

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.

General comments

Referee comment: -

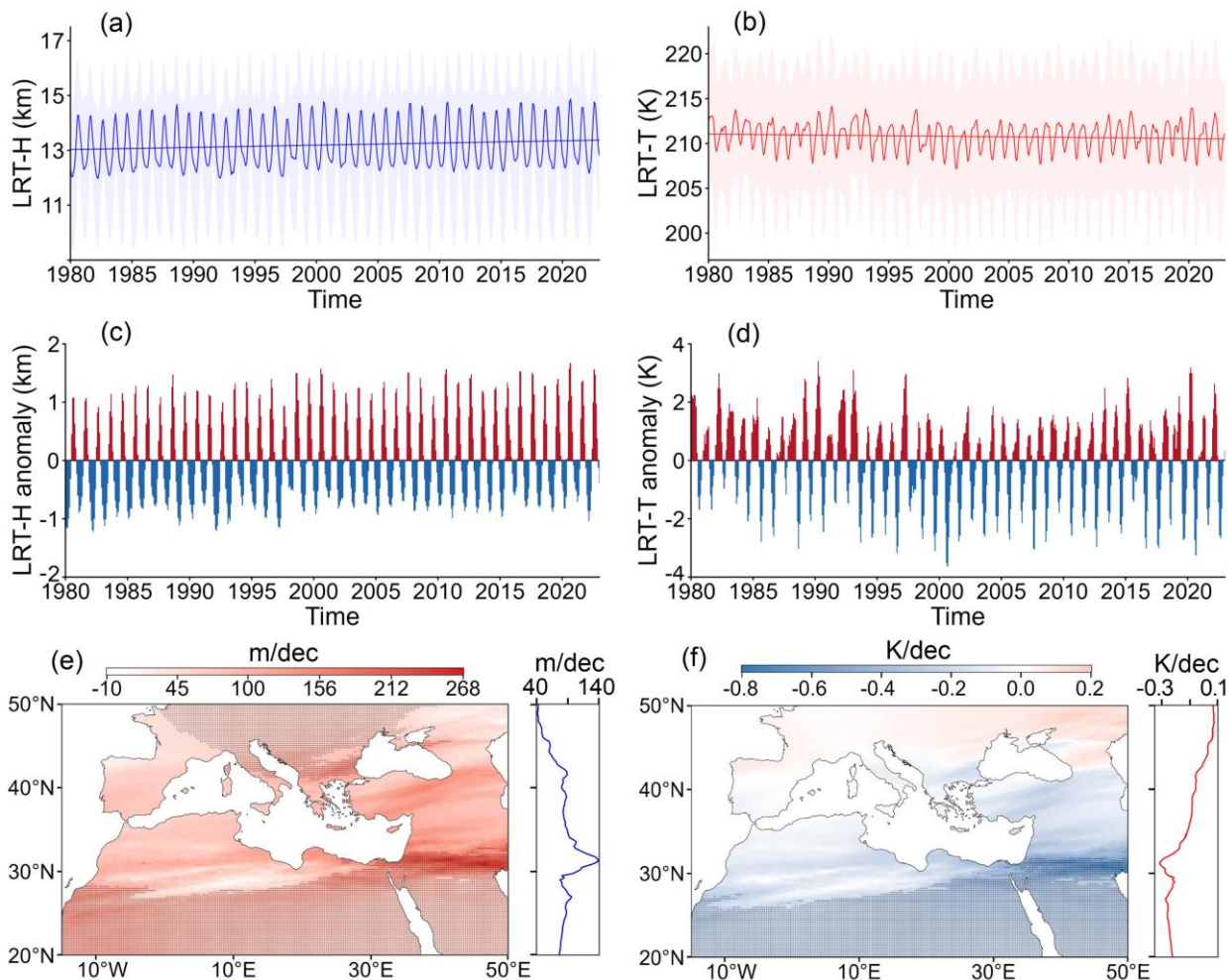
Throughout the manuscript, but especially in the figure captions the investigation period “over the period January 1980 to December 2022” is over-repeated. For example in the caption of Fig. 1 it is stated 3-times, and in the caption of Fig. 2 it is mentioned 4-times. Reduce most of the repetitions, particularly in figure captions. Moreover in the figures when time series are shown, it is not necessary to repeat the investigation period in the axis labelling – it is comprehensible from the time-axis and it is also referred to in the text. Rather state the unit e.g., “Time (years)”.

Answer: -

We thank the reviewer for this helpful suggestion. The repeated statements of the investigation period (January 1980–December 2022) have been reduced throughout the manuscript, particularly in the figure captions. The study period is now stated only where necessary, mainly in the main text when first introduced. In addition, the time-series figures' x-axis labels are modified (e.g., “Time”) instead of repeating the investigation period. These changes improve the readability and conciseness of the manuscript.

Example: As shown in Figure 1, the figure caption has been revised following the reviewer’s suggestion. Additionally, the x-axis label of the monthly time series, previously written as “Time (Jan. 1980–Dec. 2022),” has been simplified to “Time.”

Figure 1. *Monthly time series of LRT parameters in the top: (a) LRT-H and (b) LRT-T. Tropopause anomaly in the middle: (c) LRT-H anomaly time series, (d) LRT-T anomaly time series. Linear regression analysis of LRT parameters at all grid points and their decadal trends in the bottom: (e) LRT-H and (f) LRT-T. Black stippled regions indicate grid points where the trends are statistically significant at $p < 0.05$. The zonal mean is displayed on the right side of each regression map.*



Referee comment: -

The mention of seasons is not consistent e.g., in Lines 196-201 seasons are stated e.g., as “summer”, “winter”, whereas in Lines 265-276 e.g., “Summer (JJA)”, “Winter (DJF)”, and in Line 278 as “Summer”, “Winter”. I suggest to introduce the seasons in the beginning what is meant with e.g., “summer” or use the short form e.g., “JJA” throughout the text. It does not need to be mentioned every time. Also, seasons are never capitalized.

Answer: -

The presentation of seasons has been revised throughout the manuscript to ensure consistency. The seasons are now introduced at their first occurrence in the manuscript using both the full name and the corresponding abbreviation (e.g., summer (JJA), winter

(DJF), spring (MAM), and autumn (SON)). Thereafter, only the abbreviations are used throughout the text. In addition, the capitalization of seasons has been corrected so that season names are written in lowercase.

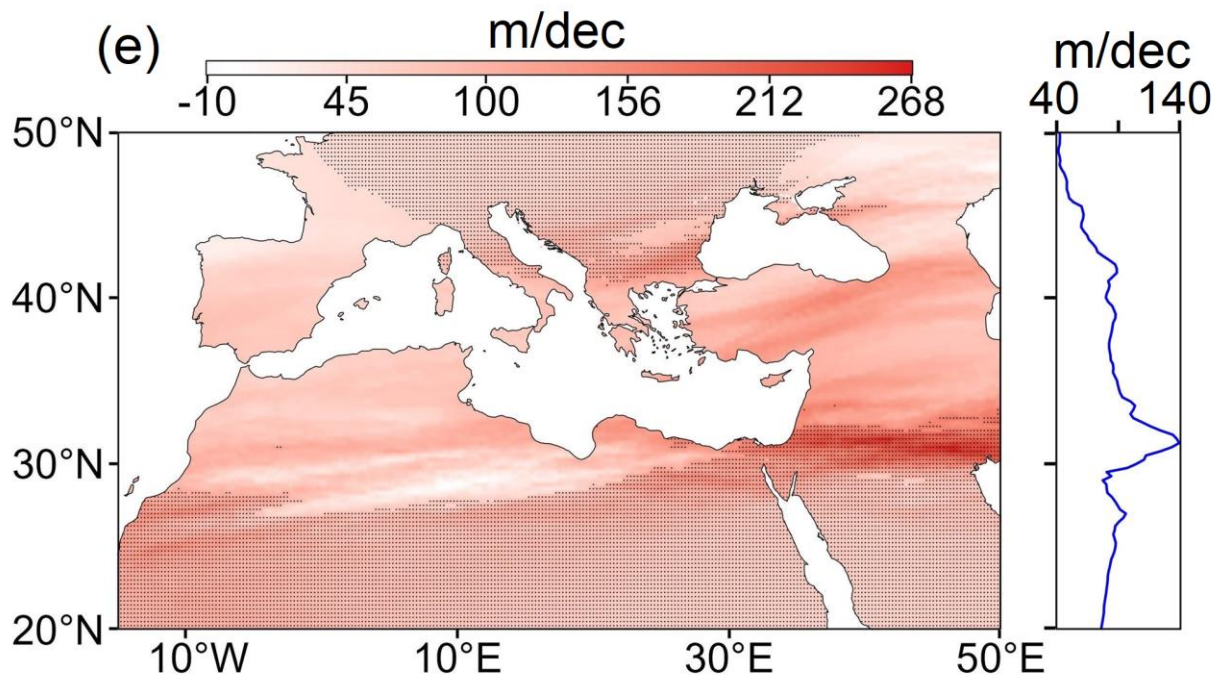
Referee comment: -

The authors state for multiple plots that “statistically significant trends at $p < 0.05$ at most of the grid points”, could you add some hatching in the respective plots to indicate the grid points for which this statement valid?

Answer: -

In the revised manuscript, we indicated the statistically significant trends ($p \leq 0.05$) in all trend maps using stippled regions. This representation highlights the grid points where the trends are statistically significant and improves the clarity of the figures. The figure captions have been updated accordingly.

Example: As shown in Figure 1e, black stippled regions indicate grid points where the trends are statistically significant at $p < 0.05$.



Referee comment: -

The authors should be more consistent with the formatting of their figures e.g., where the labels of the sub panels are located – sometimes they are at the top left whereas in other figures they are at the top right. Also the font size of the axis labels needs to be increased in all figures. And it should be considered to add coastlines in map plots for better geographical orientation.

Answer: -

The formatting of all figures has been revised to ensure consistency throughout the manuscript. The positions of the subpanel's labels have been unified and are now placed in the top left corner in all figures. In addition, the font size of the axis labels has been increased in all figures to improve readability. Furthermore, coastlines have been added to all map plots to provide clearer geographical orientation.

Referee comment: -

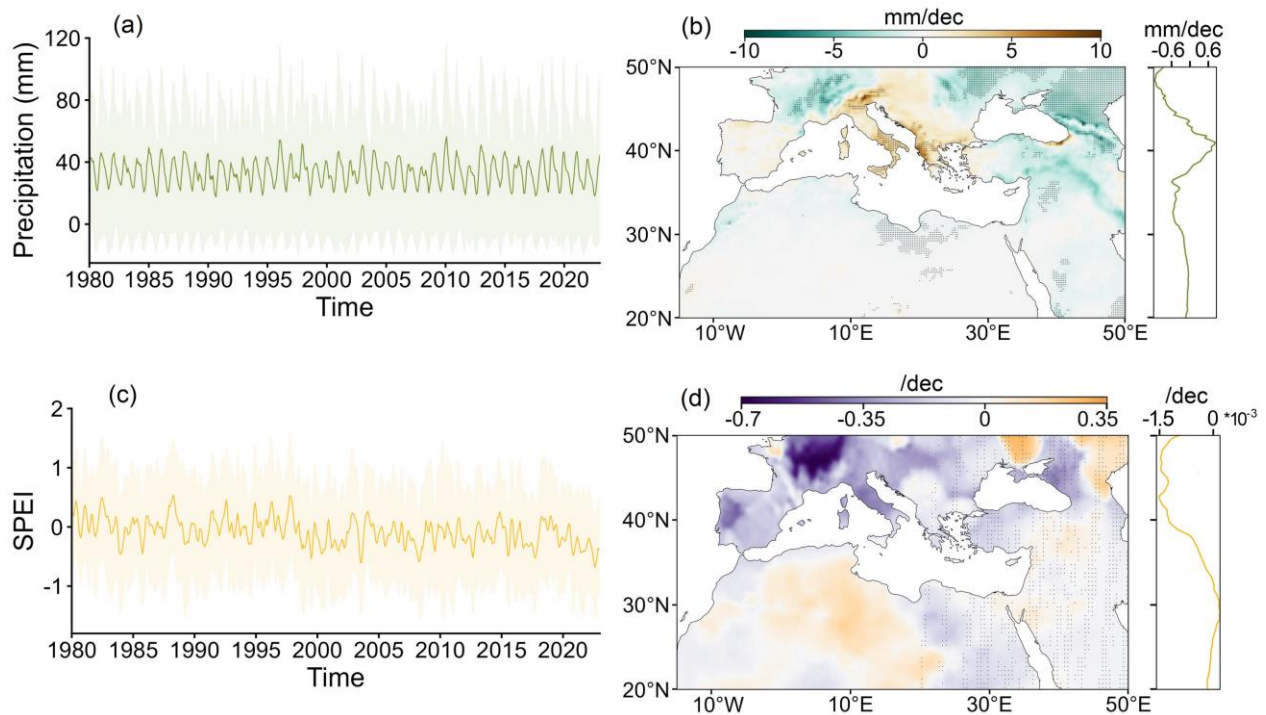
Use evenly distributed ticks for the colorbars and when possible round numbers in all the figures. This would greatly improve plot readability. Also, when using diverging colorbars, the authors should purposefully set the center, for example at zero, so that the colors are diverging from negative to positive values (e.g., Fig. 11d: Negative values are shown in teal, yellow and in brown, the same brown is then used for positive trend results. This makes the plot very difficult to interpret.)

Answer: -

All maps have been replotted to improve the readability and consistency of the figures. The colorbars now use evenly distributed ticks where it is possible, with rounded values across all figures. In addition, for plots using diverging color scales, the colorbars have been centered at zero, ensuring a clear divergence between negative and positive values. This revision ensures that negative values are represented by one color range and positive values by another, avoiding ambiguity and improving the interpretability of the plots. The colorbars in all relevant figures have been updated accordingly.

Example:

Figure 11. Monthly time series of precipitation (a) and its linear regression analysis at all grid points with decadal trends, with the zonal mean of the regression map on the right side (b). Monthly time series of SPEI (c) and its linear regression analysis at all grid points with decadal trends, with the zonal mean of the regression map on the right side (d). Black stippled areas denote grid points with statistically significant trends at $p < 0.05$.



Referee comment: -

Be consistent with the post comma digits (significant digits) e.g., Line 268 its 38.83°, Line 269 29.2° and Line 275 41°. Another example is Line 273 “-0.07 ± 0.001”.

Answer: -

We thank the reviewer for pointing out this inconsistency. The numerical values throughout the manuscript have been revised to ensure a consistent representation of significant digits. The number of digits after the decimal point has been standardized for comparable quantities, and the specific examples noted by the reviewer have been corrected.

Referee comment: -

Throughout the manuscript there are many instances where the term “Figure” is used in text, although it should be “Fig.” (e.g., Line 211 “Figure 1e” should be “Fig. 1e”).

Answer: -

We have carefully revised the manuscript, and all instances of “Figure” in the text have been replaced with the journal-preferred abbreviation “Fig.” where appropriate. These changes have been implemented consistently throughout the manuscript.

Examples:

Line 217: (right panel of Figure 1f) *changed to* (right panel of Fig. 1f)

Line 513: on the right panel of Figure 10b *changed to* (right panel of Fig. 10b)

Referee comment: -

Some references are missing the DOI, please check.

Answer: -

We carefully reviewed the entire reference list, and the missing DOIs have now been identified and added where available. The reference list has been updated accordingly in the revised manuscript.

Specific comments

Referee comment: -

Line 182: consider adding the period investigated from the other authors

Answer: -

We have added the investigated period reported in the cited study to the text and highlighted the modification in the revised manuscript to improve clarity and completeness. [consistent with Schmidt et al. (2008), who reported a global upward trend in LRT-H of 39 to 66 m/dec for the period from May 2001 to December 2007]

Referee comment: -

Figure 2:

- “TEL TPD” and “TEL TPG” should be “TPD TEL” and “TPG TEL”, check for consistency
- In sub panels (c) and (d) remove the redundant tick marks that make it look like a barcode, this is what the distribution function is showing. Also, use the same tick marks for these two sub panels (i.e., x-axis: 25, 30, 35, 40, 45, 50).

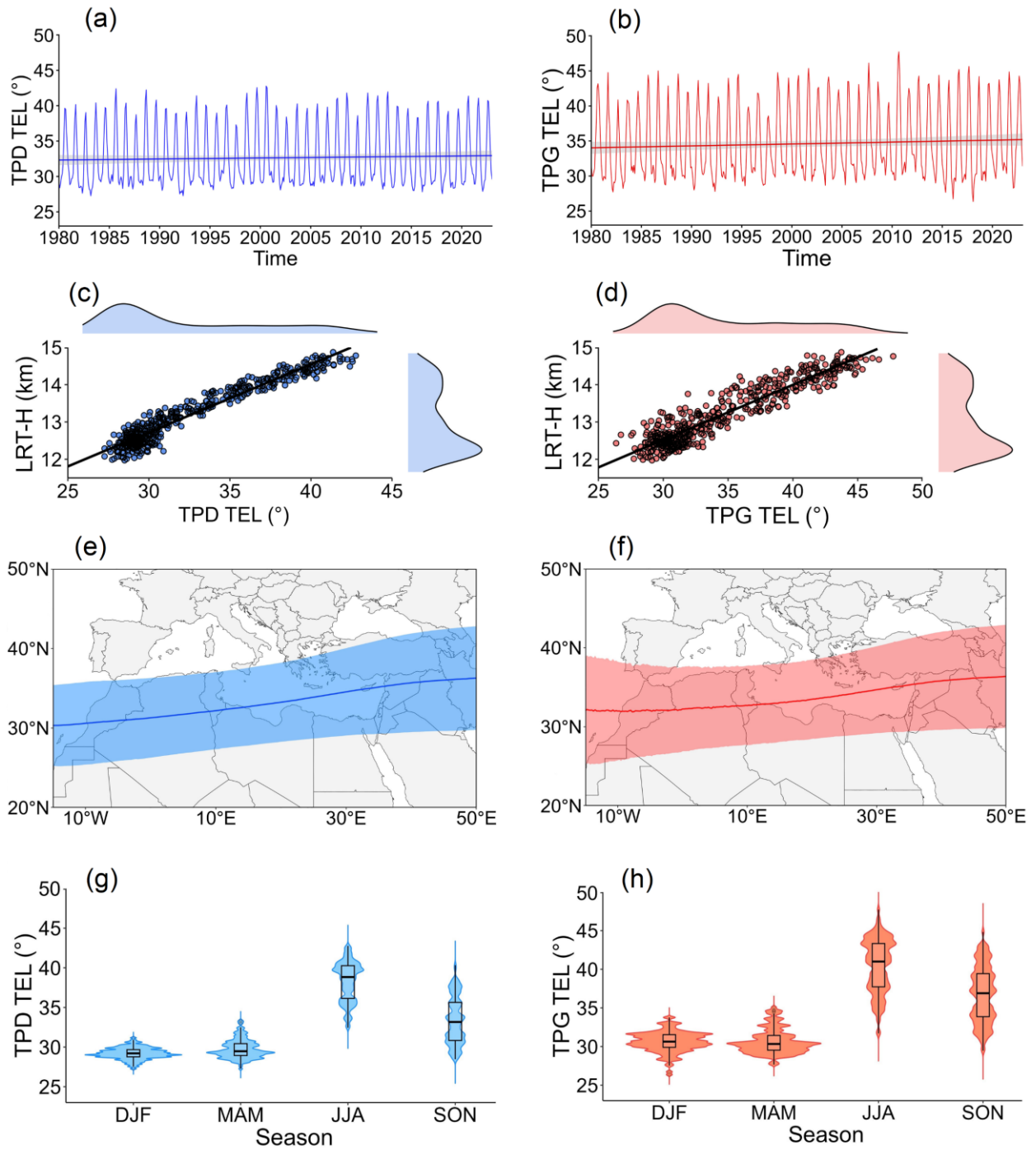
Answer: -

- The terminology has been corrected throughout the manuscript. “TEL TPD” and “TEL TPG” have been replaced with “TPD TEL” and “TPG TEL” in the entire text and in all figures to ensure consistency.
- The redundant tick marks in subpanels (c) and (d) of Figure 2 have been removed to improve clarity and to avoid the barcode-like appearance and improve the readability of the distribution functions. We also applied consistent ticks (25, 30, 35, 40, 45, 50) to the “TPD TEL” and “TPG TEL” in all subpanels of Figure 2.

We note that applying the same tick marks (i.e., x-axis: 25, 30, 35, 40, 45, 50) to Figure 2c was not possible because the density distribution in that panel will extend beyond the actual data range, and using those ticks would not properly represent the data. Therefore, the axis ticks in Fig. 2c were kept consistent with the actual data range to ensure accurate visualization.

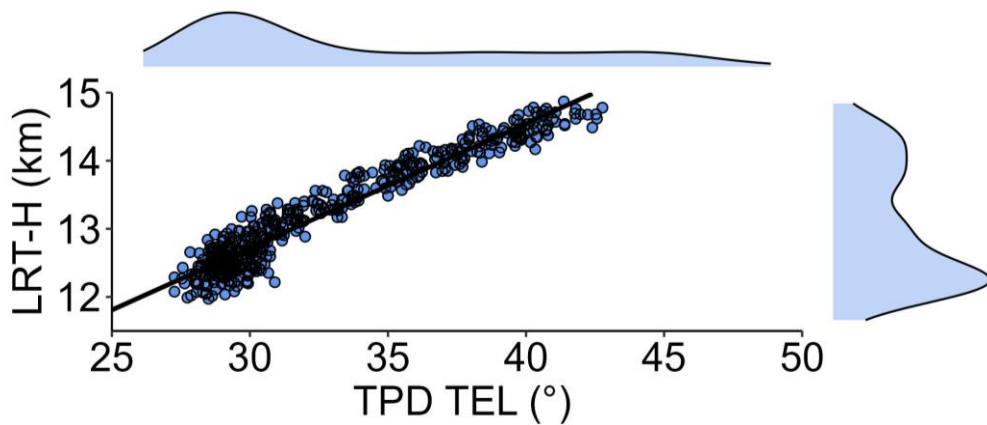
The following figures show our modifications: -

Figure 2. Monthly time series of the (a) TPD TEL method and (b) TPG TEL method. The linear regression model between TPD TEL and LRT-H (c) and the linear regression model between TPG TEL and LRT-H (d). Longitudinal variation of TEL using both methods over the Mediterranean region is displayed. The blue line in (e) represents the mean TPD TEL at each longitude over the study period, while the blue shading depicts its SD. In (f), the red line represents the mean TPG TEL at each longitude over the study period, with the red shading indicating its SD. Seasonal variation of TPD TEL (g) and TPG TEL (h).



If the same tick marks (i.e., x-axis: 25, 30, 35, 40, 45, 50) are applied to Figure 2c, the resulting appearance of the panel would be as shown below.

Figure 2c. The linear regression model between TPD TEL and LRT-H.



Referee comment: -

Line 261 & Line 262: The abbreviation for standard deviation “SD” has already been introduced in Line 203.

Answer: -

Corrected. The full-term standard deviation now appears only at its first occurrence (Line 203), and the abbreviation SD is used thereafter throughout the manuscript.

Referee comment: -

Figure 3 & Figure 4:

Be consistent with the labelling, replace TEL-D with TPD TEL and TEL-G with TPG TEL.

Answer: -

We have corrected the labeling in Figure 3 and Figure 4 to ensure consistency throughout the manuscript. The labels “TEL-D” and “TEL-G” have been replaced with “TPD TEL” and “TPG TEL,” respectively. The updated figures are included in the revised manuscript.

Figure 3. On the right side, correlation coefficients among monthly TPD TEL, TPG TEL, LRT-H, Ts, Trp, precipitation (Prec), and SPEI with 95% confidence intervals are shown. On the diagonal, the density distribution of all variables is displayed. On the left side, linear regression models between variables are depicted.

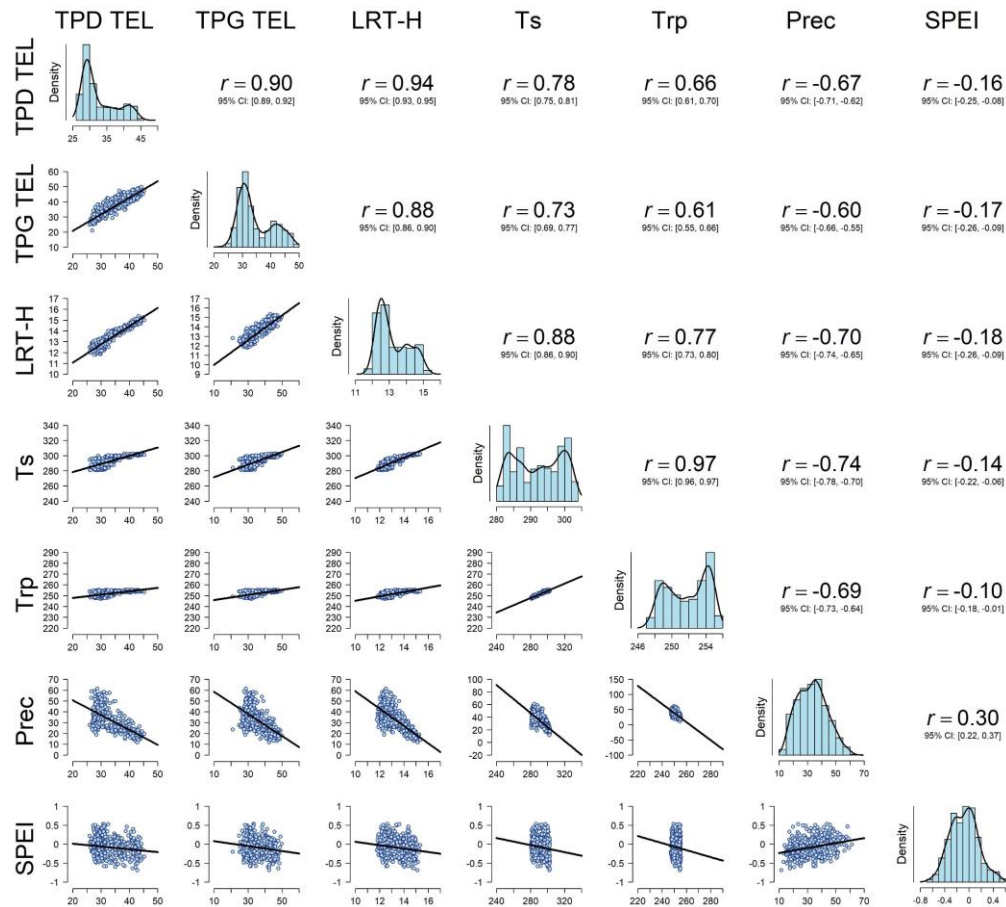
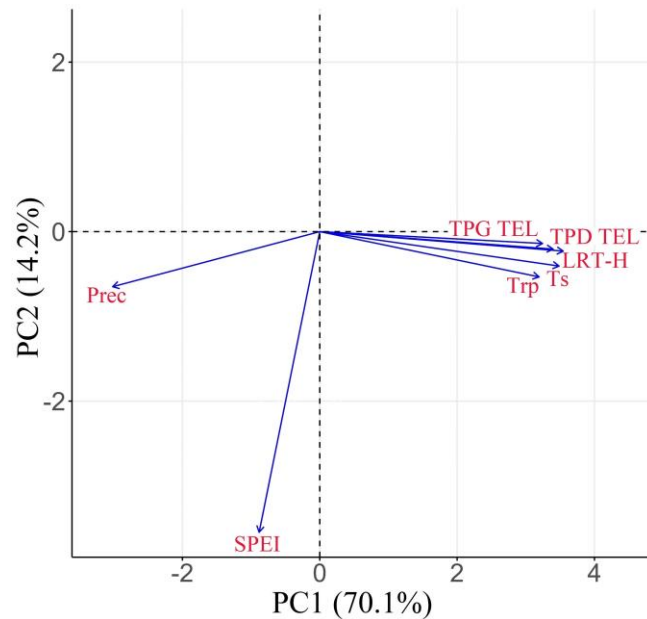


Figure 4. PCA biplot of monthly TPD TEL, TPG TEL, LRT-H, Ts, Trp, precipitation (Prec), and SPEI.



Referee comment: -

Line 403-405: The figure caption is unnecessary and the repetition can be misleading. Refer to the caption of Figure 5. Suggestion: "As in Fig. 5, but for TPG TEL."

Answer: -

To avoid repetition and improve clarity, the caption of Figure 6 has been shortened and now refers to Figure 5, as recommended. The revised caption now reads: **"Figure 6. WTC analysis as in Figure 5, but for TPG TEL and the corresponding climatic parameters."**

Referee comment: -

Figure 5 & Figure 6:

- "TEL TPD" and "TEL TPG" should be "TPD TEL" and "TPG TEL", check for consistency
- Add x-axis labelling and the respective units

Answer: -

The figures' titles "TEL TPD" and "TEL TPG" have been corrected to "TPD TEL" and "TPG TEL," respectively. Furthermore, the x-axis label has been added to clearly indicate that the analysis is based on monthly data.

Figure 5. WTC analysis between monthly TPD TEL and climatic parameters. Arrows indicate phase differences between the two series. Variables are in phase when arrows point to the right (moving in the same direction with cyclical effects on each other). If arrows point right and upward, the first variable is leading (causing the second variable); if pointing right and downward, the first variable is lagging. Variables are out of phase (having anticyclical effects) when arrows point to the left. If arrows point left and upward, the first variable is leading; if pointing left and downward, the first variable is lagging. TPD TEL and LRT-H (a), TPD TEL and Ts (b), TPD TEL and Trp (c), TPD TEL and precipitation (Prec) (d), and TPD TEL and SPEI (e).

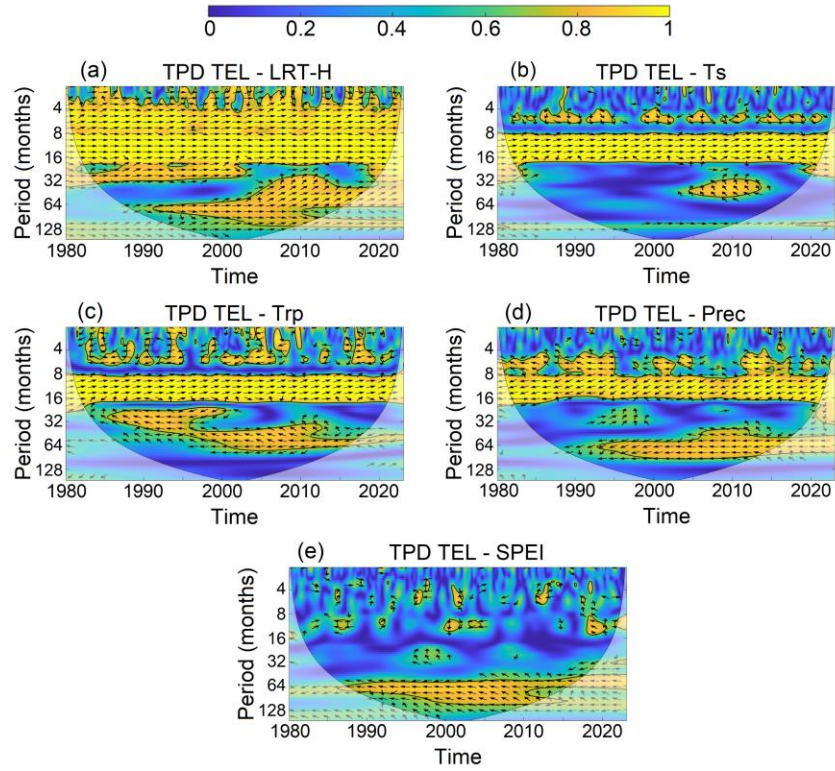
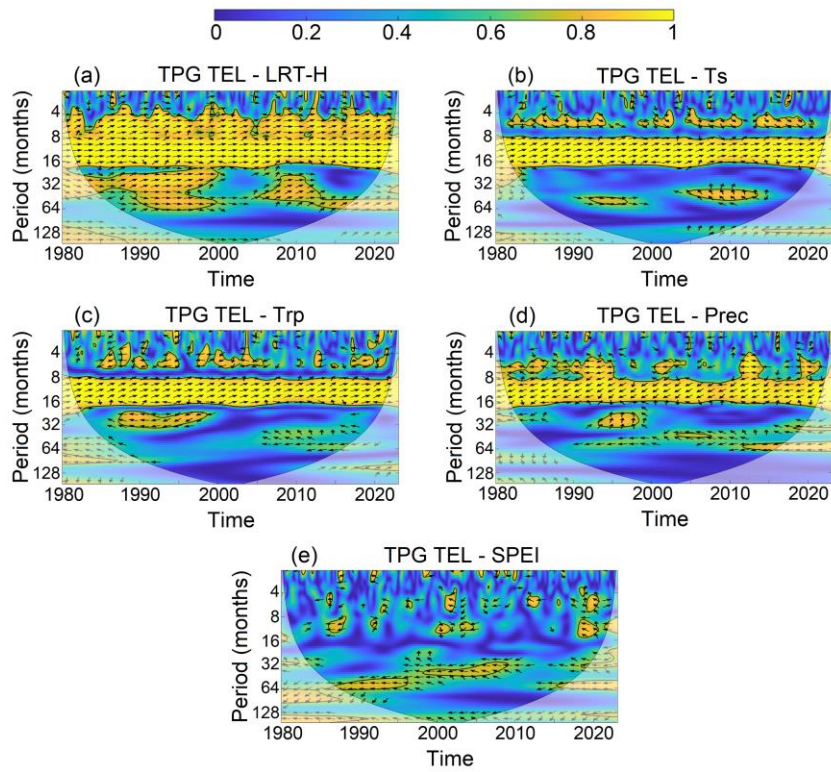


Figure 6. WTC analysis as in Figure 5, but for TPG TEL and the corresponding climatic parameters.



Referee comment: -

Figure 7:

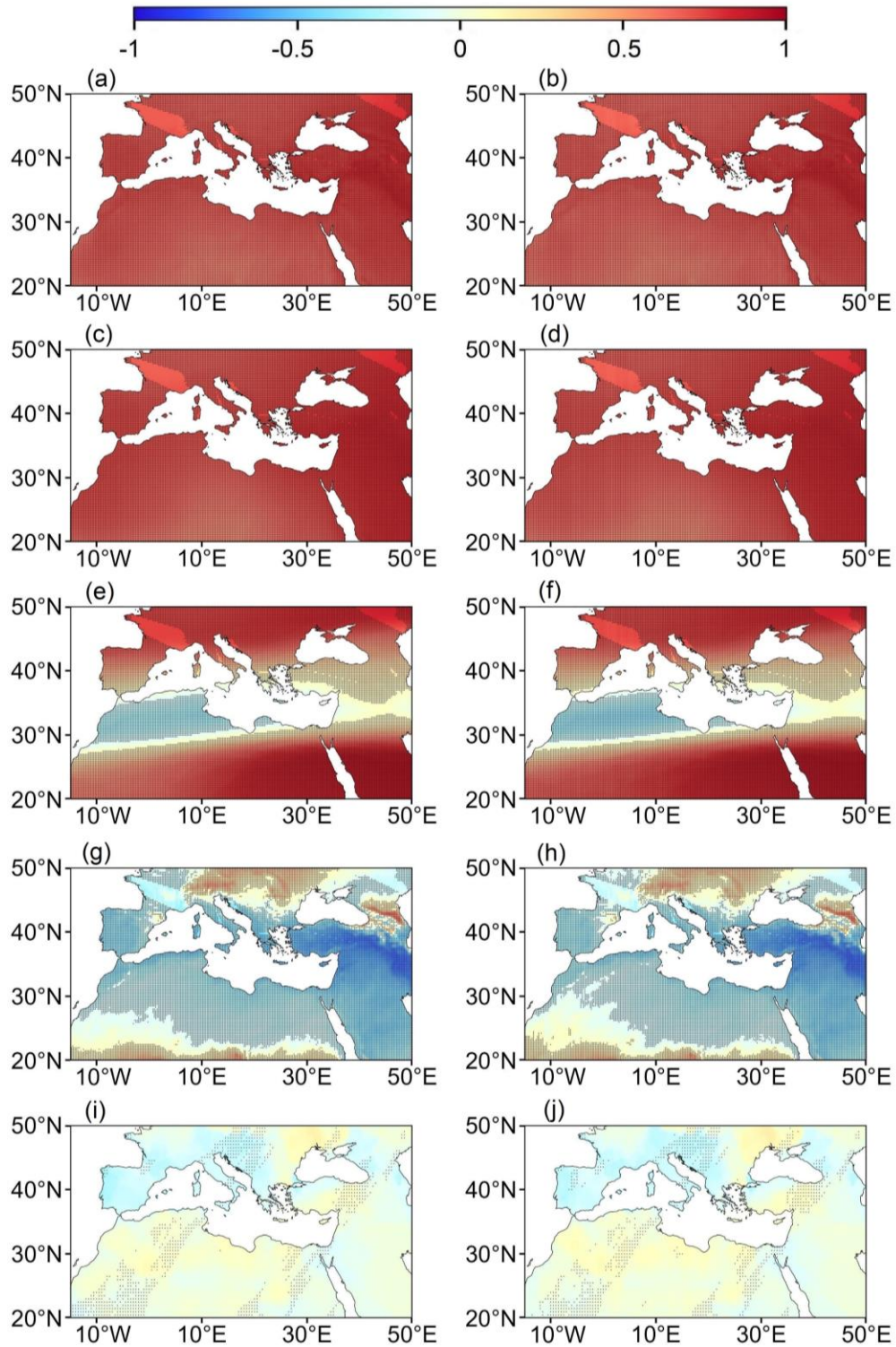
- *I suggest to have a uniform color range, so one can see how TPD TEL and TPG TEL correlate with the individual climatic parameters. Like this they are very hard to compare.*
- *Consider explaining in the text why you are now also looking at TRP-1 and TRP-2. This seems like an interesting approach, but why was it not included in the other tests and figures?*

Answer: -

- To facilitate comparison between the correlation patterns, we have modified Figure 7 by applying a single uniform color scale (colorbar) for all correlation maps. This ensures that the correlations of TPD TEL and TPG TEL with the individual climatic parameters are displayed using the same range, allowing for a more consistent and straightforward comparison. The updated figure has been included in the revised manuscript.
- We studied the relation between tropospheric temperature and TPD TEL and TPG TEL. From our experience, we know that tropospheric temperature has a positive correlation with TELs, and the relation is strong near the surface and becomes weaker upward, so in this stage of analysis we investigated the troposphere as two distinct height bands (lower tropospheric temperature from surface to 5 km height (Trp-1), and upper tropospheric temperature from 5 km to LRT level (Trp-2)), and we added in the manuscript the following section:

“To examine the relationship between TEL and Trp at different altitudes, Trp is divided into two distinct height bands. The first band corresponds to lower Trp (Trp-1) from the surface to 5 km in height, and the second band corresponds to upper Trp (Trp-2) from 5 km in height to LRT level.”

Figure 7. Spatial correlation of TPD TEL (left) and TPG TEL (right) with climatic parameters. 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 & Figure 9:

•As for Fig. 7, consider using a uniform range for the colorbar of the individual sub panels.

Line 496-500: Remove the repetitive figure caption. Refer to the caption of Figure 8.

Suggestion: “As in Fig. 8, but for TPG TEL.”

Answer: -

- To facilitate comparison, like in the case of Figure 7, we have modified Figures 8 & 9 by applying a single uniform color scale (colorbar) for all maps. This ensures that the coupling of TPD TEL and TPG TEL with the individual climatic parameters is displayed using the same range, allowing for a more consistent and straightforward comparison. The updated figures have been included in the revised manuscript.

- We have modified caption of Figure 9 to avoid any repetition “**Figure 9. SVD analysis** as in Figure 8, but for TPG TEL and the corresponding climatic parameters.”

Figure 8. First leading mode of covariability for the coupled fields of TPD TEL and climatic parameters. TPD TEL and T_s (a, b, c), TPD TEL and Trp-1 (d, e, f), TPD TEL and Trp-2 (g, h, i), TPD TEL and precipitation (j, k, l), and TPD TEL and SPEI (m, n, o). The spatial patterns for the first paired mode of covariability (SVD1) of TPD TEL (left), climatic parameter SVD1 (middle), and the time series of expansion coefficients (SC1) for the paired mode of both TPD TEL and climatic parameters (right).

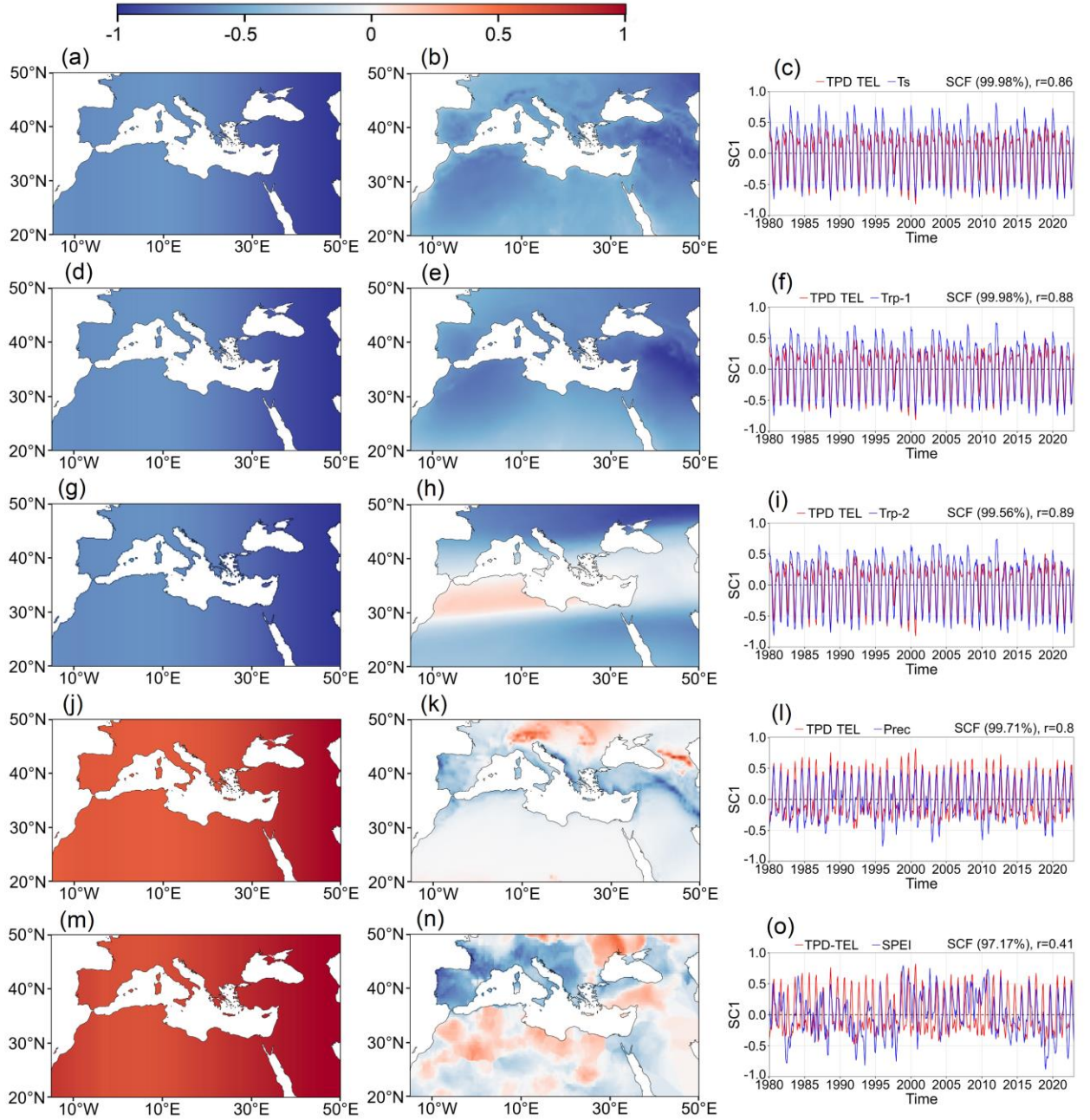
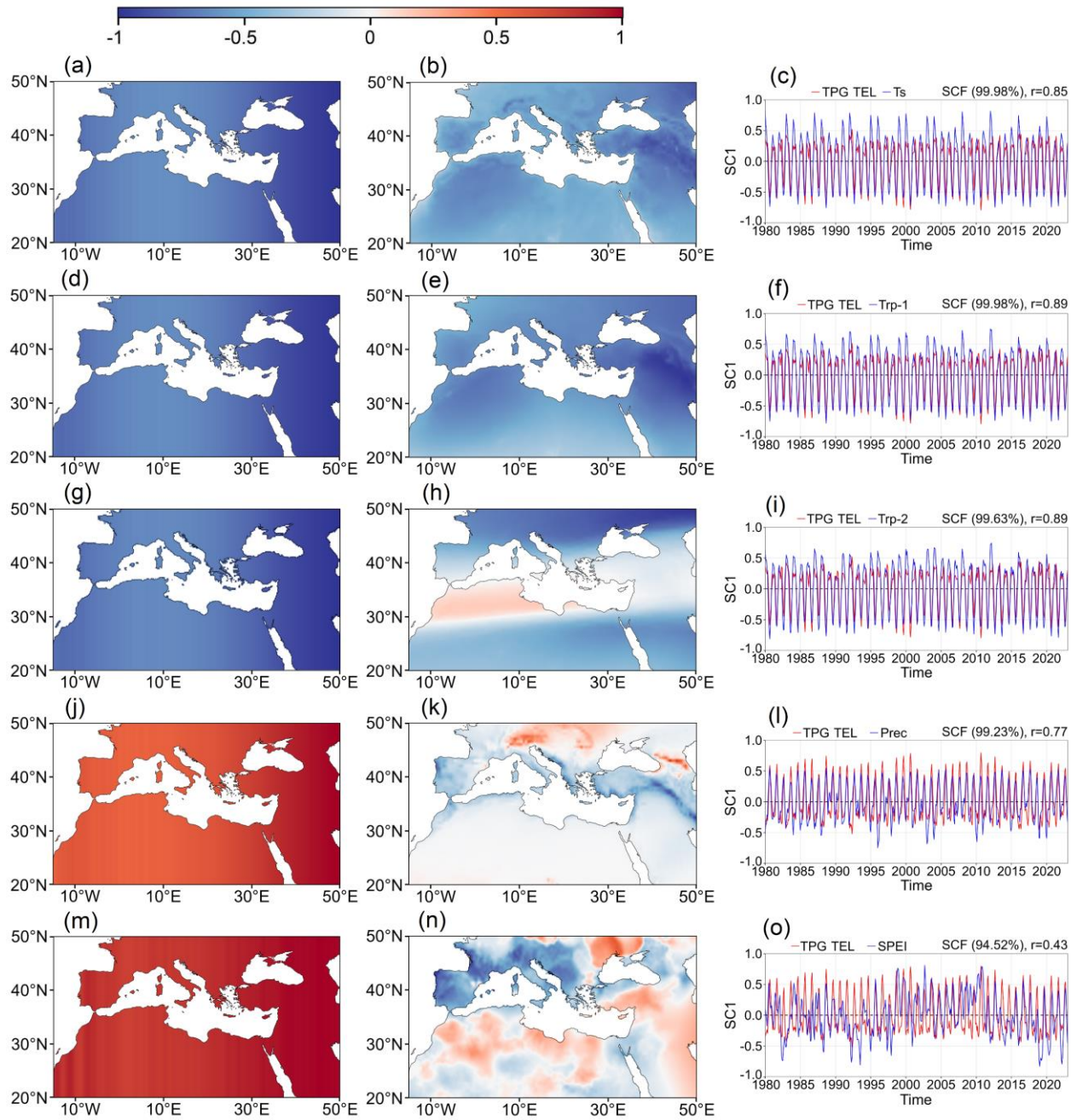


Figure 9. SVD analysis as in Figure 8, but for TPG TEL and the corresponding climatic parameters.



Referee comment: -

Lines 552-560: This caption is very repetitive – please improve it.

Answer: -

We have modified Figure 10's caption to be **“Figure 10. On the left, monthly time series of Ts (a), Trp-1 (c), and Trp-2 (e). 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 $p < 0.05$.**

Referee comment: -

Line 616: Consider discussing the lack of a significant relationship of SPEI.

Answer: -

We have added a discussion in the revised manuscript addressing the absence of a significant relationship between SPEI and other climatic variables. Specifically, we explain that this behavior is attributed to the composite nature of SPEI, which integrates both precipitation and evapotranspiration, as well as its sensitivity to time scale, regional variability, and lagged responses. These factors can obscure direct linear relationships with individual atmospheric parameters.

Technical corrections

Line 39: “greenhouse gases (GHGs) emissions” should be “greenhouse gas (GHG) emissions”

➤ Done

Line 59: it looks like a upper case zero not a “o”

➤ [Modified](#)

Line 69: add a “the” before “Hadley circulation”

➤ [Done](#)

Line 270: remove hyphen between TPD-TEL

➤ [Done](#)

Line 541, Line 544: “45° N-50° N” should be “45° N to 50° N”

➤ [Done](#)

Line 546: “20° N-30° N” should be “20° N to 30° N”

➤ [Done](#)

Line 595: “GHGs” should be “GHG”

➤ [Done](#)

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.

Major concerns

Referee comment: -

- 1. In session 2.3, pressure-level ERA5 data are interpreted to 100m resolution to calculate the tropopause. I'm wondering how accurate the interpolated data are. The cited paper (Hindley et al., 2015) used COSMIC data, which has a much higher vertical resolution than pressure-level ERA5. Have you tried using 137 model level ERA5 data and see if there is any difference in calculating the tropopause?*

Answer: -

We thank the reviewer for raising this important point regarding the vertical resolution of ERA5 data and the potential limitations associated with the use of pressure-level fields. In this study, we employed monthly averaged ERA5 data on 37 pressure levels, which were subsequently spline interpolated to a 100 m vertical grid. This approach was adopted to improve the detection of the lapse rate tropopause (LRT) by providing a smoother and more continuous representation of the temperature profile. Regarding this citation (Hindley et al., 2015), it has been removed from the manuscript.

While ERA5 model-level data (137 hybrid sigma-pressure levels) indeed offer higher intrinsic vertical resolution, their availability is typically limited to hourly temporal resolution, resulting in substantially larger data volumes and increased computational cost. These constraints pose practical challenges for long-term analyses over extended spatial domains. Importantly, the primary objective of this study is to investigate the spatiotemporal variability and long-term trends of the tropical belt edges and their interactions with climatic parameters, rather than to resolve fine-scale vertical temperature structures.

Therefore, the adopted methodology represents a balance between computational efficiency and physical consistency. To ensure the robustness of this approach, we further support it through the following analyses:

1. Validation of ERA5 (37 pressure levels) data against independent radiosonde observations.
2. Intercomparison of ERA5 (37 pressure levels) data with ERA5 (137 model levels) data.
3. Accuracy Assessment of ERA5 (37 Pressure Levels) Interpolated to 100 m vertical Resolution

1. Validation of ERA5 (37 pressure levels) data against independent radiosonde observations.

To ensure the sufficient quality of the ERA5 (37 pressure levels) data which was interpolated to 100 m vertical resolution for this study, it has been validated against collocated radiosonde temperature profiles. Atmospheric profiles data from 8 radiosonde stations on 3 January 2016 at different geographic locations spatially, while temporarily 4 profiles are in the daytime and the other 4 are in the nighttime (Fig. 1). The results of the assessment of collocated ERA5 and radiosonde profile pairs showed a high level of consistency between both techniques (Fig. 2). The correlation coefficient between ERA5 and radiosonde is approximately 0.99 at all locations (Table 1), which indicates the strong reliability of ERA5 for atmospheric sounding. The mean difference in temperature between both ERA5 (37 pressure levels) and radiosonde profiles ranges from 0.02 to 0.67 K (Table 1), demonstrating excellent agreement and confirming the reliability of ERA5 in representing the vertical temperature structure. In addition, the lapse rate tropopause height (LRT-H) estimated from both techniques shows a high level of agreement, with differences ranging from 0.1 to 1 km (Table 1).

Table 1. Distance, correlation coefficient, and mean temperature difference between collocated ERA5 (37 pressure levels) and radiosonde (RS) profile pairs for 3 January 2016 at 00 and 12 am. Additionally, the lapse rate tropopause height (LRT-H) estimated from both datasets is presented.

<i>Station name</i>	Distance (km)	Correlation coefficient	Mean difference (K)	RS LRT-H (km)	ERA5 LRT-H (km)
<i>at 00 am</i>					
DNR	10.25	0.99	0.40	9.90	10.10
KIROV	18.05	0.99	0.03	9.10	9.00
PIT	3.73	0.99	0.02	10.60	10.80
YPLM	8.52	0.99	0.40	17.30	16.90
<i>at 12 am</i>					
SBFI	8.10	0.99	0.31	17.40	16.60
ULWW	8.73	0.99	0.67	9.10	9.60
WIII	16.47	0.99	0.30	17.80	16.80
YCB	13.54	0.99	0.14	10.70	11.30

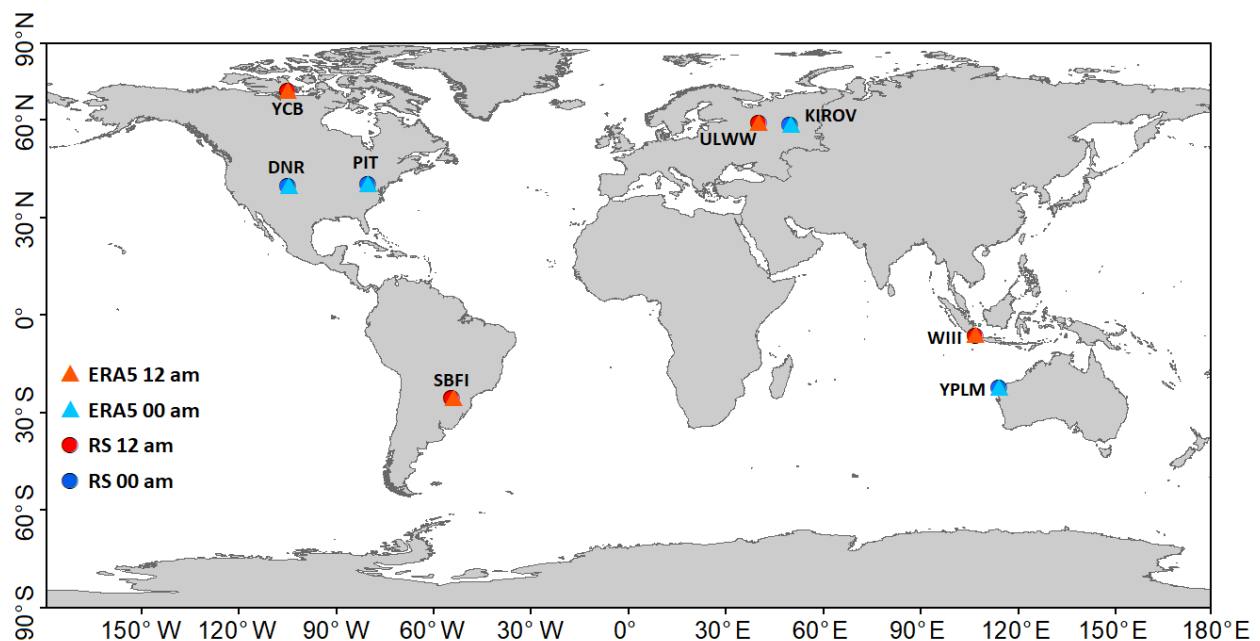


Figure 1. Geographic locations of radiosonde (RS) profiles and their corresponding ERA5 (37 pressure levels) grid locations.

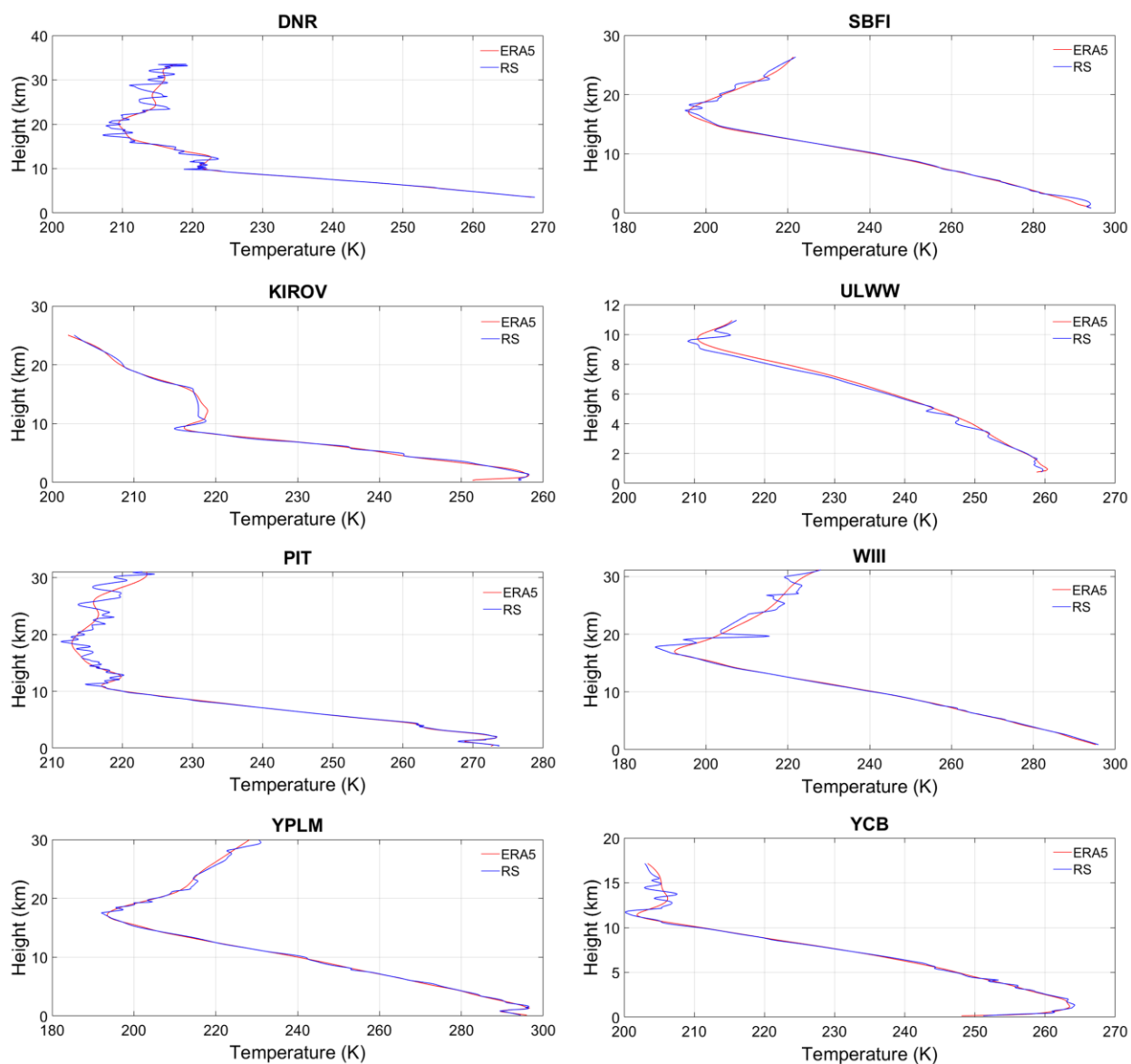


Figure 2. Vertical profiles from ERA5 (37 pressure levels) compared with radiosonde (RS) observations. The left panels represent 00 am for DNR, KIROV, PIT, and YPLM, respectively, while the right panels represent 12 am for SBFI, ULWW, WIII, and YCB.

2. Intercomparison of ERA5 (37 pressure levels) data with ERA5 (137 model levels) data.

This section presents an intercomparison between ERA5 data at 37 pressure levels and the native ERA5 137 model levels across 6 locations in the Mediterranean region, covering an altitude range from 0 to 30 km at 00 am on 1 January 2020 (Fig. 3). As summarized in Table 2, the results reveal a high level of agreement between the two datasets at all locations. The correlation coefficient is approximately 0.99 for all profile pairs, indicating an almost perfect linear correspondence and demonstrating that the interpolated 37 pressure-level dataset effectively preserves the vertical temperature structure of the original model-level data.

The mean temperature difference between the two datasets ranges from 0.02 to 0.38 K (Fig. 4), which is very small and well within the expected uncertainty associated with vertical interpolation and numerical discretization. This level of agreement confirms that the interpolation to a 100 m vertical resolution does not introduce significant distortion in the thermal structure of the atmosphere. Consequently, the ERA5 (37 pressure levels) dataset can be considered reliable for applications sensitive to vertical temperature gradients, such as tropopause detection and the identification of the tropical edge latitudes.

Furthermore, the lapse rate tropopause height (LRT-H) derived from both datasets shows strong agreement, with differences ranging from 0.08 to 0.31 km (Table 2). These small discrepancies are consistent with the inherent sensitivity of tropopause detection to vertical resolution and gradient estimation. Overall, the results demonstrate that the interpolated pressure level ERA5 dataset retains the essential dynamical and thermal features of the original high-resolution model levels, supporting its suitability for detailed atmospheric structure analysis.

Table 2. Correlation coefficient, and mean temperature difference between ERA5 (37 pressure levels) profiles (P1-P6) at altitude range 0-30 km with their equivalent ERA5 (137 model levels) profiles at 00 am 1 January 2020. Additionally, the lapse rate tropopause height (LRT-H) estimated from both datasets.

Profile No	Correlation coefficient	Mean difference (K)	ERA5 (37 level) LRT-H (km)	ERA5 (137 model level) LRT-H (km)
P1	0.99	0.11	13.21	13.48
P2	0.99	0.21	11.11	11.34
P3	0.99	0.02	13.29	13.48
P4	0.99	0.23	17.40	17.09
P5	0.99	0.23	11.89	12.05
P6	0.99	0.38	13.85	13.93

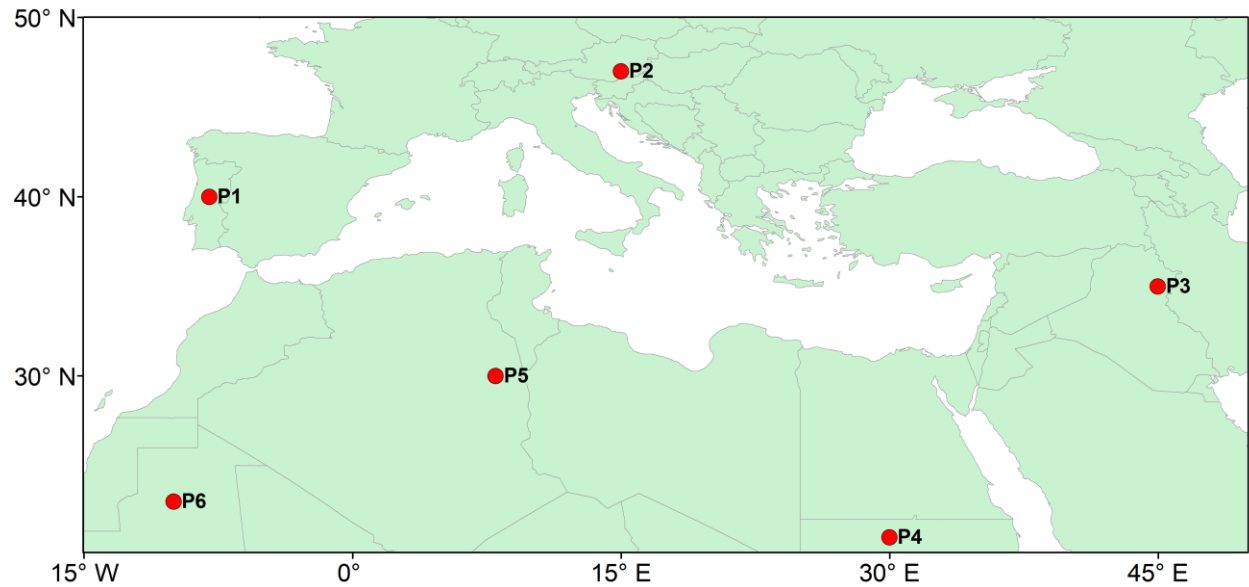


Figure 3. Geographic locations of ERA5 (37 pressure levels) profiles (P1-P6) and their corresponding ERA5 (137 model levels) profiles at the same grid points in the Mediterranean region.

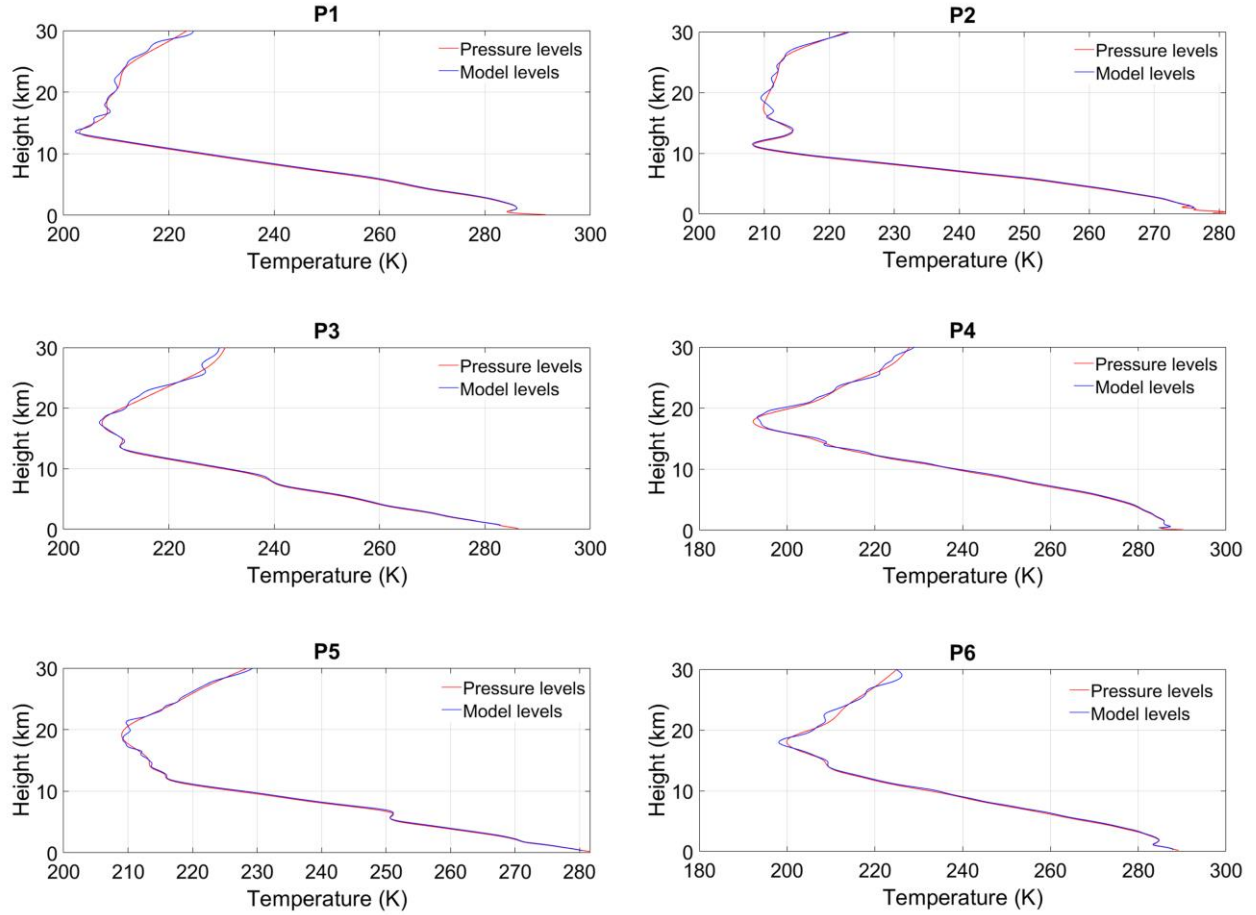


Figure 4. Vertical profiles (P1-P6) at altitude range 0-30 km from ERA5 (37 pressure levels) compared to their equivalent ERA5 (137 model levels) profiles at 00 am 1 January 2020.

3. Accuracy Assessment of ERA5 (37 Pressure Levels) Interpolated to 100 m vertical Resolution.

In this section, six ERA5 temperature profiles at 37 pressure levels, representing different geographic locations across the Mediterranean region, are used to evaluate the accuracy of vertical interpolation to a 100 m resolution (Fig. 3). The assessment is based on a reconstruction (back-interpolation) approach, which is widely used to objectively quantify interpolation performance. Specifically, the original coarse-resolution profiles are first interpolated to a fine vertical grid (100 m), and subsequently interpolated back to their original pressure levels. The reconstructed profiles are then compared with the original data using statistical metrics, including bias and root mean square error (RMSE), to

quantify interpolation-induced deviations. In addition, the preservation of vertical thermal structure is assessed through comparison of lapse rate profiles.

The results indicate an almost perfect reconstruction of the original temperature profiles at all six locations (Table 3). Both bias and RMSE are effectively zero, demonstrating that the interpolation and back-interpolation process introduces negligible numerical error. Furthermore, the mean difference in lapse rate between the original and reconstructed profiles is also approximately zero, confirming that the interpolation fully preserves the vertical temperature gradients and key atmospheric structure. These results are well within, and indeed significantly better than, the typical uncertainty thresholds reported in the literature (bias < 0.1–0.2 K and RMSE < 0.3–0.5 K), indicating an exceptionally high level of interpolation accuracy. Overall, the findings demonstrate that the interpolation of ERA5 temperature profiles from 37 pressure levels to a 100 m vertical grid is robust and does not distort the atmospheric thermal structure, thereby supporting its suitability for applications requiring high-resolution vertical analysis, particularly tropopause detection and gradient-based diagnostics.

Table 3. Bias, root mean square error (RMSE), and mean lapse rate difference between original ERA5 temperature profiles (37 pressure levels; P1–P6) and their corresponding back-interpolated profiles.

Profile No	Bias	RMSE	lapse rate mean difference
P1	0	0	0
P2	0	0	0
P3	0	0	0
P4	0	0	0
P5	0	0	0
P6	0	0	0

Referee comment: -

2. *“TPD” and “TPG” have very high correlation (0.9 shown in figure 3) and they showed very similar results. Session 3.2 have a lot of descriptions about what it’s shown in the figures from both methods. Figure 5 and Figure 6 are very similar. Left and right columns in Figure 7 are similar. Figure 8 and Figure 9 are similar. It looks redundant to me to include the discussion for both methods.*

Answer: -

We thank the reviewer for this important comment regarding the apparent redundancy between the TPD and TPG metrics and the similarity of the associated figures and discussion.

We agree that TPD and TPG show a high correlation (≈ 0.9 , Fig. 3) and produce very similar spatial and temporal patterns. However, this agreement is intentional and scientifically meaningful rather than redundant. The tropical edge latitude (TEL) is estimated here using two distinct tropopause-based diagnostics: (1) TPD, defined as the latitude where the lapse-rate tropopause height (LRT-H) decreases by 1.5 km relative to the tropical mean (15°S–15°N), and (2) TPG, defined as the latitude of the maximum poleward meridional gradient of LRT-H. While both metrics are derived from the same physical field, they represent different methodological perspectives—one based on an absolute threshold and the other on a gradient-based transition.

The use of multiple tropopause metrics is a well-established approach in the literature to ensure the robustness of tropical edge detection and to avoid method-dependent bias (e.g., Davis and Rosenlof, 2011; Ao and Hajj, 2013; Maher et al., 2019; Darrag et al., 2022; Zou et al., 2023). In this context, the strong agreement between TPD and TPG in our results provides mutual confirmation of the diagnosed expansion patterns, increasing confidence in the physical interpretation rather than introducing redundancy.

Zou, L., Hoffmann, L., Müller, R., & Spang, R. (2023). Variability and trends of the tropical tropopause derived from a 1980–2021 multi-reanalysis assessment. *Frontiers in Earth Science*, 11. <https://doi.org/10.3389/feart.2023.1177502>

Darrag, M., Jin, S., Calabia, A., & Samy, A. (2022). Determination of tropical belt widening using multiple GNSS radio occultation measurements. *Annales Geophysicae*, 40(3), 359–377. <https://doi.org/10.5194/angeo-40-359-2022>

Maher, P., Kelleher, M. E., Sansom, P. G., & Methven, J. (2019). Is the subtropical jet shifting poleward? *Climate Dynamics*, 54(3–4), 1741–1759. <https://doi.org/10.1007/s00382-019-05084-6>

Ao, C. O., & Hajj, A. J. (2013). Monitoring the width of the tropical belt with GPS radio occultation measurements. *Geophysical Research Letters*, 40(23), 6236–6241. <https://doi.org/10.1002/2013gl058203>

Davis, S. M., & Rosenlof, K. H. (2011). A multidiagnostic intercomparison of Tropical-Width time series using reanalyses and satellite observations. *Journal of Climate*, 25(4), 1061–1078. <https://doi.org/10.1175/jcli-d-11-00127.1>

Referee comment: -

3. *There are many abbreviations throughout the paper. Reducing them may improve readability*

Answer: -

We acknowledge that a relatively large number of abbreviations are used throughout the paper. This is mainly because the study investigates multiple variables and diagnostics, particularly in relation to tropopause-based metrics and derived quantities. In such cases, the use of abbreviations is necessary to maintain clarity and conciseness, especially in figures where space is limited and the use of full variable names is not practical.

Line-by-line comments

Referee comment: -

Lines 24-25: “both applied methods” is confusing because the methods are not stated earlier. I suggest revising this sentence to something like “the tropical belt shows poleward expansion ranging approximately between 0.14 °/dec and 0.27 °/dec.”

Answer: -

We thank the reviewer for this helpful comment. In response, we have revised the sentence to explicitly state the methods used, thereby removing the ambiguity associated

with the phrase “both applied methods.” The sentence now reads: “The tropical belt shows a poleward expansion of approximately 0.14 °/dec and 0.27 °/dec, estimated using the tropopause drop (TPD) and tropopause gradient (TPG) methods, respectively.” This revision improves clarity and ensures that the methods are clearly identified for the reader.

Referee comment: -

Line 25: “of both applied approaches” seems redundant.

Answer: -

Following the previous referee’s comment, we have revised the text to explicitly state the two methods (TPD and TPG), and the phrase “both applied methods” has been removed. Accordingly, this potentially redundant expression has been removed, and the phrase “both applied approaches” in Line 25 is the first to appear.

Referee comment: -

Line 40: “climate change has been documented at a magnitude that exceeds global averages” is very broad. Does climate change here means temperature, precipitation, or something else?

I notice this sentence is rephrasing “As mentioned before, Mediterranean climate change has been observed at a magnitude exceeding global means, despite the fact that the emission of greenhouse gases (GHGs) in Mediterranean countries lie at relatively low levels” from the reference. In this paper, this sentence is missing context. I’m not sure if this sentence is a good one to put at the beginning.

Answer: -

We agree that the original statement was too broad. In the revised manuscript, we have clarified that this statement primarily refers to temperature changes in the Mediterranean region, as discussed in Lange (2020). The sentence has been modified accordingly to improve precision and avoid ambiguity.

The original sentence, adapted from Lange (2020), lacked sufficient context. Our intention was to highlight the apparent discrepancy between relatively modest regional GHG emissions and the amplified warming observed in the Mediterranean, which suggests the role of additional regional factors.

In the revised manuscript, we have rephrased the sentence to improve clarity and explicitly emphasize that this statement refers primarily to temperature increase. We have also adjusted its wording to better integrate it into the introductory context and avoid it appearing as an isolated or decontextualized statement.

Referee comment: -

Lines 47-48: This sentence repeated “the Mediterranean region has experienced significant shifts of climate in the past” in Line 45.

Answer: -

Thank you for pointing out this repetition. The sentence previously appearing in Line 45 has been removed in the revised manuscript to avoid redundancy. As a result, the statement in Lines 47–48 is now presented only once, improving clarity and readability.

Referee comment: -

Lines 59-60: There is no subject in this sentence. A suggestion is “In astronomy and cartography, the tropical boundaries are at latitudes of ~23.5° north and south”.

Answer: -

Thank you for this helpful clarification. We followed your suggestion and have modified the revised manuscript accordingly to reflect that. In astronomy and cartography, the tropical boundaries are at latitudes of ~23.5° north and south.

Referee comment: -

Lines 63-64: A better flow is needed. The previous sentence is about the seasonal change and “Tropical belt expansion” in this sentence is due to climate forcing. A suggestion is adding “Under climate change,” at the beginning of the sentence.

Answer: -

We followed your suggestion and modified the sentence accordingly by adding “Under climate change” at the beginning, which improves the flow and clarifies the context in the revised manuscript.

Referee comment: -

Lines 66-67: “sea-surface temperature (SST) variability over the tropics” and “absorbing aerosols hemispheric asymmetry” don’t appear to be the changes driven by the climate change.

Answer: -

Thank you for this important comment. We agree that not all the listed factors are directly driven by climate change. In the revised manuscript, we have clarified this point by distinguishing between externally forced drivers (e.g., GHG forcing and ozone depletion) and other contributing factors such as internal variability (e.g., tropical SST variability) and hemispheric asymmetries in absorbing aerosols. The sentence has been revised accordingly to improve accuracy and clarity.

[The expansion of the tropical belt has been attributed to a variety of factors, including externally forced processes such as tropospheric warming caused by GHG forcing and stratospheric cooling caused by ozone depletion, as well as other contributing factors such as tropical sea-surface temperature (SST) variability and hemispheric asymmetries in absorbing aerosols.]

Referee comment: -

Lines 71-73: “even slight expansion of the tropical belt could cause substantial changes in the global climate system” repeats “The expansion of the tropics could cause substantial changes in the global climate system”.

Answer: -

Thank you for highlighting this repetition. The sentence “The expansion of the tropics could cause substantial changes in the global climate system” has been removed in the revised manuscript. We retained the more specific statement “even slight expansion of the tropical belt could cause substantial changes in the global climate system,” thereby eliminating redundancy while preserving the intended meaning.

Referee comment: -

Lines 76-77: I suggest revising “one of the most vulnerable regions to the effects of climate change” to “one of the most vulnerable regions affected by

Answer: -

We have revised the manuscript accordingly, modifying the sentence as recommended to improve clarity and readability.

Referee comment: -

Line 79: “increasing” to “being”.

Answer: -

We have revised the manuscript accordingly, modifying the sentence as recommended to improve clarity and readability.

Referee comment: -

Line 82: Add “continue to” before “rise”.

Answer: -

We have revised the manuscript accordingly, modifying the sentence as recommended to improve clarity and readability.

Referee comment: -

Lines 98-99: "This accelerated...and biodiversity" repeats Lines 88-89.

Answer: -

Thank you for highlighting this redundancy. We agree that the sentence in Lines 98–99 repeats the content of Lines 88–89. To improve the conciseness and readability of the manuscript, we have removed the sentence "This accelerated ... and biodiversity" from the revised version.

Referee comment: -

Lines 115-131: Most of session 2.1 repeats the content already shown in the introduction. Please consider shortening or deleting session 2.1.

Answer: -

We agree that the original Section 2.1 contained material that overlapped with the Introduction. In the revised manuscript, Section 2.1 has been substantially shortened and refocused to include mainly the essential information required to define the study domain and its geographical boundaries.

[This study investigates the Mediterranean region, including parts of Southern Europe, North Africa, and the Middle East. The study region is defined as the area between 20.00° N and 50.00° N latitude and 15.00° W and 50.00° E longitude. This spatial extent is selected to capture the full Mediterranean basin and its surrounding land–sea system, which is relevant for analyzing large-scale atmospheric variability and tropical edge dynamics. The Mediterranean basin is characterized by substantial environmental and geographical gradients, complex morphology with mountain chains, and significant land-sea contrasts. Its location in a transition zone between mid-latitude and subtropical atmospheric circulation systems contributes to its complex climate patterns (Lange, 2020). The Mediterranean hosts one of the world's richest biodiversity reserves with

numerous endemic species. However, rising temperatures, habitat loss, and changing phenological patterns pose significant threats (Coll et al., 2010; Lionello et al., 2012).]

Referee comment: -

Lines 180-181: The captions in Figures are repeated in the text. Same in Lines 192-193.

Answer: -

The repeated descriptions of the figure captions in the main text have been removed to avoid redundancy. Specifically, Lines 180–181 and Lines 192–193 have been deleted in the revised manuscript. The text has been adjusted to focus on the interpretation of the figures rather than duplicating their captions.

Referee comment: -

Lines 181-183: Previous literature also shows an increasing trend, but the values presented in this paper are much larger.

Answer: -

We have carefully revised the manuscript to clarify the comparison with previous studies and to better explain the differences in the magnitude of the reported trends. The relevant text (Lines 181–183) has been modified accordingly in the revised manuscript.

The larger values obtained in this study can be attributed to the fact that the Mediterranean region has experienced warming at rates exceeding the global average.

Referee comment: -

Line 185: Add “in LRT-T also” after “our findings”.

Answer: -

The manuscript has been modified accordingly, and the phrase “in LRT-H also” has been added after “our findings” in Line 185.

Referee comment: -

Line 189: “consistent with earlier research” appears three times in this paragraph. Please consider revising to avoid repetition.

Answer: -

The repeated use of the phrase “consistent with earlier research” has been reduced/removed by rephrasing the relevant sentences. The revised manuscript has been modified accordingly to enhance clarity and avoid redundancy.

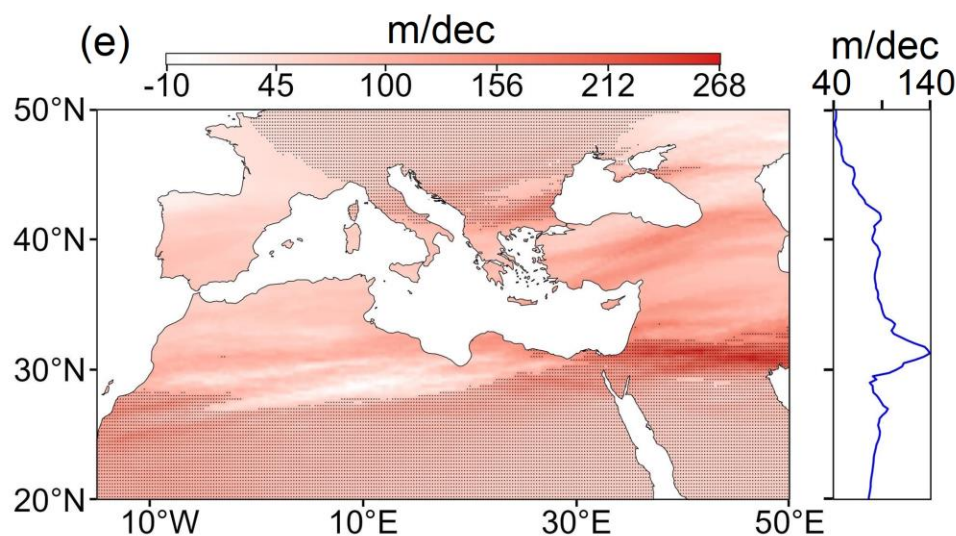
Referee comment: -

Line 207: “most of the grid points” is vague. Please consider stippling the regions where $p < 0.05$. Same for line 213, line 510, line 530, line 570.

Answer: -

In the revised manuscript, we removed “most of the grid points” and indicated the statistically significant trends ($p \leq 0.05$) in all trend maps using stippled regions. This representation highlights the grid points where the trends are statistically significant and improves the clarity of the figures. The figure captions have been updated accordingly.

Example: As shown in Figure 1e, black stippled regions indicate grid points where the trends are statistically significant at $p < 0.05$.



Referee comment: -

Figure 2: Repetition in the caption. For example, “Monthly time series of the TPD TEL method over the Mediterranean region for the period January 1980 to December 2022 (a) and monthly time series of the TPG TEL method over the Mediterranean region for the period January 1980 to December 2022 (b).” can be revised as “Monthly time series of the (a) TPD TEL method and (b) TPG TEL method over the Mediterranean region for the period January 1980 to December 2022”.

Answer: -

The repetition in the caption of Figure 2 has been removed and the caption has been revised accordingly. In addition, the repeated statements of the investigation period (January 1980–December 2022) have been reduced throughout the manuscript, particularly in the figure captions.

[**Figure 2.** Monthly time series of the (a) TPD TEL method and (b) TPG TEL method. The linear regression model between TPD TEL and LRT-H (c) and the linear regression model between TPG TEL and LRT-H (d). Longitudinal variation of TEL using both methods over the Mediterranean region is displayed. The blue line in (e) represents the mean TPD TEL at each longitude over the study period, while the blue shading depicts its SD. In (f), the red line represents the mean TPG TEL at each longitude over the study period, with the red shading indicating its SD. Seasonal variation of TPD TEL (g) and TPG TEL (h).]

Referee comment: -

Line 244: “major tropical systems” is vague.

Answer: -

We agree that the term “major tropical systems” is vague. In the revised manuscript, we have clarified this expression by specifying the relevant large-scale tropical–extratropical teleconnection processes affecting the Mediterranean region. The manuscript has been revised accordingly to improve precision and clarity.

Referee comment: -

Line 250: Why stronger land-sea contrast leads to the following statement “resulting in higher TEL values in this region”?

Answer: -

We agree that the causal link was not sufficiently explained in the original text. In the revised manuscript, we have clarified the physical mechanism by explicitly describing how stronger land–sea thermal contrasts can influence regional thermal structure and circulation patterns, which in turn affect the spatial distribution of TEL values. The sentence has been revised accordingly to improve clarity and physical justification.

Referee comment: -

Lines 283-284: “even minor expansion would have significant consequences” is repetition.

Answer: -

In the revised manuscript, this expression, “even minor expansion would have significant consequences,” has been removed to avoid redundancy and improve clarity.

Referee comment: -

Figure 3: It will be more straightforward to put the correlation numbers on the top right panels.

Answer: -

We thank the reviewer for this helpful suggestion. The correlation coefficients have now been added to the top-right panels of Figure 3 to improve clarity and readability.

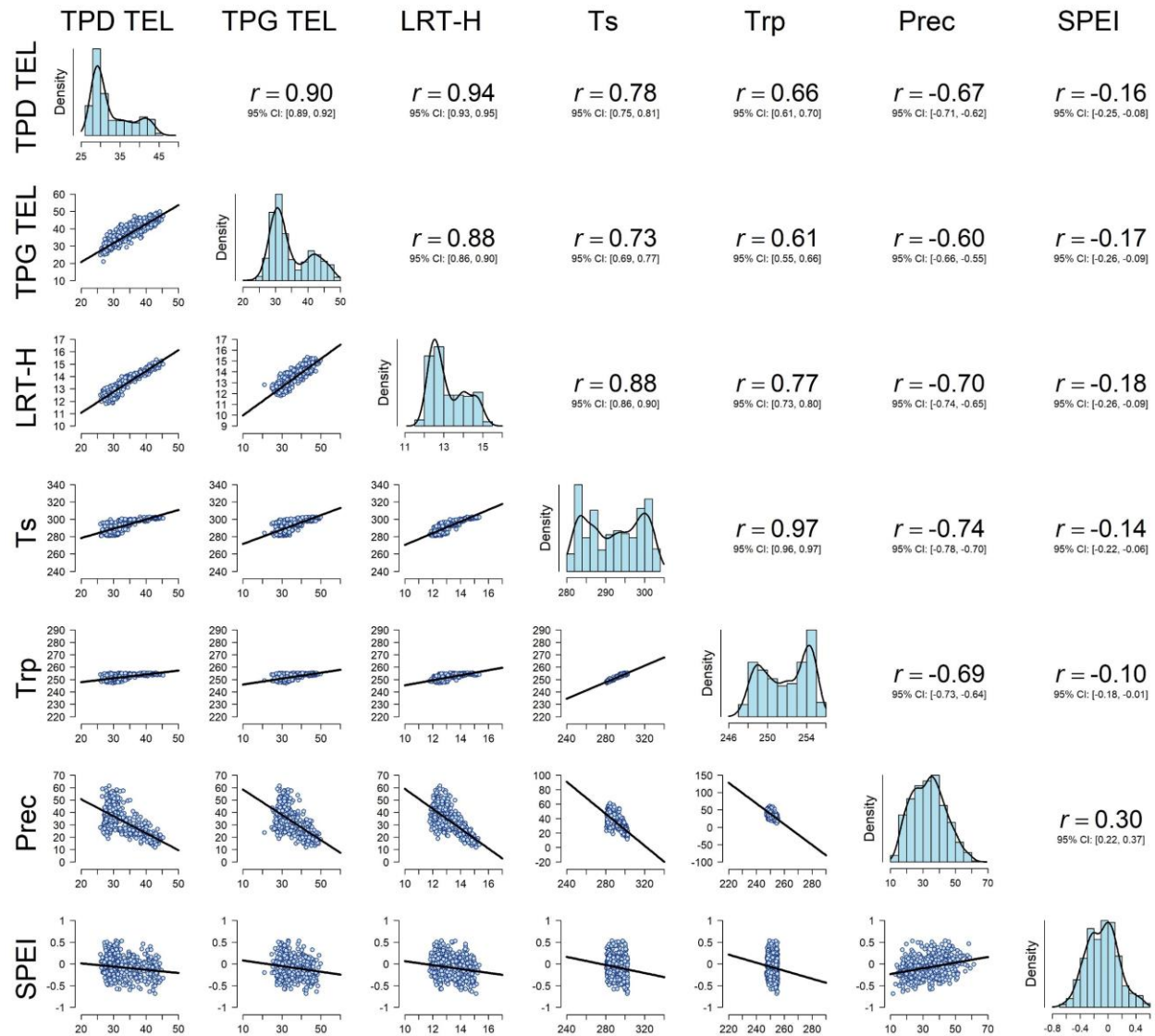


Figure 3. On the right side, correlation coefficients among monthly TPD TEL, TPG TEL, LRT-H, Ts, Trp, precipitation (Prec), and SPEI with 95% confidence intervals are shown. On the diagonal, the density distribution of all variables is displayed. On the left side, linear regression models between variables are depicted.

Referee comment: -

Figure 10: Repetition in the description of panels.

Answer: -

The description of Figure 10 has been revised to remove repetition and improve clarity.

[**Figure 10.** On the left, monthly time series of Ts (a), Trp-1 (c), and Trp-2 (e). 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 $p < 0.05$.]