

Dear Referee #1

We thank Referee #1 for the careful review of our manuscript and for the constructive and insightful comments. These suggestions have helped us improve the clarity and quality of the manuscript. Our detailed responses to each comment are provided below.

Major Comments

Referee comment: -

There appear to be unphysical vertical stripes in the left column of figures 4–7, suggesting that the values are uniform across latitude at each longitude. If these panels represent the spatial patterns of the first SVD mode, I would expect them to be two-dimensional latitude–longitude maps rather than one-dimensional patterns. Please verify the SVD calculation and plotting.

Answer: -

Thank you for this important comment. We have carefully verified the SVD calculation and plotting procedure. We would like to clarify that the left-column panels in Figures 4–7 represent the monthly Tropical Edge Latitude (TEL) fields based on both the Tropopause Drop (TPD) and Tropopause Gradient (TPG) definitions. Since TEL is originally defined as a latitude value for each month, the TEL value is assigned to all longitude points at the corresponding latitude, resulting in a two-dimensional monthly TEL field. These monthly fields are then combined over the entire study period to construct a three-dimensional TEL dataset, which is subsequently used in the SVD analysis.

Therefore, the apparent vertical stripes in the TEL panels are not caused by an error in the SVD calculation or plotting. They reflect the construction of the TEL spatial field, in which the TEL value is repeated along longitude for the corresponding latitude. The procedure used to construct the three-dimensional TEL dataset is described in Lines 401–404 of the manuscript.

Minor Comments:

Referee comment: -

*Line 155: Does Trp mean the “average” of temperature from the surface to the LRT level?
Same for lines 267&268, are Trp-1&Trp-2 calculated as layer-averaged temperatures?*

Answer: -

Thank you for pointing out this important point. We agree that the definition of the tropospheric temperature variables was not sufficiently clear in the original manuscript. We have clarified the methodology and explicitly stated that Trp represents the vertically averaged temperature from the surface to the LRT level. Similarly, Trp-1 and Trp-2 represent the layer-averaged temperatures calculated over their respective vertical layers. The corresponding descriptions have been added/revised in the manuscript to make the calculation of these parameters clear to the reader.

Referee comment: -

Lines 193-195: This paragraph starts by discussing the seasonal variability (max and min) in LRT-H and LRT-T over the decades. It's not clear that this is then described as being consistent with the standard deviation of the monthly anomalies.

Answer: -

Thank you for this helpful comment. We agree that the original placement of the paragraph could make the connection between the seasonal variability and the standard deviation of the monthly anomalies unclear. To improve the logical flow and consistency of the discussion, we have moved Lines 193–195 to immediately after the LRT-H anomaly results, where the comparison with the standard deviation of the monthly anomalies is more appropriate and clearer to the reader. The corresponding text has also been highlighted in the revised manuscript to facilitate its identification.

[LRT-H displays a maximum positive anomaly of approximately 0.41 km occurring in August 2020 and the greatest negative anomaly of approximately -0.46 km in June 1992.

After November 1997, its anomaly time series shows mostly positive values, which means that the Mediterranean region has been getting warmer (Fig. 1c). These results are consistent with Seidel and Randel (2006), who reported tropopause monthly anomalies with standard deviations (SDs) ranging between 0.20 and 0.60 km for LRT-H. In the case of LRT-T, it exhibits a maximum positive anomaly of approximately 2.01 K in January 1993 and a greatest negative anomaly of approximately -2.08 K in January 1998. It shows a dominant negative anomaly after June 1993, reflecting a predominant warming pattern over the study area (Fig. 1d).]

Referee comment: -

Line 203: The argument that “The LRT-T regression map reveals a spatial pattern opposite to that of LRT-H” doesn’t seem to hold between 40-50N, which accounts for nearly one-third of the study area. In figure 1f, temperature change between 40-50N is positive and insignificant, while LRT-H in figure 1e shows a significantly increase in the same area.

Answer: -

Thank you for pointing this out. We agree that the statement was too general and did not accurately describe the spatial patterns across the entire study region, particularly between 40–50°N. Accordingly, we have removed this sentence from the revised manuscript to avoid any potential misinterpretation.

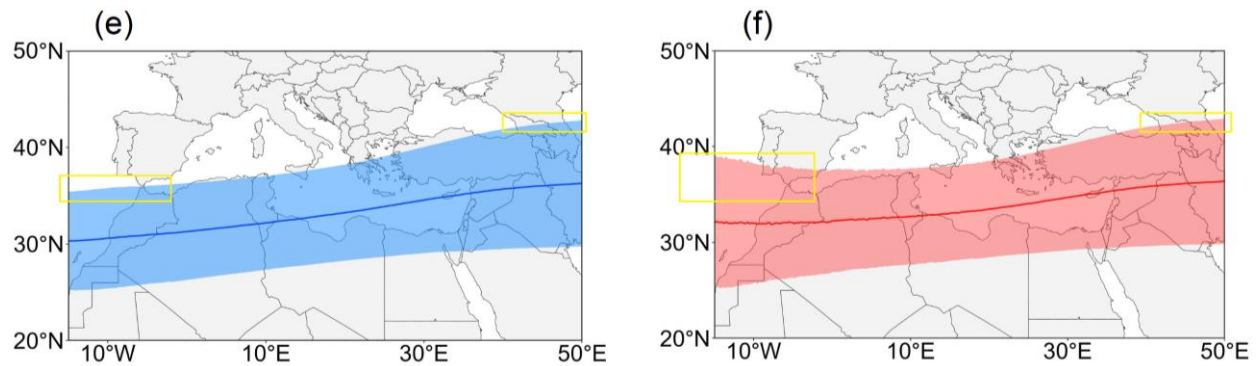
Referee comment: -

Line 231: Please clarify “TEL variability in the TPG method is higher than in the TPD method”. It’s hard to see the difference from the figures.

Answer: -

As shown in Figures 2e and 2f, the TPG TEL exhibits greater spatial variability than the TPD TEL, with relatively small variability in the eastern Mediterranean and a more

pronounced spatial pattern toward the western Mediterranean. We have clarified this point in the revised manuscript.



Referee comment: -

Lines 271-288: Could you expand the discussion of the correlation results? For example, why is the correlation between Ts and TPD TEL higher than that between Ts and TPG TEL?

Answer: -

We sincerely thank the Referee for drawing our attention to this issue. We carefully rechecked the data processing and correlation analysis underlying Figure 3 and identified the need for revision of the corresponding result. Following this re-examination, we have corrected and updated Figure 3a accordingly. The revised Figure 3a now presents the recalculated correlation pattern between surface temperature (Ts) and the TPD TEL, using the same preprocessing and analysis procedure applied to the other climatic parameters. We have also updated the corresponding description and interpretation in the abstract, results, and conclusion sections. In addition, more interpretation was added to the whole section.

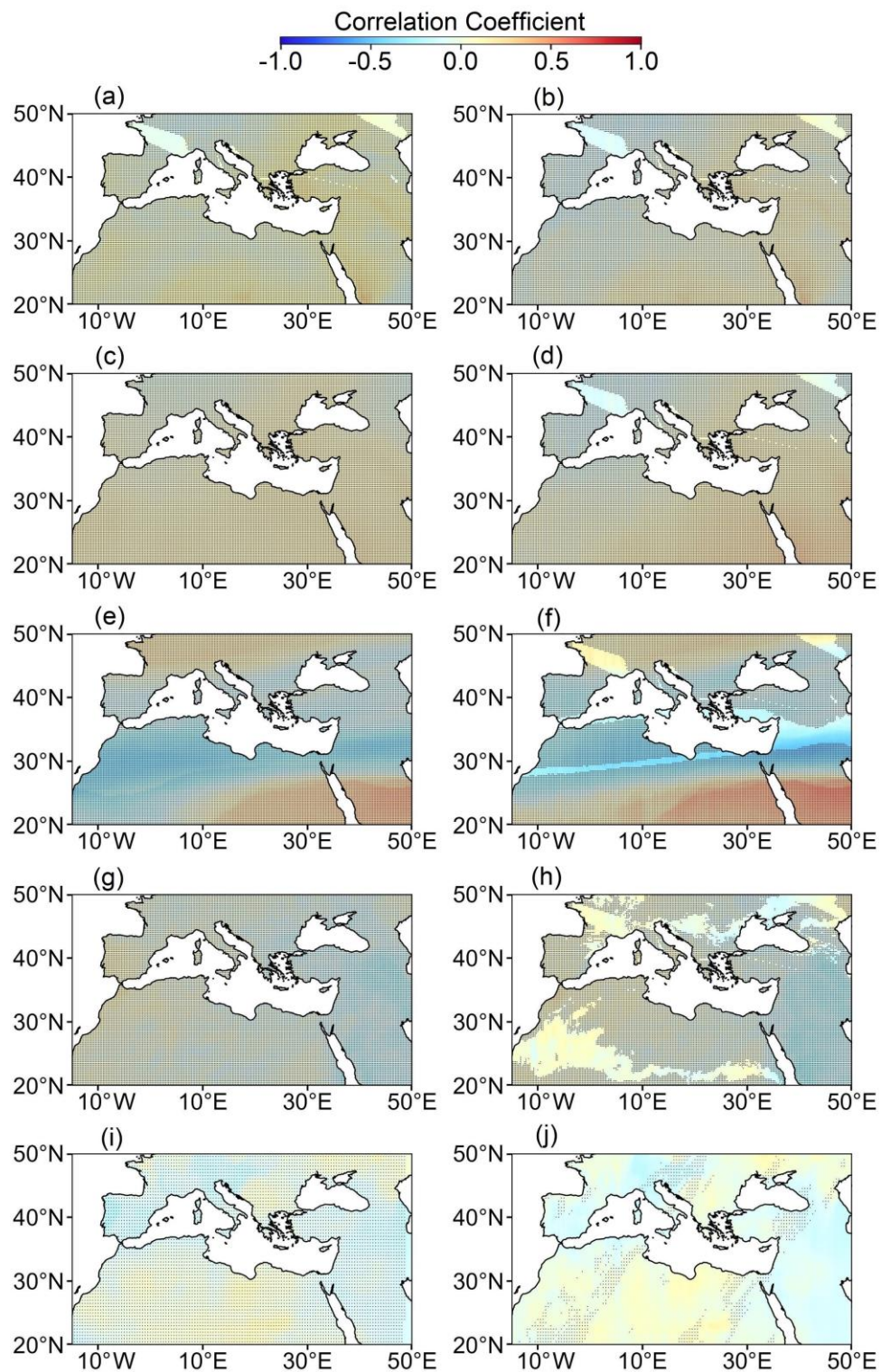


Figure 3. Correlation maps of TPD TEL (left) and TPG TEL (right) with climatic parameters, where the Pearson correlation coefficient was computed independently at each grid point. Ts (a, b), Trp-1 (c, d), Trp-2 (e, f), precipitation (g, h), and SPEI (i, j). Black stippling indicates grid points where the correlation coefficients are statistically significant at $p < 0.05$.

Referee comment: -

Figure 8: The significance stippling appears to be identical in 8d and 8f. Is this expected, or could it be a plotting issue?

Answer: -

Thank you for pointing this out. We agree that the similarity in the significance stippling between panels 8d and 8f could cause confusion and raise concerns about the plotting procedure. We have carefully checked the significance calculations and plotting and have modified Figure 8 accordingly in the revised manuscript.

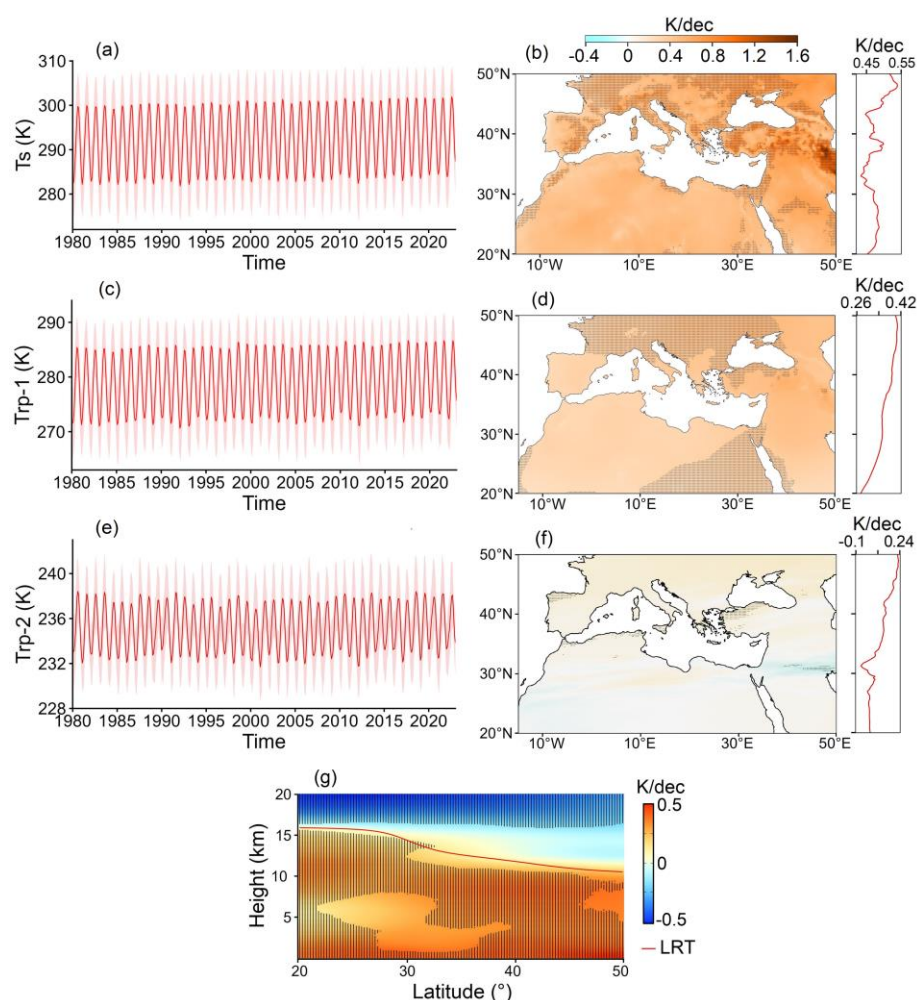


Figure 8. On the left, monthly time series of Ts (a), Trp-1 (c), and Trp-2 (e). The solid lines indicate the monthly mean values, while its surrounding light shading denotes the SD at each time step. On the right, decadal trends regression maps and their corresponding zonal mean, Ts (b), Trp-1 (d), and Trp-2 (f). Temperature trends in the troposphere and lower stratosphere (0-20 km) in addition to LRT-H represented by the red line (g). Black stippling indicates regions where the trends are statistically significant at $p < 0.05$.

Dear Referee #2

We would like to thank Referee #2 for the thorough review and valuable comments on our manuscript. We appreciate the reviewer's constructive suggestions, which have helped us significantly improve the manuscript. Our responses to the individual comments are given below.

Referee comment: -

• *As there are many different acronyms in the manuscript I suggest considering adding a list of acronyms. This could tremendously help readers to better understand the text.*

Answer: -

Thank you for this valuable suggestion. We agree that a list of acronyms would improve the readability of the manuscript. Accordingly, we have added a List of Acronyms to the revised manuscript, including the main acronyms used throughout the text, to facilitate readers' understanding and reference.

Appendix A: List of abbreviations (in alphabetic order)

<i>AR5</i>	<i>Fifth Assessment Report</i>
<i>DJF</i>	<i>winter</i>
<i>GHG</i>	<i>greenhouse gas</i>
<i>GNSS-RO</i>	<i>global navigation satellite systems radio occultation</i>
<i>IPCC</i>	<i>Intergovernmental Panel on Climate Change</i>
<i>JJA</i>	<i>Summer</i>
<i>LRT</i>	<i>lapse rate tropopause</i>
<i>LRT-H</i>	<i>LRT height</i>
<i>LRT-T</i>	<i>LRT temperature</i>
<i>MAM</i>	<i>Spring</i>
<i>NH</i>	<i>Northern Hemisphere</i>
<i>r</i>	<i>Correlation coefficient</i>
<i>R²</i>	<i>Coefficient of determination</i>
<i>SC</i>	<i>Expansion coefficients</i>

<i>SCF</i>	<i>Squared covariance fraction</i>
<i>SD</i>	<i>Standard deviations</i>
<i>SON</i>	<i>Autumn</i>
<i>SPEI</i>	<i>Standardized Precipitation Evapotranspiration Index</i>
<i>SST</i>	<i>Sea-surface temperature</i>
<i>SVD</i>	<i>Singular value decomposition</i>
<i>TEL</i>	<i>Tropical edge latitude</i>
<i>TPD</i>	<i>Tropopause drop</i>
<i>TPG</i>	<i>Tropopause gradient</i>
<i>Trp</i>	<i>Tropospheric temperature, averaged from the surface to the LRT level</i>
<i>Trp-1</i>	<i>Lower Trp, averaged from the surface to 5 km in height</i>
<i>Trp-2</i>	<i>Upper Trp, averaged from 5 km in height to LRT level</i>
<i>Ts</i>	<i>Surface temperature</i>
<i>WMO</i>	<i>World Meteorological Organization</i>

Referee comment: -

- *Abstract: are all these acronyms really necessary in the Abstract? For example, “LRTH”, “TPD”, “TPG”, “SVD1, and “SVD2” are introduced but never reused in the Abstract.*

Answer: -

Thank you for this valuable suggestion. We agree that the use of acronyms in the Abstract should be limited to those that are necessary and repeatedly used. Accordingly, we have revised the Abstract and removed the acronyms LRT-H, TPD, TPG, SVD1, and SVD2, replacing them with their full terms where appropriate. This revision improves the readability and clarity of the Abstract and avoids introducing acronyms that are not reused within the Abstract.

Referee comment: -

- *Line 75: either write “in the ocean circulation” or “in ocean circulations”*

Answer: -

Thank you for pointing this out. We modified it to be [*“in ocean circulations”*]

Referee comment: -

• Line 125-127: Please check if this sentence is correct. Do you really employ multiple datasets of monthly temperature data on pressure levels from ERA5 to determine the lapse rate tropopause (LRT) parameters (height and temperature)? Which “multiple temperature datasets from ERA5” do you refer to? In case, additional information would be helpful

Answer: -

Thank you for pointing this out. We agree that the original wording was ambiguous and could incorrectly suggest that multiple ERA5 temperature datasets were used to determine the LRT parameters. We have therefore revised the sentence to clarify the datasets and their temporal coverage. The revised text now reads:

“We employ multiple datasets spanning January 1980 to December 2022. Monthly averaged temperature data on pressure levels from ERA5, the fifth-generation ECMWF reanalysis, are utilized to determine lapse rate tropopause (LRT) parameters (height and temperature).”

Referee comment: -

• Line 149: Is the additional term “poleward” necessary? I suggest: “maximum LRT-H meridional gradient”. This is also more similar to how the cited papers phrase it.

Answer: -

Thank you for this helpful suggestion. We agree that the term “poleward” is unnecessary in this context and that the suggested wording is more consistent with the terminology used in the cited studies. Accordingly, we have revised the manuscript and replaced

“maximum poleward LRT-H meridional gradient” with “maximum LRT-H meridional gradient” as suggested.

Referee comment: -

• Line 193-195: *This sentence only refers to LRT-H, so moving it right after your LRT-H result in Line 190 would improve the flow for the reader. If this sentence stays in its current place, I as a reader, miss a similar reference for LRT-T.*

Answer: -

We agree that moving this sentence immediately after the LRT-H result improves the logical flow and readability of the manuscript. Accordingly, we have moved the sentence to follow the LRT-H result and modified the manuscript accordingly.

Referee comment: -

• Line 254: *I suggest: “due to warming at the surface and in the troposphere”.*

Answer: -

Thank you for pointing out this.

Done.

Referee comment: -

• Line 259-261: *This sentence is really complicated to understand; please rephrase it.*

Answer: -

We followed your suggestion and have modified the revised manuscript accordingly.

[The TPG TEL median values are higher than those of TPD TEL, being maximum in JJA at about 41.00° and minimum in MAM at about 30.33°.]

Referee comment: -

- Line 445, 451, 452: remove the comma in “TPD, TEL” and “TPG, TEL”; I assume you mean “TPD TEL” and “TPG TEL”.

Answer: -

Done.

Referee comment: -

- Line 511: The sentence is grammatically not complete, my suggestion is: “reported that the Eastern Mediterranean and the Middle East are”.

Answer: -

Done.

Referee comment: -

- Line 513: The last part of the sentence (“and particular locations far more drastic changes.”) sounds vague, please improve or remove it.

Answer: -

Done. We removed it.

Referee comment: -

- Line 514: It should be “shows” instead of “showing”.

Answer: -

Done.

Referee comment: -

- *Line 529-531: This sentence sounds slightly misleading. Consider removing “over height ranges” to improve the clarity of the sentence.*

Answer: -

Thank you for this helpful suggestion. We agree that the phrase “over height ranges” may be misleading and could affect the clarity of the sentence. Accordingly, we have removed “over height ranges” from the manuscript and revised the sentence to improve its clarity and readability.

Referee comment: -

- *Line 553-557: This sentence is grammatically incorrect and very long, please improve*

Answer: -

Thank you for this helpful comment. We have revised the sentence to improve its clarity and scientific interpretation. The modified text in the manuscript now reads:

[This is in accordance with previous studies that reported a clear trend toward declining precipitation, particularly during DJF months, which poses serious implications for the region's ecosystems and water resources (Cos et al., 2022; Delworth et al., 2022; André et al., 2024).]

Referee comment: -

- *Line 572: Please remove “While” or rephrase the sentence so that it is grammatically correct.*

Answer: -

Done.

Referee comment: -

- Line 586: Add “patterns” after “LRT-H anomaly”.

Answer: -

Done.

Referee comment: -

- Line 587-588: The text says: “Moreover, LRT-H shows dominant upward trends over the study area, [...]”. This appears repetitive with your newly added sentence in lines 585-587 where you state that LRT-H anomalies are predominantly positive which indicates a progressive rise.

Answer: -

To avoid repetition, we modified Line 587-588 to be: [The LRT-H shows maximum upward trend of approximately 266.50 m/dec in the eastern Mediterranean, reflecting intensifying warming conditions.]

Referee comment: -

- Line 617: remove “nearly”

Answer: -

Done.

Referee comment: -

- Line 641: remove the comma after variability

Answer: -

Done.