RC1: 'Comment on egusphere-2024-345', Anonymous Referee #1

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 work uses a novel method to detect tropopause especially the double tropopause and shows the statistics of the tropopause using this new method. The definition of the tropopause is an important question in the upper troposphere lower stratosphere dynamics and chemistry, and the information presented in this paper is very quantitively and clear. However, the discrepancy between this new method and existing method seems to be too large and I suggest the authors show more clarification in section 3, please see major comments for details. I suggest accepting this paper after resolving this issue.

Major comments:

1. Figure 8, and lines 281-290. This part needs more detailed discussion and clarification:

Line 281-282: "of which the largest proportion (11384 profiles) is identified as DT by bi-Gaussian method but ST by LRT", this result is astonishing. According to the WMO double tropopause definition, 'If the average lapse rate above this "first tropopause" between any level and all higher levels within 1 km exceeds 3°C/km, then a "second tropopause" is defined by the same criterion as the first', I checked the significance test in section 2 and only find that "the slope is not less than 0.5°C/km", is it a reason for this very different result between the bi-Gaussian method and LRT?

Reply:

1) The threshold for "the slope" in the significance test does affect the identification of the second tropopause. The threshold of 0.5 °C/km in the manuscript is set based on the statistical results of a research (Fig.5 in Randel et al. (2007)], the average strength of the inversion is defined by the temperature difference between Z_{LRT1}+2 km and Z_{LRT1}) (Randel et al., 2007). In the revised manuscript, we also explained that the threshold of "the slope" is one of the reasons for the difference in recognition results between the two methods.

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. (2007)), 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 %)

3) the reasons for choosing 0.5 °C/km as the threshold, as below.

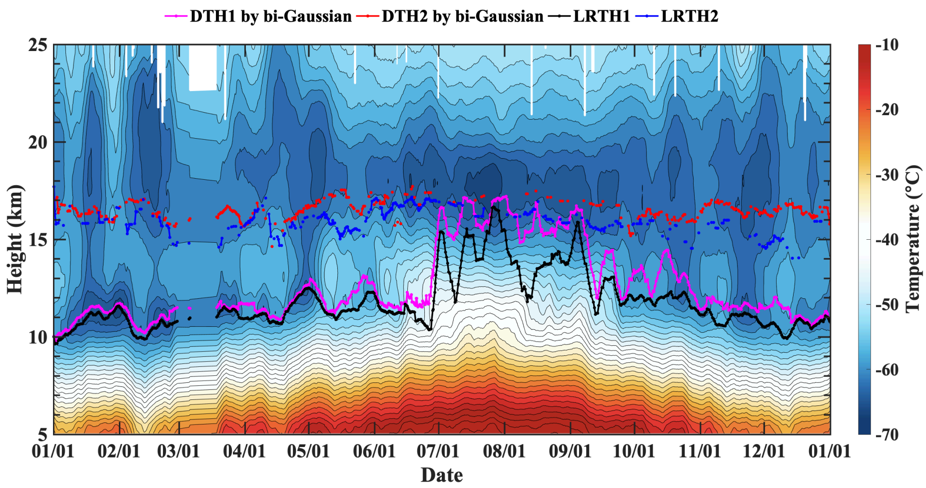

Figure 1: Temperature profiles from radiosondes in 2014 at Kuqa site (119.7 °E, 49.25 °N).

The evolution of the temperature field at the Kuqa site (119.7 °E, 49.25 °N) in 2014 is shown in Fig.1. There are obviously two local temperature minimum layers from January to May along the vertical direction, and the DT structure occurs frequently. With the increase of the surface temperature, the lower local temperature minimum layer was elevated from June to September, prevailing ST structure. After October, it re-evolved into two local temperature minima layers, prompting the formation of DT structures. The DT structures identified by Bi-Gaussian are mainly concentrated in winter and spring, while LRT identified a large proportion of DT structures from May to September. Therefore, we believe that the identification results of bi-Gaussian are more reasonable and more consistent with the evolution process of atmospheric thermal stratifications. In addition, the upper local temperature minima in November and December are too weak to be detected by LRT.

Bi-Gaussian function has a good ability to express the temperature profiles in the UTLS, and is able to more stably and obviously identify the spatial and temporal distribution characteristics of the thermal tropopauses. If a higher threshold is set, some DT structures are difficult to identify, as well as the LRT. As shown in the Fig.1, the threshold of 0.5 °C/km ensures that bi-Gaussian has a good ability to identify the weak inversion layers. Fig.1 also reflects the differences in the recognition results of the two methods (as listed in Table 4 in the revised manuscript). The LRT identified more DT structures in summer than bi-Gaussian, while the opposite was true in winter.

4) For the 8,682 profiles, defined as DT by bi-Gaussian but only ST by LRT, we made a detailed analysis.

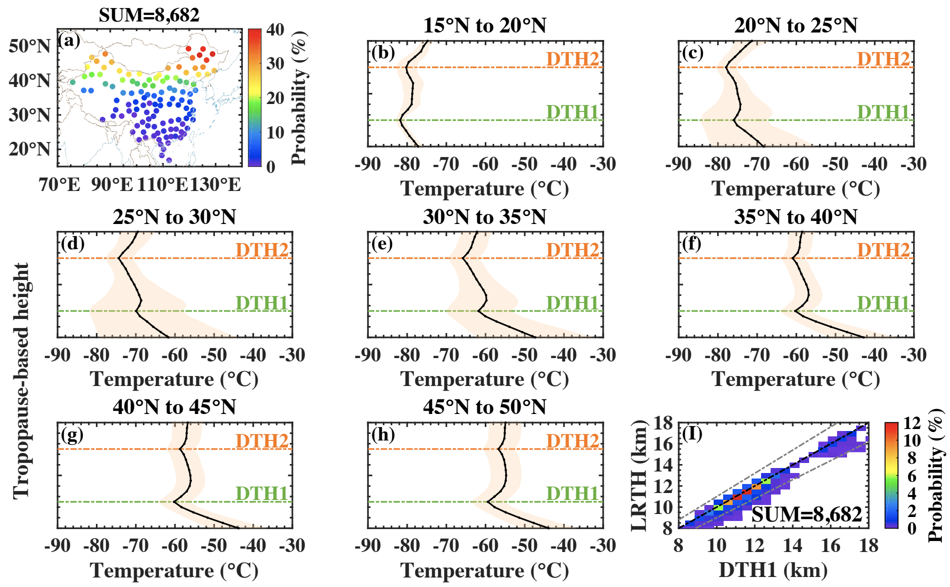

Figure 2: The cases that were identified as DT by the bi-Gaussian method but only ST by LRT. (a) ratio (contradictory results/ all observation of this site) distribution for the 8,682 temperature profiles. (b) − (h) annual average temperature profiles in 5° latitude bands. A tropopause-based average is adopted by using (DTH1+ DTH2)/2 as a reference level, and −0.5 and 0.5 accurately indicate the locations of DTH1 and DTH2, respectively. (I) the comparison of DTH1 by bi-Gaussian and LRTH for the 8,682 profiles.

It can be clearly noticed that there is an inversion layer at both DTH1 and DTH2, and the strength of the inversion layer at DTH2 is significantly weaker than that at DTH1, and the bimodality is more pronounced at middle and high latitudes. LRT often fails to capture the weak stability transition (Tinney et al., 2022). The temperature lapse rate between DTH1 and DTH2 is mainly distributed in [–1.26 ºC/km, –2.54 ºC/km], not satisfying ‘the average lapse rate between any level and all higher levels within 1 km exceeds 3 °C/km’. Therefore, the LRT definition of the second tropopause is not satisfied and defines these cases as ST. As can be seen from Fig.2 (I), LRTH is significantly consistent with DTH1, indicating that LRT could accurately identify the first tropopause, even though fail to identify the second tropopause.

2. Figure 8a: I suggest also showing ratio (contradictory results/ all observation of this station) in addition to population.

Reply:

Thanks for your suggestion. We have revised the expression.

3. line 287: ‘peak at 0.5… peak at -0.5’: I find it difficult to understand this normalized height. Does this mean that for all first DT, the altitude is -0.5, and for all second DT, the altitude is 0.5? Could you please add more explanation to the text? Or maybe do not define ‘0.5’ and ‘-0.5’, just use text ‘first DT’ and ‘second DT’, because 0.5 maybe misleading, looks like 0.5 km.

Reply:

Thanks for your suggestion. We have revised the expression. A description of the normalization process has also been added to the figure caption.

4. Line 288 ‘the bimodality become gradually unobvious poleward’: in figure 8a, it looks like that the DT events happens more frequently at higher latitude, but the bimodality is not very clear? Could this be a result of overestimating DT events over higher latitude? Could you please add more discussion on this result?

1) We greatly admire your keen insight. We did make an error in calculating the average temperature profiles with tropopause-based height, missing some temperature profiles satisfying the conditions, but it is not related to the results identified by the bi-Gaussian method.

2) We deleted ‘the bimodality become gradually unobvious poleward’ to avoid ambiguity.

3) More discussions can be found in response to Comment 1, which have been added to the revised manuscript.

5. In addition to the tropopause definition described in this work, in the subtropics, dynamics tropopause based on PV or PV gradient is also widely used to detect the transport between stratosphere and troposphere. This paper also describes PV field in section 5, and shows a good agreement between the PV field and the tropopause. It will be interesting to add discussion regarding the dynamics tropopause.

Reply:

Potential vorticity (PV) is commonly used to define a dynamic tropopause definition, and a 2 potential vorticity unit (PVU; $1PVU=10^{-6}\ m^2\ K\ kg^{-1}\ s^{-1}$) value is often chosen to represent the tropopause in synoptic-scale studies (Gettelman et al., 2011; Kunz et al., 2011). PV considers both the atmospheric static stability and the three-dimensional horizontal motion, ensuring the continuity of the dynamical tropopause distribution over large temporal and spatial scales. Therefore, PV is a well–characterized tracer in the study of stratosphere–troposphere interactions (Kunz et al., 2011).

As shown in Fig.14 in the revised manuscript, the 2 PV-based dynamic tropopause is significantly consistent with the thermal tropopause based on bi-Gaussian, which also proves the feasibility and accuracy of the bi-Gaussian method.

Therefore, for the discussion in Sec.5 of this manuscript, we use the PV as an important reference for studying the atmospheric motion of the middle and upper level, which will help us to deeply understand the formation mechanism of the double tropopause structures. Relevant discussions have added to the Discussion in Sec. 5.

Minor comments:

1. Figures 1, 9, 10, 11: please add longitude and latitude to your map

Reply:

We have added the longitude and latitude labels in all figures if needed, as shown below.

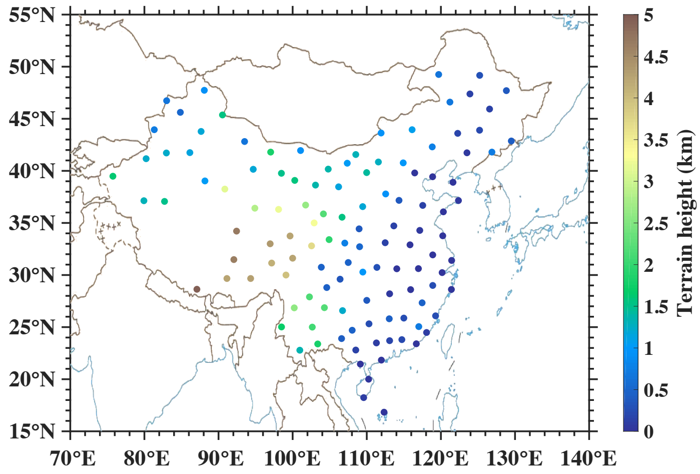

Figure 3: Spatial distribution of sounding sites (dots) and relevant terrain heights (color-coded).

2. Figures 6, 8, 9, 10: text is blur

Reply:

We have replaced these figures with blur text.

3. Line 9-11: I would say 'the tropopause is an important transition layer, and can be a diagnostic of .. '

Reply:

Thanks for your suggestion. We have revised the expression.

4. Line 23-24: 'in the latitude range [16°N, 50°N] ' and 'at mid-latitudes [30°N, 40°N]': please use the same format. This problem in also in lines 300-308.

Reply:

Thanks for your suggestion. We have revised the expression throughout the whole manuscript.

5. Line 41: ', climate model simulations': replace ',' into 'and'

Reply:

Thanks for your suggestion. We have revised the expression.

6. Line 58: ‘buoyancy frequency N has been introduced’, not ‘introduced’ because it is already defined earlier. It is just ‘used’.

Reply:

Thanks for your suggestion. We have revised the expression.

7. Line 66: ‘from different monsoon circulation systems, such as the Asian summer monsoon and polar vortex..’, polar vortex is not a monsoon circulation system

Reply:

Thanks for your suggestion. We have modified ‘different monsoon circulation systems’ to ‘atmospheric circulation systems’.

8. Line 101: ‘as described in detail in the literature (Guo et al., 2016)’

Reply:

We have modified ‘as described in detail in the literature (Guo et al., 2016)’ to ‘as described in Guo et al. (2016)’.

9. Line 102: ‘representing an excellent opportunity’, sounds wired, consider use ‘providing an excellent opportunity.’

Reply:

Thanks for your suggestion. We have revised the expression.

10. Table 1: incorporate the most important information in the text. For example, mention that the vertical resolution is 5-8 m when saying ‘higher vertical resolution than reanalysis’.

Reply:

Thanks for your suggestion. We have revised the expression. ‘Once- or twice-daily radiosondes, launched at 08:00 and 20:00 (local time), throughout four seasons have a higher vertical resolution (about 5 to 8 m) than reanalyses.’

11. Line 110: ‘there are 37 vertical layers from 1000 hPa to 1 hPa’: what is the vertical resolution over the levels of interest in this paper?

Reply:

We have modified ‘there are 37 vertical layers from 1000 hPa to 1 hPa’ to ‘there are 23 layers in vertical direction, including 850, 825, 800, 775, 750, 700, 650, 600, 550, 500, 450, 400, 350, 300, 250, 225, 200, 175, 150, 125, 100, 70, 50 hPa.’.

12. Line 119: between the upper (stratosphere) and lower (troposphere) parts: this is ambiguous, consider just say between the stratosphere and troposphere, or stratosphere (upper altitude) and troposphere (lower altitude).

between the stratosphere and troposphere

Reply:

We have modified ‘between the upper (stratosphere) and lower (troposphere)’ to ‘between the stratosphere and troposphere’.

13. Line 125: ‘in view of’ this sentence is blur. The three sentences in this paragraph are: ‘in view of the fact.. in addition’ are both a description previous works, but ‘next’ follows by the work in this paper. This logic flow does not make sense.

Reply:

Thanks for your suggestion. We have revised the expression. The five thermodynamic definitions are first described and the deviation of the identification results for the same profiles is shown to elicit the necessity for the proposed new method.

14. Section 2.3.1 the title is ‘tropical tropopause layer’, but in figure 2 it is a subtropical station

Reply:

Thanks for your suggestion. 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'.

In the revised manuscript, we replaced the data from a tropical site (112.33 °E, 16.83 °N), and the five methods were applied to the temperature profiles. The results are shown in Fig. 4 as below.

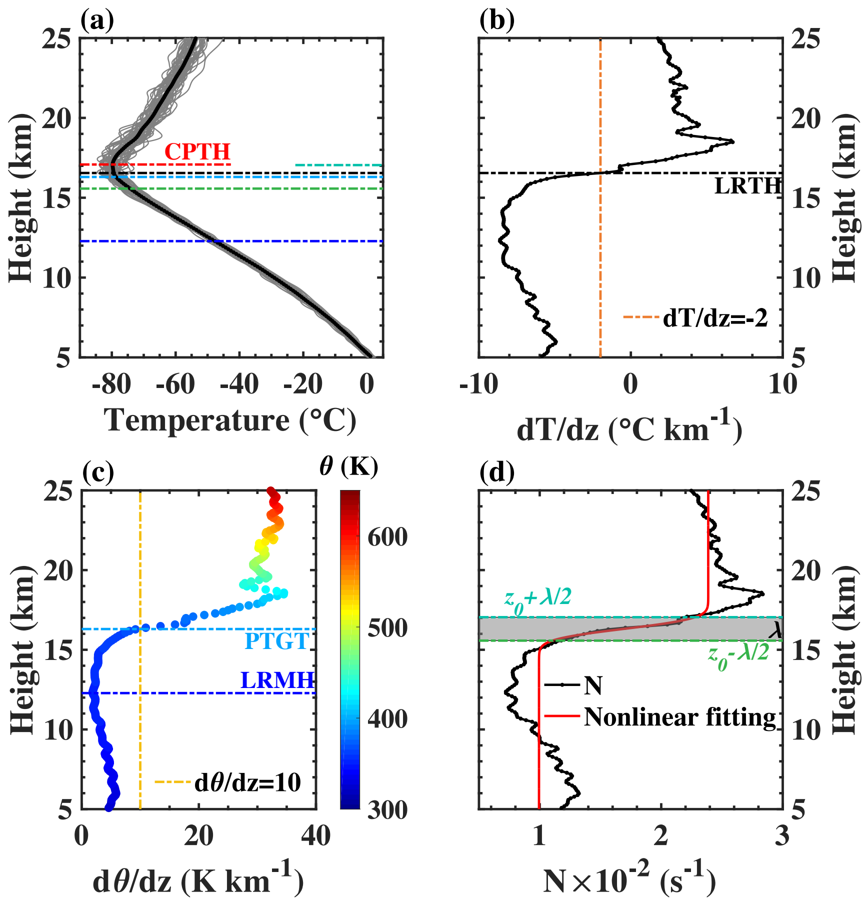

Figure 4: Five different thermal definitions were shown in a tropical site (112.33 °E, 16.83 °N).

15. Line 326: 'Bi-Gaussian method prefers to define higher and colder temperature inversion layer as DTH2, which leads to an increase in the occurrence frequency and thickness of DT': could you explain more about this logic chain?

Reply:

Similar to that expressed in Figure 8. However, the expression in the original manuscript does lack clarity and has been deleted.

16. Line 344: ‘tropopause height has an increasing trend under global warming’ I doubt this value may not be very large, could you please quantify it according to the estimation in your reference?

Reply:

As reported in Meng et al. (2021), tropopause heights increase about 50 to 60 m/decade, which really isn't a great value.

17. Line 345: ‘the change trend’ ‘trend’ is misleading with the trend in the last paragraph. It sounds like a trend changing with time.

Reply:

We have modified ‘The change trend of tropopause height from tropical to subtropical regions is discontinuous’ to ‘The meridional distribution of tropopause height from tropical to subtropical regions is discontinuous’

18. Line 365: ‘(Buchart, 2022)’ this citation is not included in the reference. I didn’t check the full reference list and the authors should double check it to make sure this mistake does not happen again.

Reply:

Thanks for your careful check. We have checked all references to make sure this mistake does not happen again.

19. Section 5: I suggest use another name instead of ‘discussion’, since this is an important part of this paper, not a discussion.

Reply:

Thank you for your suggestion. We have modified the caption title to ‘Discussion on the formation mechanism of double tropopause in mid-latitude region in winter’.

Reference

Gettelman, A., Hoor, P., Pan, L. L., Randel, W. J., Hegglin, M. I., and Birner, T.: The extratropical upper troposphere and lower stratosphere, Rev. Geophys., 49, RG3003, 10.1029/2011rg000355, 2011.

Kunz, A., Konopka, P., Müller, R., and Pan, L. L.: Dynamical tropopause based on isentropic potential vorticity gradients, J. Geophys. Res. Atmos., 116, https://doi.org/10.1029/2010JD014343, 2011.

Meng, L., Liu, J., Tarasick, D. W., Randel, W. J., Steiner, A. K., Wilhelmsen, H., Wang, L., and Haimberger, L.: Continuous rise of the tropopause in the Northern Hemisphere over 1980-2020, Science Advances, 7, 10.1126/sciadv.abi8065, 2021.

Randel, W. J., Wu, F., and Forster, P.: The extratropical tropopause inversion layer: Global observations with GPS data, and a radiative forcing mechanism, J. Atmos. Sci., 64, 4489-4496, 10.1175/2007jas2412.1, 2007.

Tinney, E. N., Homeyer, C. R., Elizalde, L., Hurst, D. F., Thompson, A. M., Stauffer, R. M., Vomel, H., and Selkirk, H. B.: A modern approach to a stability-based definition of the tropopause, Mon. Weather Rev., 150, 3151-3174, 10.1175/mwr-d-22-0174.1, 2022.