RC2: 'Comment on egusphere-2024-345', Anonymous Referee #3

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.

Comments

This paper proposes a new method to identify the tropopause using a “bi-Gaussian function” that identifies local minima in temperature within a profile. While exploration of novel methods to improve definition of the tropopause is a worthwhile effort, I unfortunately found the present study to be critically lacking in myriad ways which I elaborate upon below. Some of the critical shortcomings could be resolved by improved narrative and discussion and others require more extensive analysis and demonstration of the proposed method (or an alternative).

General Comments

1. First, the fundamental requirement of any tropopause definition is that it provides a demonstrated reliable identification of the troposphere-stratosphere transition layer. Existing definitions have been demonstrated to do this in myriad ways, with composition observations being the best utilized for such demonstration. The present study does not demonstrate that the new definition captures well the troposphere-stratosphere transition (or often more simply thought of as a boundary), with any such efforts limited to comparison with the WMO lapse-rate tropopause (LRT) definition. Even so, there is a surprisingly large number of cases where the authors’ application of the LRT or the proposed bi-Gaussian method fail to identify a tropopause. This result

alone is surprising and questionable, as the LRT definition virtually never fails to identify a tropopause so long as a sufficiently deep profile of data that encompasses the upper tropopause and lower stratosphere exists. Perhaps the authors did not control for this in their dataset or perhaps their application of the existing, well-demonstrated LRT method is flawed. Regardless, the result that the proposed method fails to identify a tropopause in ~12.5% of profiles is a major shortcoming that is not addressed.

Reply:

1) To avoid unrealistically high or low tropopause heights and to increase computational speed, the search range for the LRT and bi-Gaussian is limited to between TH_{min} and TH_{max} (Liu et al., 2021) in the manuscript.

$$TH_{min} = 2.5 \times (3 + \cos(lat \times 2)) \quad (1)$$

$$TH_{max} = 2.5 \times (7 + \cos(lat \times 2)) \quad (2)$$

where, lat is the latitude of observation sites. TH_{min} and TH_{max} is the bottom and top limits of tropopause height, respectively.

There are two reasons for constraining the search range.

(i) In previous studies (Reichler et al., 2003; Li et al., 2017), we have also found precedents for constraining the search range (e.g. between 550 hPa and 75 hPa (approx. 5–18 km)) to avoid unrealistically high or low tropopause heights and to increase computational speed. However, we used a dynamic range [TH_{min}, TH_{max}], referring to Liu et al. (2021). In addition, the cases of missed detection caused by limiting the search scope also exists in the previous study (Li et al., 2017)。

(ii) 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. An example can be referred to in Fig. S3 in the Supplement.

2) We re-identified the LRT heights using the LRT code provided by Tinney et al. (2022) without limiting the search range, LRT did not fail.

3) In order to avoid misjudgment of the tropopause structure due to local temperature fluctuations caused by atmospheric fluctuations, we have improved

constraints in the significance test, by changing the range of the linear fitting to [valid LCPH(s), valid LCPH(s)+2] (referring to Randel et al. (2007b)), rather than [valid LCPH(s), valid LCPH(s)+1], but still used a threshold of 0.5 ºC/km. (Please see the Line 223 in the revised manuscript.) Therefore, the DT occurrence frequency based on the new constraint is reduced compared to the original manuscript.

We re-identified the LRT heights using the LRT code provided by Tinney et al. (2022), but still restricted the search range, and the results compared with the bi-Gaussian method are shown in Table 1 (the percentages represent the proportion of temperature profiles in each case), as below. Compared with the results in the original manuscript, both methods work better. The missed detection of LRT (means that there is no value satisfying the definitions within the search range) is reduced, because we calculated the average temperature lapse rate in the revised manuscript by the LRT code provided by Tinney et al. (2022).

Table 1: Identification results of the bi-Gaussian and LRT. The percentages represent the proportion of temperature profiles in each case. "Missed detection" means that there is no value satisfying the definitions within the search range.

Identification results		Bi-Gaussian		
		Missed detect	ST	DT
LRT	Missed detect	85 (0.11 %)	174 (0.22 %)	67 (0.09 %)
	ST	758 (0.96 %)	54,935 (69.75 %)	**8,682 (11.02 %)**
	DT	257 (0.32 %)	**4,439 (5.64 %)**	9,362 (11.89 %)

According to the latest statistics, bi-Gaussian method and LRT fails to identify a tropopause in 1.39 % and 0.42 % of profiles, slightly higher than the missed detection rate of LRT. There is no failure rate of about 12.5% that you mentioned, even in the original manuscript.

4) In the revised manuscript, it is clarified that the LRT algorithm is also limited by the search range, and the meaning of 'Missed detection' is labelled in Table 4.

2. Second, the physical meaning and justification of a definition based on local minima in temperature is not clear and otherwise presumed to be weak. Past literature demonstrates thoroughly that cold-point definitions are not appropriate outside of the

tropics and even in the tropics commonly result in identification of a level that is not dynamically or chemically relevant to the purposed use of such a definition – to accurately identify the bound (or transition zone) between troposphere and stratosphere air. Conversely, temperature minima near and above often result from convection and wave activity and can be an important failure mode for some existing definitions. To rely upon an error-prone basis of tropopause definition as local temperature minima provide is therefore highly questionable. Moreover, because the LRT has been comprehensively demonstrated to be reliable most of the time, differences between the LRT and any proposed definition solicit increased scrutiny of an alternative definition. It must be clearly demonstrated why an alternative definition is more reliable than the LRT or a similarly reliable definition (there are recent relevant studies not cited), otherwise the exercise presents simply a difference without explanation or significance.

Reply:

1) 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. By definition of the CPT, CPT can only return one identification result for both single and multiple structures, which is exactly why CPT cannot identify multiple structures. Therefore, we use local cold point instead of CPT, and only the local cold points that have passed the significance test are considered to be the tropopause heights.

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) We made a detailed comparative analysis according to the identification of bi-Gaussian and LRT, including the same and contradictory results.

(i) There is remarkable consistency between bi-Gaussian and LRT for the cases of same identification results, but bi-Gaussian is slightly larger than the LRT, which may be determined by the inherent properties of the two definitions (see Fig.S5 in the Supplement).

(ii) Especially in view of the contradictory cases, some examples and statistical analysis are shown to explain for the contradiction. Please refer to Fig.S1–Fig.S4 in the Supplement and the Fig.8 in the main text.

4) 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.1 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.

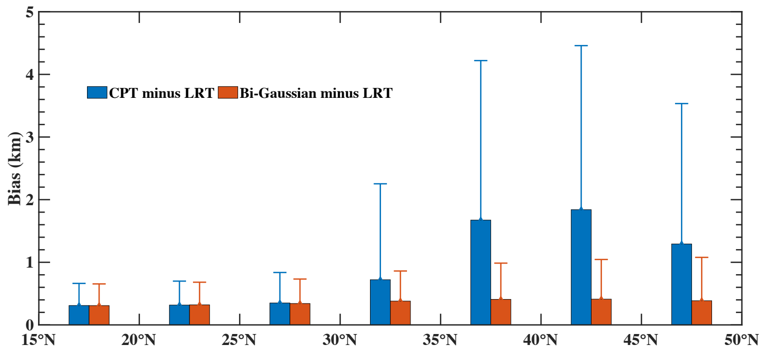

Figure 1: The biases of bi-Gaussian and CPT against LRT in different latitudes.

3. Third, unless a definition is created to serve a very specific region or purpose, I consider global comparisons of a new tropopause definition with existing ones to be a

necessary element of such a study. The narrow focus on China in this study is thus a major shortcoming given the aim of the effort.

Reply：

1) The radiosonde data in China used in the manuscript cover tropical, subtropical, temperate and plateau climate zones, which can verify the feasibility and accuracy of the bi-Gaussian method.

2) In the next research work, we plan to further analyze the global tropopause vertical structure with more extensive data covering a wider area, such as GPS occultation.

4. Fourth, while I do sincerely appreciate the authors' attempt to identify multiple tropopauses since only two proven definitions currently do so, the result that double tropopause occurrences increase from ~3% based on the LRT to more than 70% with the new definition is extremely concerning. Namely, as is true and necessary for any tropopause definition, an identified tropopause (primary or otherwise) in a profile should have an important physical or dynamical meaning. Otherwise, you attain nothing but vast identification of arbitrary levels that happen to have a local minimum in temperature. I do not expect the authors to demonstrate physical or dynamical linkages for their multiple tropopause definitions, but such have been well documented for double tropopauses that result from the LRT definition. The fact that you see such a tremendous increase casts serious doubt on the potential utility of such a definition, especially because it has also been demonstrated that multiple tropopauses identified by the LRT do not always have a clear physical or dynamical explanation.

Reply：

1) According to the statistical results listed in Table 4, the DT occurrence frequency defined by LRT and bi-Gaussian is 16.89% and 27.69 %, respectively.

2) In order to avoid misjudgment of the tropopause structure due to local temperature fluctuations caused by atmospheric fluctuations, we have improved constraints in the significance test, by changing the range of the linear fitting to [valid LCPH(s), valid LCPH(s)+2] (referring to Randel et al. (2007b)), rather than [valid

LCPH(s), valid LCPH(s)+1], but still used a threshold of 0.5 ºC/km. Therefore, the occurrence frequency of DT in the revised manuscript decreased. Spatial distribution characteristics of DT occurrence frequency in China based on bi-Gaussian method are shown in the Fig.11 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., 2007a; Peevey et al., 2012; Xu et al., 2014).

5. Fifth, an important – though not mandatory – expectation for a tropopause definition is that its application is straightforward and not prone to confusion or misuse by others. The proposed definition is quite complicated, with many conditional steps that are likely to be inconsistently and inappropriately applied by others. Thus, simplification of the procedure should be a priority. Moreover, it is never specified what units are used for the conditional elements of the proposed definition, which are ultimately necessary for others to replicate this work in the future.

Reply:

According to the latest identification results of bi-Gaussian, it has a good agreement with LRT, and can stably identify the continuous evolution process of the thermal tropopause structures. In the following research, we will optimize and simplify the algorithm, such as realizing the identification of triple tropopauses.

Specific Comments

1. Because of the substantial concerns I have with the design and execution of the study, I will not list myriad technical corrections here, but highlight some additional problematic statements or impressions. There are multiple recent efforts to develop tropopause definitions that are not acknowledged or cited. There are also many other contextual works that would help greatly in the presentation, framing, justification, and

discussion of such work. I encourage the authors to dive deeper into literature review to improve upon these issues, which will help direct future efforts towards accomplishing this study or another iteration.

Reply:

We sincerely appreciate the valuable comment. As suggested by the reviewer, we have checked the literature carefully and added more references (e.g. Pan et al. (2004), Maddox and Mullendore (2018), Tinney et al. (2022), Boothe and Homeyer (2017), and Ivanova (2013)) about developing the tropopause definitions into INTRODUCTION part in the revised manuscript.

2. Lines 34-36: the tropopause does not perform a role in stratosphere-troposphere exchange (STE), but its definition is required to assess it; dynamic mechanisms are the role for STE.

Reply：

Thanks for your suggestion. We have rewritten it to ‘The tropopause is a transitional layer between the upper troposphere-lower stratosphere (UTLS)’.

3. Line 39: there are many other (and increasingly comprehensive) studies of the tropopause and its relation to climate change that are not cited.

Reply：

We sincerely appreciate the valuable comment. We have checked the literatures carefully and added more references (e.g. Meng et al. (2021), Xian and Fu (2017), Seidel et al. (2001), Shepherd (2002), Seidel and Randel (2006), and Thompson et al. (2021)) on the relationship between tropopause and climate change into INTRODUCTION part in the revised manuscript.

4. Line 60: should acknowledge here and elsewhere that this “cliff-like decline” is broadly recognized as the “tropopause break” and cite additional work.

Reply：

We have modified “cliff-like decline” to “tropopause break”, and cited relevant literatures (e.g. Xian and Homeyer (2019), Rieckh et al. (2014), Palmen (1948), and Randel et al. (2007a)).

5. Line 77: “subject to controversy” is overstated. It would be better described as “active areas of research”

Reply：

Thanks for your comment. We have revised it as the comment.

6. Lines 94-96: this is not appropriate motivation for the use of radiosonde observations. Radiosonde observations are the traditional and most widely used data for studying the upper troposphere and lower stratosphere and defining the tropopause.

Reply：

Thanks for your suggestion. We have rewritten the sentence as “Radiosonde observations of air temperature, the traditional and most widely used, are crucial and essential for studying the fine tropopause structures”.

7. Line 102: this is also a very unusual introductory statement and motivation. There have been multiple well-cited studies that demonstrate why double tropopauses are frequent in the midlatitudes.

Reply：

We have deleted “In order to investigate why DT structures in the mid-latitudes are frequent,”.

8. Lines 106-117: this is presented suddenly and without explanation of its significance and intended use.

Reply：

We have re-written this part according to your suggestion. Transitional sentence, “The stratospheric polar vortex is a large-scale circulation system over the polar region in the Northern Hemisphere winter, which is related to tropospheric circulation anomalies and plays an important role in the stratosphere–troposphere coupling (Ren and Cai, 2007; Zhang et al., 2016; Liang et al., 2023).” has been added at the beginning of the paragraph to introduce “the polar vortex intensity” and “ERA5 reanalysis”.

9. Line 119: this statement is not true in multiple ways and is contradicted throughout the article. Most existing tropopause definitions have been demonstrated to be chemically, physically and/or dynamically meaningful. At least two existing definitions have been demonstrated to be universal – the LRT and the recently-developed potential temperature gradient tropopause (PTGT) definition.

Reply:

Thanks for your suggestion. We have rewritten this part. And, the potential temperature gradient tropopause (PTGT) definition was cited in the revised manuscript.

10. Figure 2: are the lines in panels (b)-(d) averages? This analysis is not well explained or described.

Reply:

The red lines in panels (b)-(d) do indicate the mean profiles. More information for analysis was described.

11. Section 2.3.2: there are several issues here. First, it is presented as though only the Brunt-Väisälä frequency is used for tropopause definition. Second, one curve-fitting method from a single study (Homeyer et al. 2010) is used without explanation that such is the source.

Reply:

1) We have modified the content of Section 2.3, by replacing ‘2.3.1 Tropical tropopause layer’ to ‘2.3.1 Cold point tropopause and potential temperature lapse rate minimum tropopause’, replacing ‘2.3.2 Extratropical tropopause’ to ‘2.3.2 Lapse rate tropopause’, adding ‘2.3.3 Curve fitting to Brunt-Vaisala frequency’ and ‘2.3.4 Potential temperature gradient tropopause’.

2) We have emphasized in the revised manuscript that curve-fitting method is proposed by Homeyer et al. (2010).

12. Line 183: TH is not defined and is difficult to follow its meaning here and after.

Reply:

We have replaced ‘TH’ with ‘tropopause height’ and deleted all ‘TH’ abbreviations in the text.

13. Line 225: extremely overstated. A high correlation for the fitting process does not demonstrate potential for accurate tropopause definition, but rather that you have success at identifying local temperature minima.

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.

Reference

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