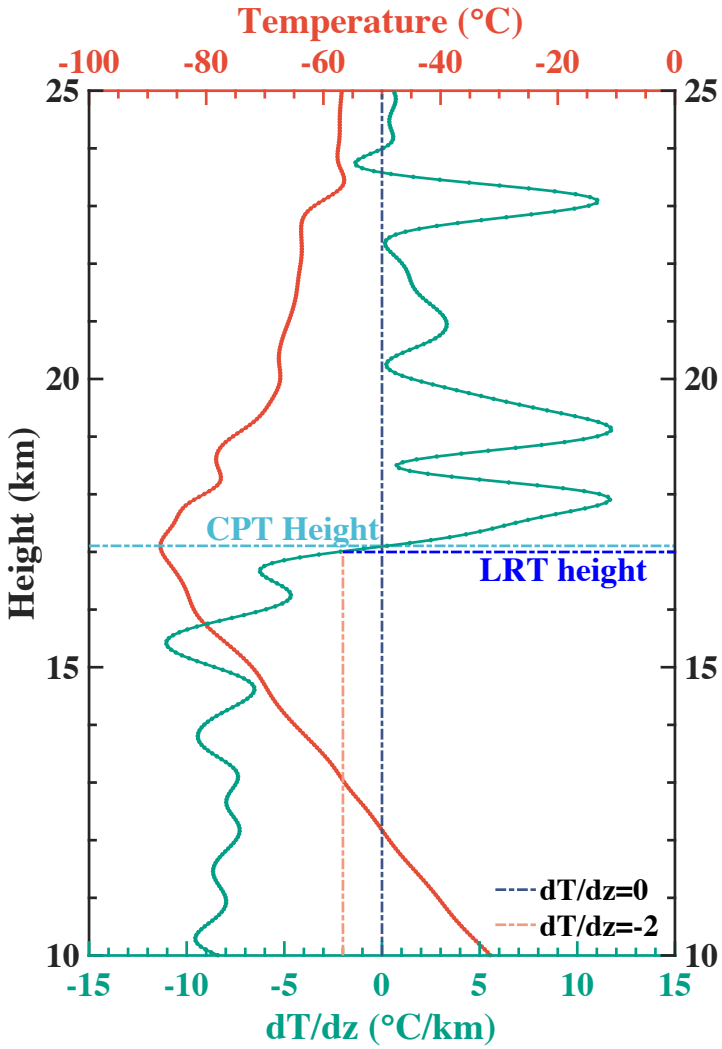

Figure 1: An example to explain the inherent bias of CPT height over LRT height.

4) The CPT is defined by the minimum in the temperature profile and marks a sharp increase in stability, above which the potential temperature profile is close to radiative equilibrium (Gettelman and Forster, 2002; Randel and Park, 2019; Pan et al., 2018; Pan et al., 2014). CPT definition has better applicability in the tropics because of the simpler vertical structure of atmospheric temperatures in the tropics, with fewer atmospheric temperature inversions. In other words, CPT is still highly reliable for identifying single tropopause, and its limitations will be exposed in multiple tropopause

structures. According to CPT definition, CPT can only return one identification result for both single and multiple structures, which is exactly why CPT cannot identify multiple structures. Therefore, we define the local coldest point(s) instead of CPT in the new bi-Gaussian method as the possible tropopause height(s), and only the local coldest point(s) that have passed the significance test are considered to be the tropopause heights.

5) Compared with CPT, bi-Gaussian improves accuracy. Specifically, bi-Gaussian can not only identify the double tropopauses, but also identify the same temperature inversion layer as LRT, and the identification results have less deviation from LRT, as shown in Fig.2 as below. The bias between CPT and LRT is distributed at [0.31 km, 1.84 km], while the bias between bi-Gaussian and LRT is stable at 0.37 km, even at mid-latitudes.

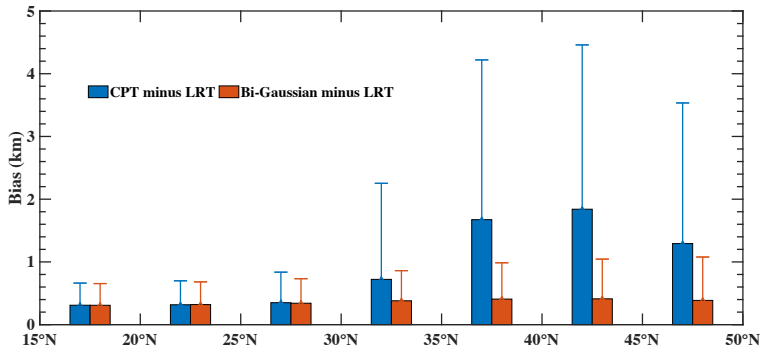

Figure 2: The biases of bi-Gaussian and CPT against LRT in different latitudes.

6) In some mid-latitude areas, the single tropopause height can be elevated 17km in summer, such as the Tibetan Plateau. So, many TPHs are quite high (>17 km), which looks very tropics-like.

Detailed Comments:

1. L11: 'physiochemical' unusual wording, please change.

Reply:

Thanks for your suggestion. We have modified ‘physiochemical coupling’ to ‘physical–chemical coupling’.

2. L15: ‘in mathematical statistics’ not clear to me why this term is necessary.

Reply:

We have deleted ‘in mathematical statistics’.

3. L37: ‘stratosphere vis this “gate”’ Is vis really the correct wording here?

Reply:

Thanks for your suggestion. We have modified ‘vis’ to ‘through’.

4. L40: delete ’in’

Reply:

Thanks for your suggestion. We have revised it according to the comment.

5. L46: ‘concept of the dynamical tropopause’

Reply:

Thanks for your suggestion. We have revised it according to the comment.

6. L55: lapse rate minimum tropopause (LRM)

Reply:

Thanks for your suggestion. We have revised it according to the comment.

7. L57: gauge -> estimate

Reply:

Thanks for your suggestion. We have revised it according to the comment.

8. L59: what do you mean with ‘ideal models’? please clarify.

Reply:

Here, we refer to the sentence 'Idealized models of the tropopause usually assume a discrete jump in the static stability from relatively low values in the well-mixed troposphere to high values in the stable stratosphere' in Homeyer et al. (2010). To avoid misunderstandings, we have deleted the 'ideal models'.

9. L74: 'key stratification' sounds misleading to me.

Reply:

We have modified 'key stratification' to 'key transition layer'.

10. L128: Is there a lower boundary of the tropopause? Please, clarify.

Reply:

According to the results in Gettelman and Forster (2002), the upper and lower boundary of the tropical tropopause layer is well characterized by the CPT and LRM, respectively. We rewritten the sentence: 'In addition, the CPT and LRM are also adopted to characterize the upper and lower boundaries of the tropical tropopause layer.'

11. L129: 'four' I count only three TP definitions (LRT, CPT, and N^2). Please, clarify.

Reply:

In the previous manuscript, four definitions were CPT, LRM, LRT, and N2 (as shown in Fig. 2 in the revised manuscript). In the revised manuscript, we added the PTGT method, so there are five methods in total in Fig. 2.

12. L143: delete 'And': The cold point ...

Reply:

Thanks for your suggestion. We have revised it according to the comment.

13. L166: what is different? Please be more specific with your statements.

Reply:

We have rewritten the sentence as 'the tropopause heights identified by the above five definitions are quite different'.

14. L167: please correct, ‘close to the CPTH’

Reply:

Thanks for your suggestion. We have revised it according to the comment.

15. L171: ‘highly effective’ for what? Do you mean the methods?

Reply:

We have rewritten it as ‘CPT and LRT have good applicability in the tropics’.

16. L172: … in the extratropics …

Reply:

Thanks for your suggestion. We have revised it according to the comment.

17. L176: DT, you may have to introduce DT not only in the Abstract but also in main text.

Reply:

Thanks for your suggestion. We have revised it according to the comment.

18. L200-215: How do you handle triple structures of the TP? Is the method robust, does it detect the upper or lower 2nd TP?

Reply:

What cannot be ignored is the presence of triple tropopauses, even if the occurrence frequency of triple tropopauses is very low. The third tropopause is mainly distributed at ~50 hPa (Anel et al., 2007; Xu et al., 2014), so we assume that there are double tropopauses at most in the search range. This is one of the important reasons for constraining the search range. An example can be referred to in Fig. S3 in the Supplement.

19. L220: The parameter of the formula of Table 3 are frequently used in the manuscript. Consequently, they must be introduced in text and not in the table, as well as a more detailed description is necessary.

Reply:

Thanks for your suggestion. We have revised it according to the comment.

20. L230: I cannot follow the arguments on R^2 and why this number should give me confidence that the TP is detected correctly. It's just the quality of the fit. It is necessary to check the quality of the fit.

Reply:

1) We only want to use R2 to evaluate the expression ability of the bi-Gaussian function to atmospheric temperature profiles in UTLS. Higher R2 indicate better goodness of the bi-Gaussian function. R2 is greater than 0.8 in at least 90% temperature profiles, and the average R2 of all profiles reaches 0.9. Consequently, the bi-Gaussian function exhibits remarkable potential for accurately explicating temperature profiles in UTLS, ensuring that LCPs are successfully identified.

2) In the revised manuscript, we have deleted the exaggerated description of R2 in the comparison of LRT and bi-Gaussian.

21. L254: 'darkest patches' ? Red is not dark compared to blue. 'The majority of the events are located on the …'

Reply:

Thanks for your suggestion. We have revised it according to the comment. 'The majority of the distribution are located on the line y=x.'

22. L274: Please reword the sentence. It is not clear to me what you like to say. Why is a threshold critical for an accurate result of the TP? It's part of the definition.

Reply:

According to the LRT definition, (–2 ºC/km, 2 km) and (–3 ºC/km, 1km) are the lapse rate and thickness thresholds for the first and second tropopause, respectively. Sensitivity test of lapse rate and thickness thresholds to tropopause estimates on LRT criteria was performed in Hoffmann and Spang (2022). The statistical analysis of the lapse rates from the middle troposphere to the lower stratosphere suggests that the

thermal tropopause critically depends on the lapse rate threshold and the layer depth applied in the WMO definition.

Of course, the lapse rate and thickness thresholds ((–2 ºC/km, 2 km) and (–3 ºC/km, 1km)) are not absolutely universal, because lapse rates at specific locations may indicate different levels of stability. Since the strength of stability plays an important role in convective transport, it is worthwhile to note that a fixed temperature lapse rate does not necessarily correspond to a fixed stability threshold (or vice versa) (Maddox and Mullendore, 2018).

We have deleted the sentence in the revised manuscript.

23. L282: by the bi-Gaussian method, but only ST by LRT.

Reply:

Thanks for your suggestion. We have revised it according to the comment.

24. L280: I cannot really follow the description and conclusions of Fig. 8. I would suggest writing the whole section and caption new. More details on the methods are necessary. Why are both TPHs constant on +/- 0.5 units? The normalization is not really described in detail and difficult to follow. The arguments with R^2 are again very confusing.

Reply:

25. L300: new section and subsection, please introduce 'the occurrence frequency' of what kind of parameter?

Reply:

We have modified to 'Double tropopauses structures: occurrence frequency and thickness'.

26. L307: Please rewrite this sentence 'The thickness …'. I can't get a handle on the terms 'latitudinal plain' and 'giant topography'.

Reply:

We have modified to ‘The thickness in the area [90 ^{o}E−100 ^{o}E, 26 ^{o}N−32 ^{o}N] is obviously greater than that of the adjacent plain in same latitude, which may be resulted from the complex topography of the Tibetan Plateau’.

27. L333-344: The discussion is misleading. It is always clear that CPT and LRT will not deliver the same tropopause height due to the definition of both parameters. In the tropics there should be an offset, and this becomes obvious in your Fig. 6. Of course you can show these comparisons, but it is no proof about your TP determination, because the comparison works with ‘apple and oranges’. You may quit this part.

Reply:

As discussed above, bi-Gaussian is not a replacement for CPT, but an upgraded and improved identification method. Therefore, we have kept some statements and removed some unnecessary comparisons.

28. L352: Not the TP is a source of gravity waves but processes in the TP region trigger GW formation.

Reply:

We have revised to “Tibetan Plateau, a source of gravity waves (Hoffmann et al., 2013; Khan et al., 2016), may be one of the contributors to the asymmetry between the northern and southern hemispheres”.

29. L364: Here went something wrong ‘atmospheric dynamic processes …’, please reword.

Reply:

Thanks for your correction. The sentence has been revised.

30. L382: ‘… and high static stability of the air masses creates …’

Reply:

Thanks for your correction. The sentence has been revised.

31. L427: delete ‘which is more than half …’

Reply:

Thanks for your correction. The sentence has been deleted.

32. L432: Is TT1 introduced before?

Reply:

“TT1” was replaced to “DTT1” in the revised manuscript.

33. L435: and increases DTT2.

Reply:

Thanks for your correction. The word has been revised.

34. L437: ‘… intensifies the atmospheric mixing’ may be better.

Reply:

Thanks for your correction. The word has been revised.

35. L442: I have doubts that the argumentation with R^2 makes sense, especially in the conclusion section (see above and concerns by other reviewers).

Reply:

We re-written the Conclusion, and deleted some confusing sentences.

36. L449: Again, I cannot follow the argument ‘… ambiguity of LRT constrained by thresholds.’. The bi-Gaussian method is not constrained by thresholds but by the bi-Gaussian fit approach and the quality of the fit, which is also very likely a threshold criterium.

Reply:

We re-written the Conclusion, and deleted some ambiguous sentences.

37. L470: formatted -> formed

Reply:

Thanks for your correction. The word has been revised.

Technical issues:

1. Most of figures show a lack in resolution, which makes it difficult to read numbers and figure legends. For publication this needs definitely a substantial improvement (Fig 1, 5, 6, 7 -10)

Reply:

We have updated all Figures with low resolution.

2. Fig 3: please enlarge the figure and especially the font size. What do mean with 'Modal'? This is not used in the text, please change this term.

Reply:

We have updated Fig.3 with your suggestion. The "Modal 1" and "Modal 2" are defined at first appearance, which are two modals for bi-Gaussian function.

3. Fig 3b: What is the red sub-plot in (b), Temp versus Altitude. This is not explained in the Figure capture and makes no sense to me at all. If possible, just delete it.

Reply:

We have updated Fig.3 with your suggestion, deleting the sub-plot.

4. Fig. 5: Fonts are far too small!

Reply:

We have updated Fig.5 with your suggestion.

5. Fig. 7: please, enlarge the text fonts (e.g. dT/dz). In addition, there seems something wrong in the wording 'Case A indicates that presents …'. Could it be better: 'Case A indicates the presence of a higher …'

Reply:

We have updated Fig.7 with your suggestion.

6. Fig.10: For me it would be better to use identical TP height ranges for all three TPHs. The color code is misleading, e.g. why should STH be higher than DTH2, but it is just the color code? Again, the resolution of the figure is not good enough. It is not possible to read all the letters and numbers properly.

Reply:

We have updated the Fig.10, using identical ranges. Meanwhile, the resolution was improved.

7. Fig 12a: Is this PV plot presented for a specific theta level? If so, please add this important information.

Reply:

Thanks for your careful check. “at 315 K isentropic surface” have added to the figure caption and title of the colorbar in Fig.12(a).

Reference

Anel, J. A., Antuna, J. C., de la Torre, L., Nieto, R., and Gimeno, L.: Global statistics of multiple tropopauses from the IGRA database, Geophys. Res. Lett., 34, 10.1029/2006gl029224, 2007.

Gettelman, A. and Forster, P.: A Climatology of the tropical tropopause layer, J. Meteorol. Soc. Jpn., 80, 911-924, 2002.

Hoffmann, L. and Spang, R.: An assessment of tropopause characteristics of the ERA5 and ERA-Interim meteorological reanalyses, Atmos. Chem. Phys., 22, 4019-4046, 10.5194/acp-22-4019-2022, 2022.

Homeyer, C. R., Bowman, K. P., and Pan, L. L.: Extratropical tropopause transition layer characteristics from high-resolution sounding data, J. Geophys. Res. Atmos., 115, D13108, 10.1029/2009jd013664, 2010.

Maddox, E. M. and Mullendore, G. L.: Determination of best tropopause definition for convective transport studies, J. Atmos. Sci., 75, 3433-3446, 10.1175/jas-d-18-0032.1, 2018.

Pan, L. L., Honomichl, S. B., Bui, T. V., Thornberry, T., Rollins, A., Hintsa, E., and Jensen, E. J.: Lapse rate or cold point: The tropical tropopause identified by in situ trace gas measurements, Geophys. Res. Lett., 45, 10756-10763, 10.1029/2018gl079573, 2018.

Pan, L. L., Paulik, L. C., Honomichl, S. B., Munchak, L. A., Bian, J., Selkirk, H. B., and Voemel, H.: Identification of the tropical tropopause transition layer using the

ozone-water vapor relationship, J. Geophys. Res. Atmos., 119, 3586-3599, 10.1002/2013jd020558, 2014.

Peevey, T. R., Gille, J. C., Randall, C. E., and Kunz, A.: Investigation of double tropopause spatial and temporal global variability utilizing High Resolution Dynamics Limb Sounder temperature observations, J. Geophys. Res. Atmos., 117, 10.1029/2011jd016443, 2012.

Randel, W. and Park, M.: Diagnosing observed stratospheric water vapor relationships to the cold point tropical tropopause, J. Geophys. Res. Atmos., 124, 7018-7033, 10.1029/2019jd030648, 2019.

Randel, W. J., Seidel, D. J., and Pan, L. L.: Observational characteristics of double tropopauses, J. Geophys. Res. Atmos., 112, D07309, 10.1029/2006jd007904, 2007.

Schmidt, T., Wickert, J., Beyerle, G., and Reigber, C.: Tropical tropopause parameters derived from GPS radio occultation measurements with CHAMP, J. Geophys. Res. Atmos., 109, D13105, 10.1029/2004jd004566, 2004.

Xia, P., Shan, Y., Ye, S., and Jiang, W.: Identification of tropopause height with atmospheric refractivity, J. Atmos. Sci., 78, 3-16, 10.1175/jas-d-20-0009.1, 2021.

Xu, X., Gao, P., and Zhang, X.: Global multiple tropopause features derived from COSMIC radio occultation data during 2007 to 2012, J. Geophys. Res. Atmos., 119, 8515-8534, 10.1002/2014jd021620, 2014.