

Tropical belt expansion and its impacts on climate variability in the Mediterranean from 1980 to 2022

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Abstract.

This paper explores the long-term variability of climatic parameters over the Mediterranean region and their relationship with tropical belt expansion by investigating observational and reanalysis data from January 1980 to December 2022 through multiple approaches including correlation, linear regression, singular value decomposition (SVD), wavelet coherence (WTC), and principal component analysis (PCA). The lapse rate tropopause height (LRT-H) exhibits upward trends of approximately 80.58 m/dec. Concurrently, 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. The tropical edge latitudes (TELs) of both applied approaches are in phase and have a strong positive correlation with LRT-H, surface temperature (Ts), and tropospheric temperature (Trp) while being of strong negative correlation and out of phase with precipitation. However, there is no substantial correlation for the Standardized Precipitation Evapotranspiration Index (SPEI) with TELs or other climatic parameters. The results of SVD analysis depict that the Ts and lower tropospheric temperature (Trp-1) have evident coupling with the TELs in the eastern Mediterranean. Furthermore, Ts and Trp-1 have significant increasing trends, which are abundant in the eastern Mediterranean. On the other hand, both precipitation and SPEI exhibit downward trends. Over the Mediterranean, an apparent spatial and temporal variation of climatic parameters is observed. The results confirm the linkage between climatic parameters' variability, coherence, and covariability with the TELs variability patterns over the study area, especially in the eastern Mediterranean region.

Keywords Climate change · Mediterranean region · Tropical belt · Tropopause · Climatic parameters

1 Introduction

Despite the fact that greenhouse gas (GHG) emissions in Mediterranean countries are generally modest, climate change in the Mediterranean region, particularly in terms of temperature increase, has been documented at a magnitude that exceeds global averages (Lange, 2020). The Mediterranean region is situated in a transition zone between the North Africa arid climate and

Central Europe temperate and wet climate, and it is influenced by interactions between mid-latitude and tropical processes. This makes the Mediterranean region potentially sensitive to climate change (Lionello et al., 2006; Ulbrich et al., 2006; Urdiales-Flores et al., 2023). In fact, the Mediterranean has been highlighted as one of the most important "Hot-Spots" in climate change future projections (Giorgi, 2006). This region, which comprises a semi-enclosed sea and neighboring lands, has seen substantial shifts in climate patterns over the last several decades. These changes are corroborated by evidence from the Mediterranean basin, which shows altered temperature trends and precipitation regimes and an increase in extreme weather events' frequency and severity (Luterbacher et al., 2006; Insua-Costa et al., 2022; Androulidakis et al., 2023; Yavaşlı and Erlat, 2024). Moreover, climate change in the Mediterranean basin has far-reaching implications that influence critical socioeconomic areas in addition to meteorological concerns. These changes have significant implications for agriculture, water resource management, coastal zone planning, and the protection of sensitive ecosystems (Noto et al., 2023). Understanding and forecasting climatic patterns is crucial for developing effective adaptation strategies and making informed policy decisions in a highly reactive region to reduce climate change effects (Mastrorillo et al., 2024; Jin et al., 2006 and 2011).

In astronomy and cartography, the tropical boundaries are at latitudes of $\sim 23.5^\circ$ north and south (Gnanadesikan and Stouffer, 2006). While in climatology the tropical edge latitudes (TELs) vary seasonally, and in response to climate forcing. They migrate poleward in the summer (JJA) and equatorially in the winter (DJF) (Davis and Birner, 2013). Under climate change, tropical belt expansion has been robustly detected across the globe using a variety of data sets and approaches (Lucas et al., 2014). 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 (Seidel et al., 2008; Allen et al., 2012, 2014; Grise et al., 2018). The sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) shows that the Hadley circulation (tropics) is expanding poleward at a rate of approximately $0.50\text{--}1.00^\circ$ per decade, with significant regional and seasonal variability (Mathew and Kumar, 2018; Staten et al., 2018). Even slight expansion of the tropical belt could cause substantial changes in the global climate system, manifesting as altered precipitation patterns, poleward-shifting storm tracks and jet streams, variations in stratospheric trace gas distribution, and changes in ocean circulation (Seidel et al., 2008; Lucas et al., 2014).

The IPCC has repeatedly identified the Mediterranean as one of the most vulnerable regions affected by climate change (IPCC, 2021a,b). One of the primary drivers of this susceptibility is the expansion of the tropical belt, which has a significant impact on subtropical and mid-latitude climates (Seidel et al., 2008). The Mediterranean basin is tropicalizing, with its waters being warmer and saltier. The enclosed sea warms four times quicker than the global norm for coastal waters (Bianchi and Morri, 2003; Borghini et al., 2014), and it is anticipated that these rates will

continue to rise throughout this century as climate change progresses (Somot et al., 2006; Rilov and Crooks, 2009). The widening of the tropical belt has direct implications for precipitation patterns, temperature regimes, and the frequency of extreme weather events in the Mediterranean. As the subtropical dry zones move poleward, the Mediterranean region experiences longer droughts, lower rainfall, and more intense heatwaves (Giorgi, 2019). These changes impair agricultural production, water availability, and ecosystem stability, worsening socioeconomic vulnerability (Lionello et al., 2006). Furthermore, Mediterranean Sea warming alters marine biodiversity and accelerates tropical species migration, threatening native ecosystems and fisheries. Desertification processes, driven by decreased soil moisture and increased evapotranspiration, strain terrestrial ecosystems and impede sustainable development in the region (Kuglitsch et al., 2010; Cramer et al., 2018).

The Mediterranean region has experienced major variations in climatic parameters during recent decades. Its unique geographical position, bounded by Europe, North Africa, and the Middle East, makes it particularly vulnerable to global warming and climate variability impacts (Giorgi, 2006). Climate models and observational data consistently indicate that the Mediterranean basin is warming at a rate higher than the global average. The region has warmed by approximately 1.40°C since the late 19th century, exceeding the global mean temperature rise of 1.10°C (Lionello et al., 2012; Cramer et al., 2018; Lange, 2020). Over the Mediterranean region, precipitation is distributed unevenly throughout the year, with a significant decline in the warm season. The region is also recognized for its wide spatial and temporal variation in precipitation levels (Lionello et al., 2006; Vicente-Serrano et al., 2025). Shifts in precipitation patterns have also been observed across the Mediterranean. Projections indicate that precipitation could decline by 10-30% by the end of the 21st century, exacerbating drought conditions and increasing water scarcity (Gao and Giorgi, 2008). Thus, understanding the interplay between tropical belt expansion and regional climate variability is essential for developing adaptive strategies to mitigate the adverse effects of climate change in the Mediterranean. This paper explores the multifaceted impacts of tropical expansion on Mediterranean climate. Section 2 describes the datasets used and methods for deriving TELs. Section 3 presents the analysis results, and Section 4 provides our conclusions.

2 Data and methods

2.1 Study area

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).

2.2 Data

We employ multiple datasets spanning January 1980 to December 2022 of monthly averaged temperature data on pressure levels from ERA5, the fifth generation ECMWF reanalysis, to determine lapse rate tropopause (LRT) parameters (height and temperature). ERA5 provides data at $0.25^\circ \times 0.25^\circ$ horizontal resolution (approximately $31 \text{ km} \times 31 \text{ km}$) with 37 vertical pressure levels ranging from 1,000 hPa to 1 hPa (Hersbach et al., 2019a). Monthly averaged surface temperature (Ts) and total precipitation data are also obtained from ERA5 at $0.25^\circ \times 0.25^\circ$ resolution (Hersbach et al., 2019b) to explore the impacts of tropical belt expansion on temperature and precipitation patterns over the Mediterranean region. Additionally, monthly precipitation and potential evapotranspiration (PET) data at $0.50^\circ \times 0.50^\circ$ resolution from the Climatic Research Unit (CRU) Time-Series (Harris et al., 2020) are used to compute the Standardized Precipitation Evapotranspiration Index (SPEI) as a meteorological drought indicator, following the methodology of Vicente-Serrano et al. (2010) and Beguería et al. (2013).

2.3 Methods

We apply the LRT definition to determine tropopause parameters (height and temperature) using ERA5 temperature data on pressure levels. Temperature data are first vertically spline interpolated to a regular 100 m height resolution. Following the WMO definition, the thermal LRT is identified as the lowest level at which the lapse rate decreases to $2^\circ\text{C}/\text{km}$ or less, provided the average lapse rate between this level and all higher levels within 2 km does not exceed $2^\circ\text{C}/\text{km}$ (WMO, 1957). Long-term trends of tropopause parameters over the Mediterranean region are examined using linear regression analysis at all grid points. The TEL, which indicates tropical belt width, is estimated using two tropopause height metrics. The first method to estimate the TEL is based on tropopause drop (TPD), and it defines the TEL as the latitude at which LRT height (LRT-H) drops 1.50 km below the tropical average (15.00°S - 15.00°N) (Birner, 2010; Davis and Rosenlof, 2012). While the second method to determine the TEL relied on the tropopause gradient (TPG), it signifies the TEL as the latitude of the maximum LRT-H meridional poleward gradient (Davis and Rosenlof, 2012; Davis and Birner, 2017).

We assess the relationships between TEL and key climatic variables using a suite of statistical techniques, including correlation analysis, linear regression, singular value decomposition (SVD), wavelet coherence (WTC), and principal component analysis (PCA) (Minh et al., 2024). The analysis focuses on how tropical expansion relates to tropopause characteristics, Ts (considered both as a potential driver and a response to tropical belt shifts), tropospheric temperature (Trp) (from the surface to the LRT level), precipitation, and SPEI as an indicator of meteorological drought. WTC analysis is used to examine time-frequency covariability between TEL estimates from both methodological approaches and the selected climatic parameters. WTC quantifies

localized correlation in time-frequency space, with coherence values ranging from 0 to 1 (Grinsted et al., 2004). Complementarily, the SVD analysis identifies dominant coupled modes of variability between TEL and the climatic fields. This method extracts pairs of spatial patterns (one for each field) and their associated temporal coefficients, each pair explaining a fraction of the shared covariance. To compute the SVD, we construct the temporal cross-covariance matrix between the two space-time fields, which may differ in spatial resolution but must cover the same temporal period (Bjornsson and Venegas, 1997; Darrag et al., 2024). Prior to the SVD analysis, all variables are detrended and deseasonalized to remove long-term trends and annual cycles. This preprocessing step ensures that the extracted SVD modes reflect genuine covariability between TEL and the climatic parameters, rather than artifacts arising from shared seasonal structure or long-term evolution.

3 Results and discussion

3.1 Tropopause and tropical belt characteristics

Our analysis reveals that LRT-H has increased by approximately 80.58 ± 3.07 m/dec since January 1980 (Fig. 1a). Previous literature also shows an LRT-H increasing trend, but the values presented in this paper are greater. 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. Schmidt et al. (2008) indicated a global upward trend in LRT-H of 39 to 66 m/dec for the period from May 2001 to December 2007. This tropopause height increase is attributed to global warming driven by increasing atmospheric GHG concentrations (Meng et al., 2021). These findings in LRT-H also aligned with previous studies documenting global tropopause height increases from global navigation satellite systems radio occultation (GNSS-RO) data (Darrag et al., 2022), radiosonde observations (Seidel and Randel, 2006), and reanalysis datasets (Santer et al., 2004). LRT temperature (LRT-T) exhibits a downward trend of -0.12 ± 0.02 K/dec (Fig. 1b), showing a strong negative correlation of -0.86 with LRT-H. These results of LRT parameter characteristics are in agreement with those reported in earlier studies (Sausen and Santer, 2003; Schmidt et al., 2004; Seidel and Randel, 2006; Pisoft et al., 2021).

Tropopause parameters exhibit significant anomalies driven by atmospheric dynamics, climate change, and natural variability. LRT-H displays stronger positive anomalies than negative ones, with the maximum positive anomaly of approximately 1.67 km occurring in September 2020 and the greatest negative anomaly of approximately -1.22 km in April 1982. Positive anomalies dominate during JJA and autumn (SON), while negative anomalies dominate during DJF and spring (MAM) (Fig. 1c). Conversely, LRT-T exhibits stronger negative anomalies than positive ones, with a maximum positive anomaly of approximately 3.40 K in April 1990 and a greatest negative anomaly of approximately -3.62 K in September 2000. In contrast to LRT-H, LRT-T positive anomalies dominate during DJF and MAM, while negative anomalies dominate during JJA and SON (Fig. 1d). The anomalies of both tropopause parameters are dominated by inter-

annual oscillations and vary across different months. 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.

Linear regression of LRT-H shows a dominant upward trend evident across almost the entire study area (Fig. 1e). The eastern Mediterranean region at approximately 30.00° N exhibits the maximum LRT-H increasing trends, reaching 266.50 m/dec, attributed to the stronger influence of the South Asian monsoon system in this area (Tyrlis and Lelieveld, 2013). The zonal mean of the LRT-H regression map (right panel of Fig. 1e) indicates increasing trends at all latitudes, with the latitudinal band between 30.00° N and 33.75° N showing maximum upward trends. For LRT-T (Fig. 1f), the majority of the study area displays decreasing trends with statistically significant values at $p < 0.05$. The LRT-T regression map reveals a spatial pattern opposite to that of LRT-H, consistent with previous studies (Darrag et al., 2022, 2024). The greatest LRT-T downward trend occurs in the eastern Mediterranean region around 30° N, with maximum decreasing trends of approximately -0.75 K/dec. The zonal mean of the LRT-T regression map (right panel of Fig. 1f) shows decreasing trends at all latitudes except the northern zone of the Mediterranean region between 43.50° N and 50.00° N, with the latitudinal band from 20.00° N to 32.25° N exhibiting maximum downward trends.

Figure 2 depicts TEL derived from ERA5 data based on both TPD and TPG methods. The TPD method shows an increase in tropical belt coverage of approximately 0.14 ± 0.05 °/dec (Fig. 2a). The TPG method exhibits more poleward TEL occurrences than the TPD method. Tropical belt coverage expanded by approximately 0.27 ± 0.06 °/dec using the TPG method (Fig. 2b). Meng et al. (2021) reported the latitudinal zone from 30.00° N to 40.00° N exhibits the largest LRT-H trends, attributable to the poleward shift of the subtropical jet and tropical belt widening over the past 40 years (Staten et al., 2018). The TPD TEL demonstrates a strong positive association with LRT-H, with a linear regression model yielding a coefficient of determination (R^2) of 0.93 (Fig. 2c). Similarly, the TPG TEL exhibits a strong positive association with LRT-H, with $R^2 = 0.87$ (Fig. 2d).

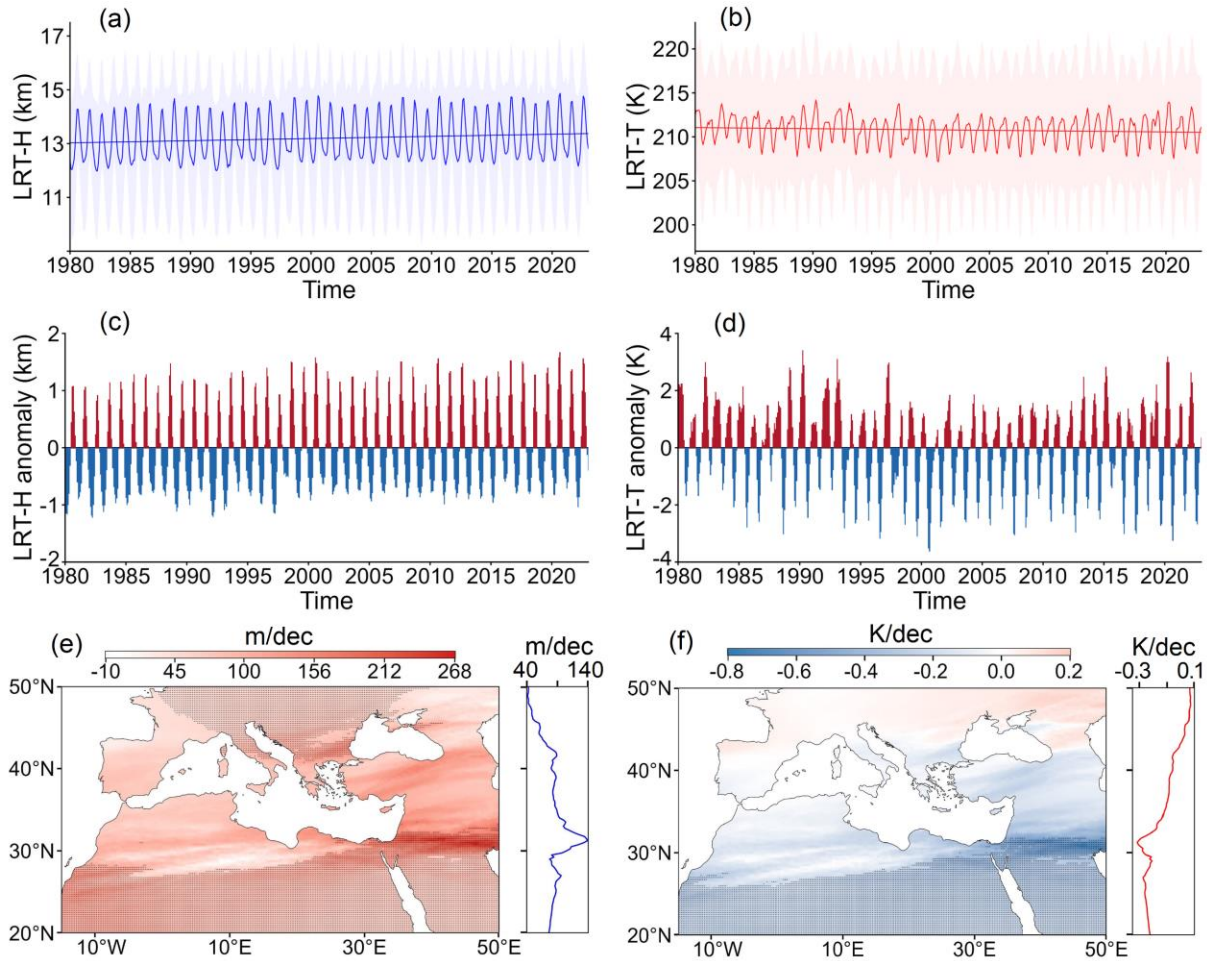
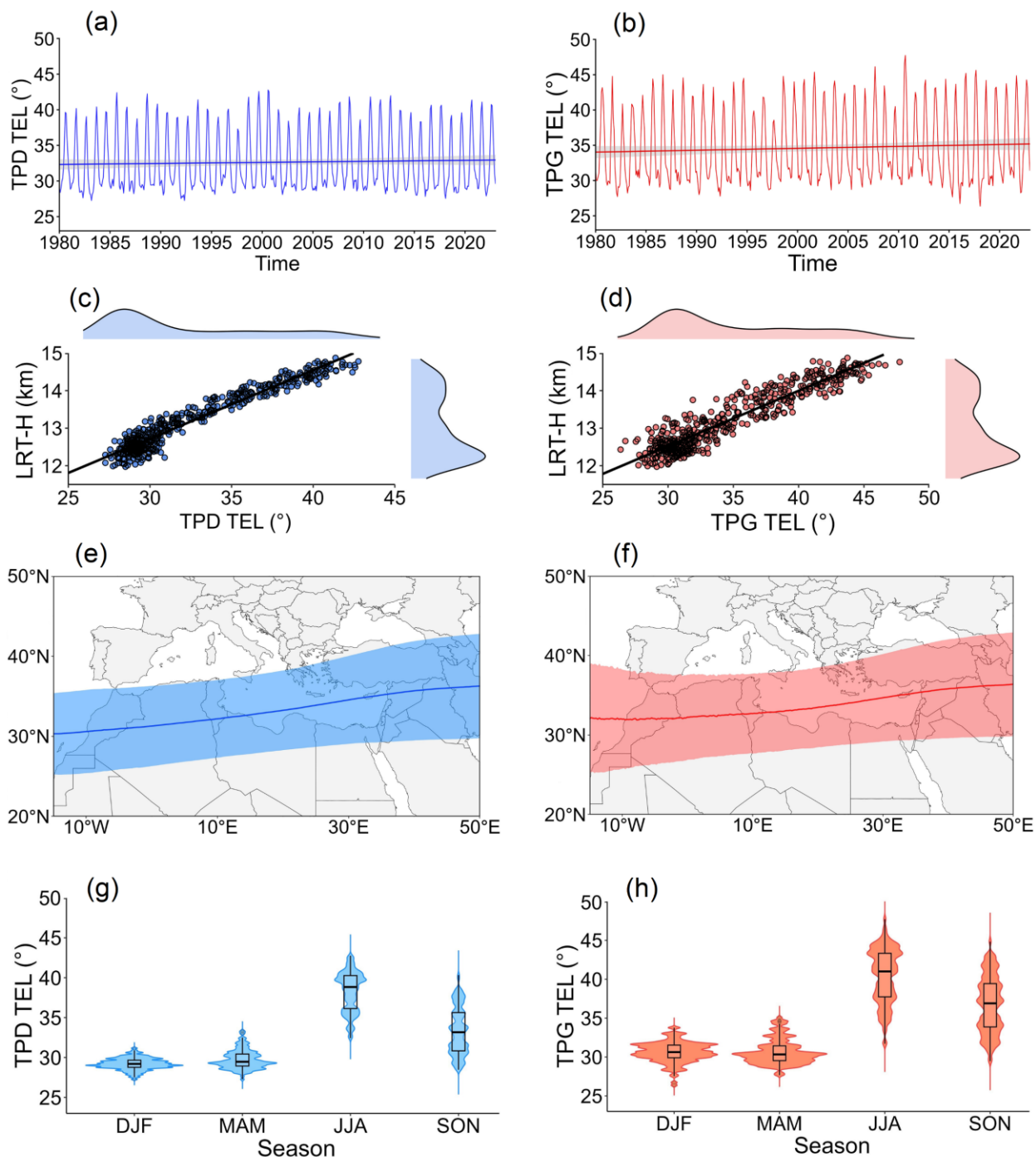


Figure 1. Monthly time series of LRT parameters in the top: (a) LRT-H and (b) LRT-T. Tropopause anomaly in the middle: (c) LRT-H anomaly time series, (d) LRT-T anomaly time series. Linear regression analysis of LRT parameters at all grid points and their decadal trends in the bottom: (e) LRT-H and (f) 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.

The longitudinal variation of TEL for both approaches over the Mediterranean region is depicted in Figure 2e,f. Both methods display clear longitudinal variation across the study area showing TEL in the eastern Mediterranean located more poleward than in the western Mediterranean. This pattern results from multiple factors, including the eastern Mediterranean region's exposure to strong natural climate variability associated with tropical–extratropical teleconnection processes. Furthermore, the Mediterranean region's dual climate influence (situated between the subtropical high-pressure systems of the Hadley cell and the mid-latitude westerlies) causes longitudinal differences in TEL through variations in these circulation patterns (Alpert et al., 2005; Trigo et al., 2006). The stronger land–sea thermal gradient in the eastern Mediterranean influences regional thermal structure and circulation, leading to higher TEL values in this region (Lionello, 2012). Additionally, SST variability influences longitudinal TEL variation, as its patterns affect atmospheric circulation and climate boundary positions (Meli et al., 2023). As shown in Figure 2, TEL variability in the TPG method (Fig. 2f) is higher than in the TPD method (Fig. 2e). Moreover,

239 the TPG TEL occurrences are more poleward, with a maximum value of approximately 42.88° N,
 240 compared to the TPD TEL maximum of approximately 42.78° N.



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

Figures 2g and 2h depict the seasonal variation of both TPD TEL and TPG TEL, respectively. In the case of TPD TEL, JJA and SON show higher interannual variability than that in DJF and MAM. The TPD TEL median values exhibit the anticipated seasonal pattern, being maximum in JJA at about 38.83° due to warming in the surface and troposphere. On the other hand, the TPD TEL median is minimum in DJF at about 29.20° because of the cooling of the surface and troposphere. All seasons show a multimodal distribution of the TPD TEL, which is clearly evident in JJA and SON. For TPG TEL, the seasonal variation follows the same pattern as that of TPD TEL, being of higher variability in JJA and SON than in DJF and MAM, displaying multimodal distribution of the TPG TEL values in all seasons. However, TPG exhibits TEL median values higher than those in the case of TPD TEL, being greatest in JJA at about 41.00° and lowest in MAM instead of DJF in the case of TPD, at about 30.33°. Our analysis results are in agreement with previous research that reported a pronounced seasonal cycle of the TELs typically moving poleward in the JJA and equatorward in the DJF with amplitude of the seasonal cycle is approximately 5-10° latitude (Davis and Rosenlof, 2012; Davis and Birner, 2013; Lucas et al., 2014; Luan et al., 2020).

3.2 Interaction of TEL and climatic parameters

As shown in Figure 3, TELs estimated using both TPD and TPG methods exhibit a high correlation of 0.90. Furthermore, TELs from both definitions show strong correlations with LRT-H, Ts, Trp, and precipitation. TPD TEL provides higher correlations with these climatic parameters than TPG TEL. Correlations between TPD TEL and LRT-H, Ts, Trp, and precipitation are 0.94, 0.78, 0.66, and -0.67, respectively. These results are in agreement with those of Darrag et al. (2022). Additionally, Trp depicts a strong correlation with Ts of approximately 0.97. However, no significant correlation exists between SPEI and all other climatic parameters. TEL from both definitions, LRT-H, Ts, and Trp display bimodal distributions, while precipitation and SPEI exhibit unimodal distributions. TPD and TPG TEL show strong positive linear associations with LRT-H, Ts, and Trp. Furthermore, Trp demonstrates strong associations with other parameters, with the strongest relationship observed with Ts. Moreover, both precipitation and SPEI display negative correlation with all other parameters while exhibiting a weak positive relation with each other.

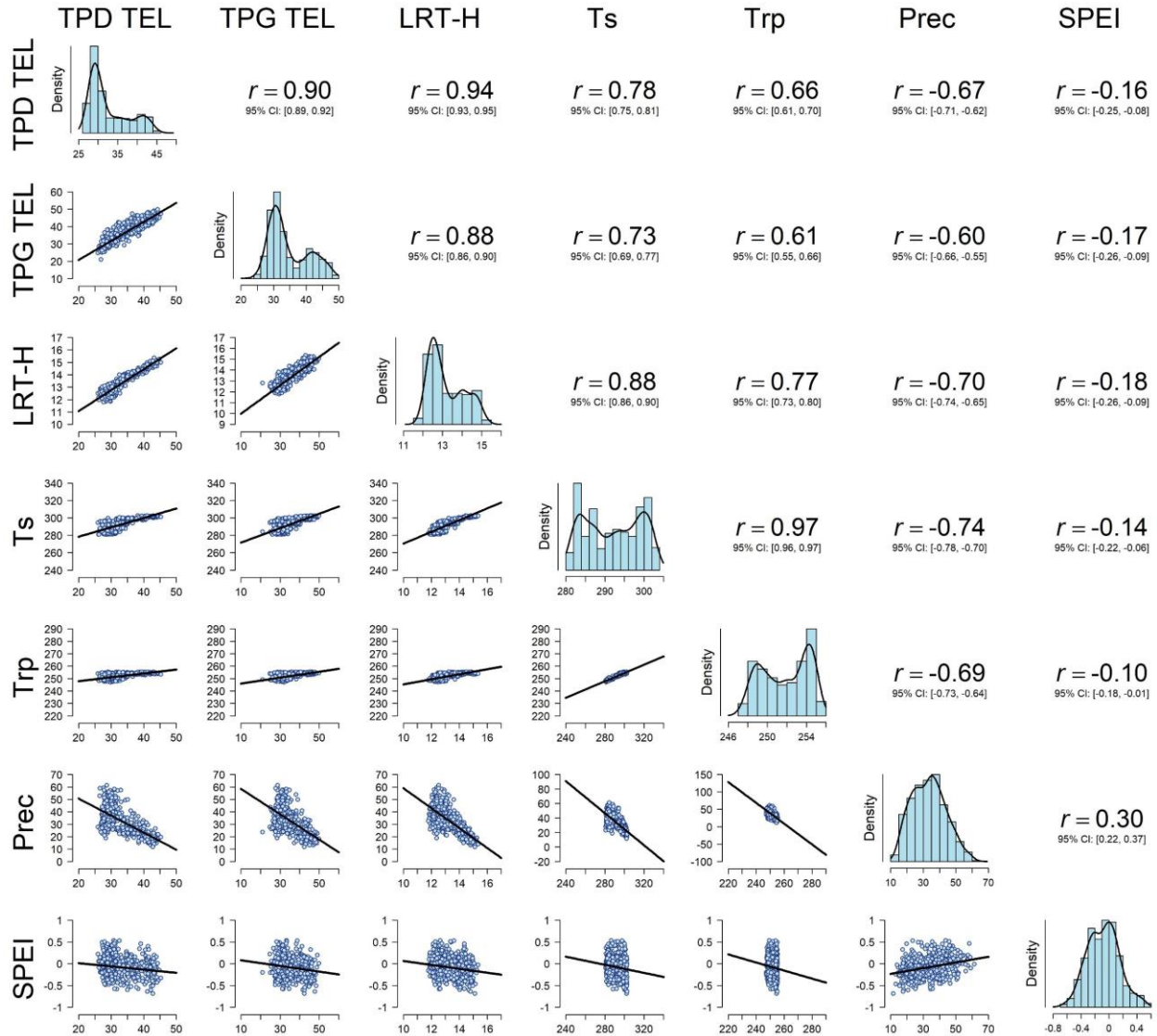


Figure 3. On the right side, correlation coefficients among monthly TPD TEL, TPG TEL, LRT-H, Ts, Trp, precipitation (Prec), and SPEI with 95% confidence intervals are shown. On the diagonal, the density distribution of all variables is displayed. On the left side, linear regression models between variables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

The PCA biplot of monthly averaged TEL from TPD and TPG methods, LRT-H, Ts, precipitation, Trp, and SPEI reveals that TELs from both methods are highly positively correlated (Fig. 4). Furthermore, the TPD TEL contributes more to variability than the TPG TEL. LRT-H, Ts, and Trp are highly correlated with each other and with both TEL definitions. Conversely, precipitation and SPEI are weakly positively related. Precipitation shows negative correlations with TELs from both methods, LRT-H, Ts, and Trp. Furthermore, SPEI depicts no observable relationship with TELs or other climatic parameters, showing high agreement with results in Figure 3.

WTC analysis between TPD TEL and climatic parameters (LRT-H, Ts, Trp, precipitation, and SPEI) is presented in Figure 5. The TEL locations are in phase and exhibit high coherence with LRT-H, Ts, and Trp at time scales of 4 to 20 months, 8 to 20 months, and 8 to 20 months,

respectively. In relation to LRT-H, Ts, and Trp, TEL is leading, as indicated by arrows pointing to the right and upward (Fig. 5a,b,c). Conversely, TPD TEL and precipitation show coherence at a time scale of 8 to 16 months, are out of phase, and TPD TEL is lagging (Fig. 5d). Furthermore, no significant coherence exists between TPD TEL and the SPEI drought index (Fig. 5e). As shown in Figure 6, WTC analysis results between TPG TEL and climatic parameters (LRT-H, Ts, Trp, precipitation, and SPEI) are nearly identical to those of TPD TEL (Fig. 5) but with shorter time scales of high coherence. Our analysis outputs are consistent with Darrag (2024), who applied similar analyses in both hemispheres based on TELs estimated from GNSS-RO data on a global scale.

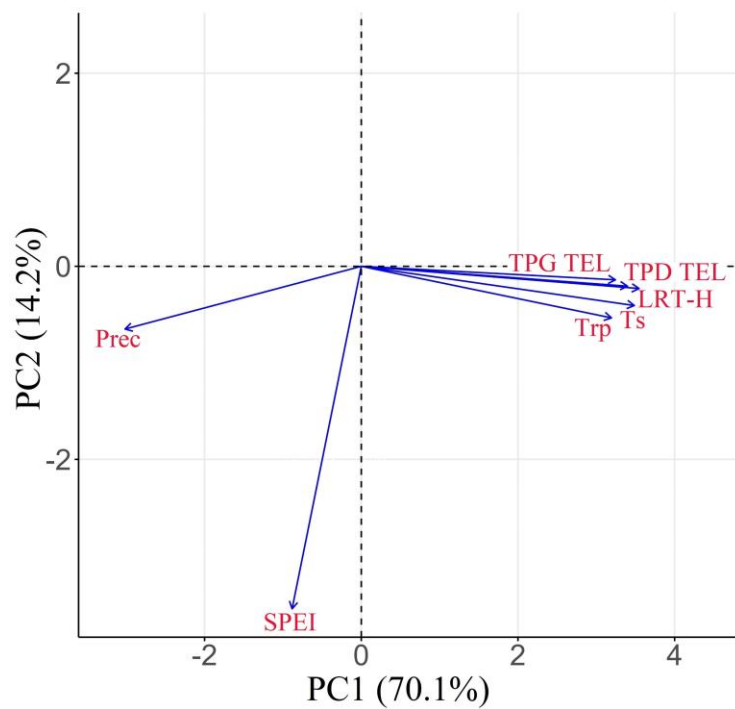


Figure 4. PCA biplot of monthly TPD TEL, TPG TEL, LRT-H, Ts, Trp, precipitation (Prec), and SPEI.

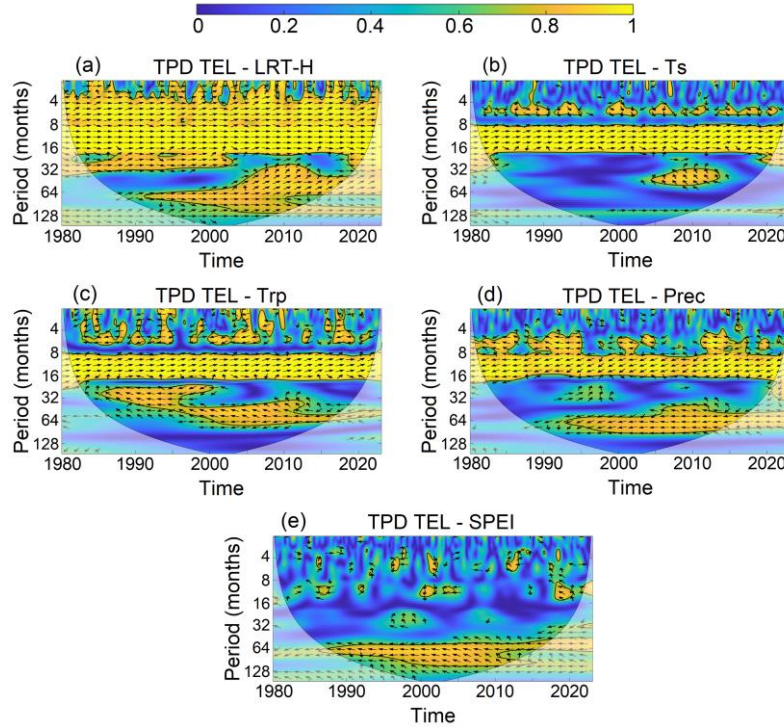


Figure 5. WTC analysis between monthly TPD TEL and climatic parameters. Arrows indicate phase differences between the two series. Variables are in phase when arrows point to the right (moving in the same direction with cyclical effects on each other). If arrows point right and upward, the first variable 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).

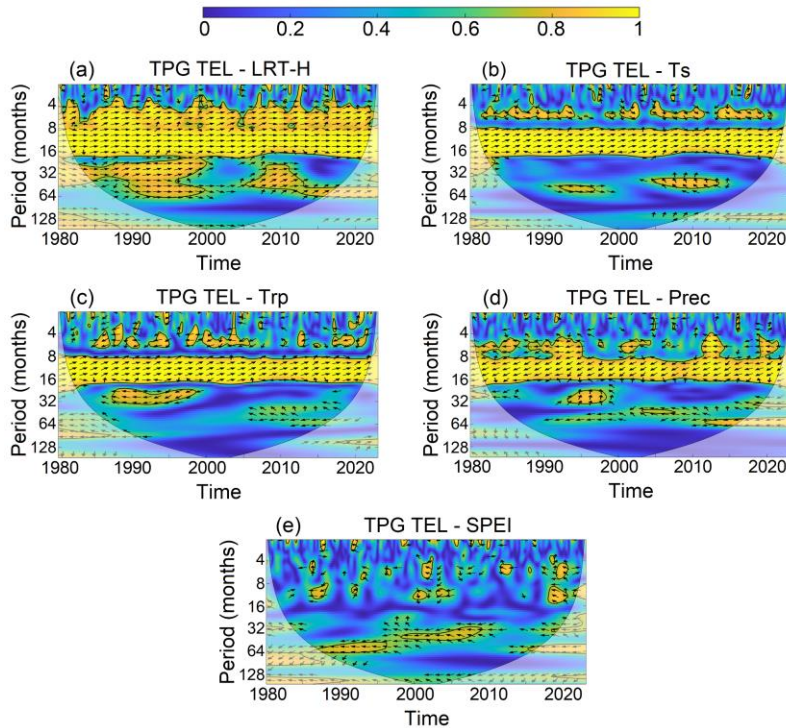


Figure 6. WTC analysis as in Figure 5, but for TPG TEL and the corresponding climatic parameters.

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 exhibits the spatial correlation of both TEL definitions with climatic parameters (Ts, Trp-1, Trp-2, precipitation, and SPEI). In Figure 7a,b, Ts displays positive correlations with TPD and TPG across the entire study area, with a maximum correlation of approximately 0.92 over the eastern Mediterranean region. Similarly, Trp-1 exhibits positive correlations with both TEL definitions over all grid cells (Fig. 7c,d), with a maxima correlation over the eastern Mediterranean region, reaching approximately 0.88 for Trp-1 and TPD TEL. For Trp-2, positive correlations with TELs dominate and cover near the entire Mediterranean region (Fig. 7e,f), except the latitudinal band where TELs vary poleward and equatorward. The positive correlation of Trp-2 with TELs from both definitions reaches a maximum of approximately 0.95. Conversely, the greatest negative correlation is between Trp-2 and TPG TEL of about approximately -0.38. In the case of precipitation, strong negative correlations with both TEL definitions dominate in the eastern Mediterranean region, reaching -0.75, while positive correlations cover areas in the north and south zones of the study area but weaker than the negative correlations in the eastern Mediterranean (Fig. 7g,h). SPEI shows weak correlations with both TPD and TPG TEL (Fig. 7i,j). These results demonstrate the spatial correlation patterns of TEL from both definitions with climatic parameters are nearly identical and it is in good accordance with the findings of Darrag (2024).

For further investigation into the effects of poleward tropical belt expansion on climatic parameters in the Mediterranean region, SVD analysis is performed to reveal coupled patterns of covariability between TEL position and climatic parameters. First, we constructed 3D geospatial data using monthly TEL values by repeating TEL values along all longitudes for each timestep. This process was performed for both TPD TEL and TPG TEL methods, resulting in 3D matrices for monthly TEL values in the same spatial and temporal domain as the climatic parameters. For the SVD analysis results, we consider only the first dominant mode of covariance. SVD1 depicts the spatial patterns for the first paired mode of covariability, whereas SC1 represents the time series of expansion coefficients for the same mode. For all parameters employed in the SVD examination, their SC1 time series and related SVD1 maps of spatial variability are scaled to range from -1 to 1 to enable comparison and description of the paired modes of covariability (Darrag et al., 2024).

For the coupled fields of TPD TEL and Ts, the squared covariance fraction (SCF) of the first leading mode explains 99.98% of the total covariability of both fields. As shown in Figure 8c, there is a strong positive correlation between the SC1 of TPD TEL and Ts of approximately 0.86. Furthermore, inter-annual oscillations dominate the SC1 for the temporal variability-paired mode of TPD TEL and Ts. The first coupled mode of spatial variability, SVD1, shows that Ts (Fig. 8b) is characterized by observed fluctuations in the eastern Mediterranean region accompanied by TPD TEL fluctuations of the same sign over the same region (Fig. 8a). For the coupled fields of TPD TEL and Trp-1, the SCF of the first prevailing mode accounts for approximately 99.98% of the total covariability of both fields. As depicted in Figure 8f, there is strong coupling between the

SC1 of TPD TEL and Trp-1 with a correlation of 0.88. Additionally, inter-annual oscillations dominate the SC1 for the temporal variability-paired mode of TPD TEL and Trp-1. The SVD1 exhibits that Trp-1 (Fig. 8e) is characterized by strong observed fluctuations in the eastern Mediterranean region, accompanied by TPD TEL fluctuations of the same sign over the same region (Fig. 8d). In the case of coupled fields of TPD TEL and Trp-2, the SCF of the first dominant mode describes approximately 99.56% of the total covariability of both fields. As shown in Figure 8i, there is a strong correlation between the SC1 of TPD TEL and Trp-2 of approximately 0.89. Moreover, inter-annual oscillations dominate the SC1 for the temporal variability-paired mode of TPD TEL and Trp-2. The SVD1 depicts that Trp-2 (Fig. 8h) has clear coupling of the opposite sign with TPD TEL (Fig. 8g) in the southernmost part of Europe and the northernmost part of Africa, while in the southernmost part and the northernmost part of the study area both show fluctuations of the same sign.

In the case of the coupled fields of TPD TEL and precipitation, the SCF of the first leading mode explains approximately 99.71% of the total covariability of both fields. As exhibited in Figure 8l, there is a high correlation between the SC1 of TPD TEL and precipitation of approximately 0.80. Additionally, inter-annual oscillations dominate the SC1 for the temporal variability-paired mode of TPD TEL and precipitation. The SVD1 depicts that precipitation (Fig. 8k) is characterized by two narrow signals of strong fluctuations in the eastern Mediterranean region, one associated with TPD TEL fluctuations of the same sign and the other with TPD TEL fluctuations of opposite sign, and another two covariability zones in southern Europe of the same characteristics as that of the eastern Mediterranean region (Fig. 8j). For the coupled fields of TPD TEL and SPEI, the SCF of the first dominant mode represents approximately 97.17% of the total covariability of both fields. As shown in Figure 8o, the correlation between the SC1 of TPD TEL and SPEI is weaker than with other parameters, approximately 0.41. Moreover, inter-annual oscillations dominate the SC1 for the temporal variability-paired mode of TPD TEL and SPEI. The SVD1 depicts that SPEI (Fig. 8n) has clear coupling of the same sign with TPD TEL (Fig. 8m) in major areas of the eastern Mediterranean region and northern Africa, while in major areas of western Europe, both show fluctuations of opposite sign. The first leading mode of covariability for the coupled fields of TPD TEL and climatic parameters (Fig. 9) shows coupling patterns nearly identical to those for TPD TEL (Fig. 8). The SVD analysis results show that the patterns of combined TELs and climatic parameters are more closely coupled for Ts and Trp-1. Furthermore, their combined fields are significantly related in the eastern Mediterranean region, which shows a more poleward TEL position compared to the entire study area.

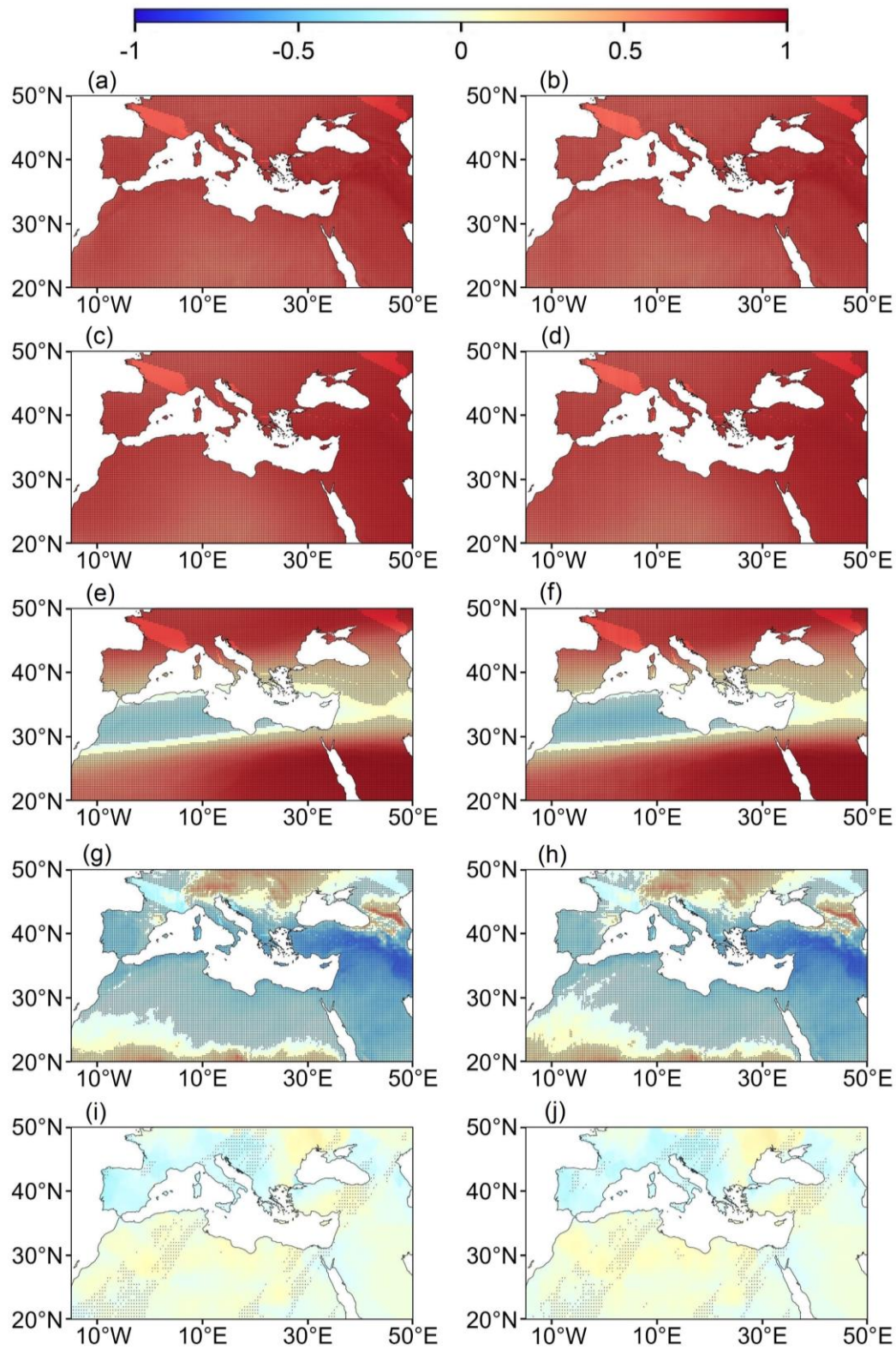


Figure 7. Spatial correlation of TPD TEL (left) and TPG TEL (right) with climatic parameters. Ts (a, b), Trp-1 (c, d), Trp-2 (e, f), precipitation (g, h), and SPEI (i, j). Black stippling indicates grid points where the correlation coefficients are statistically significant at $p < 0.05$.

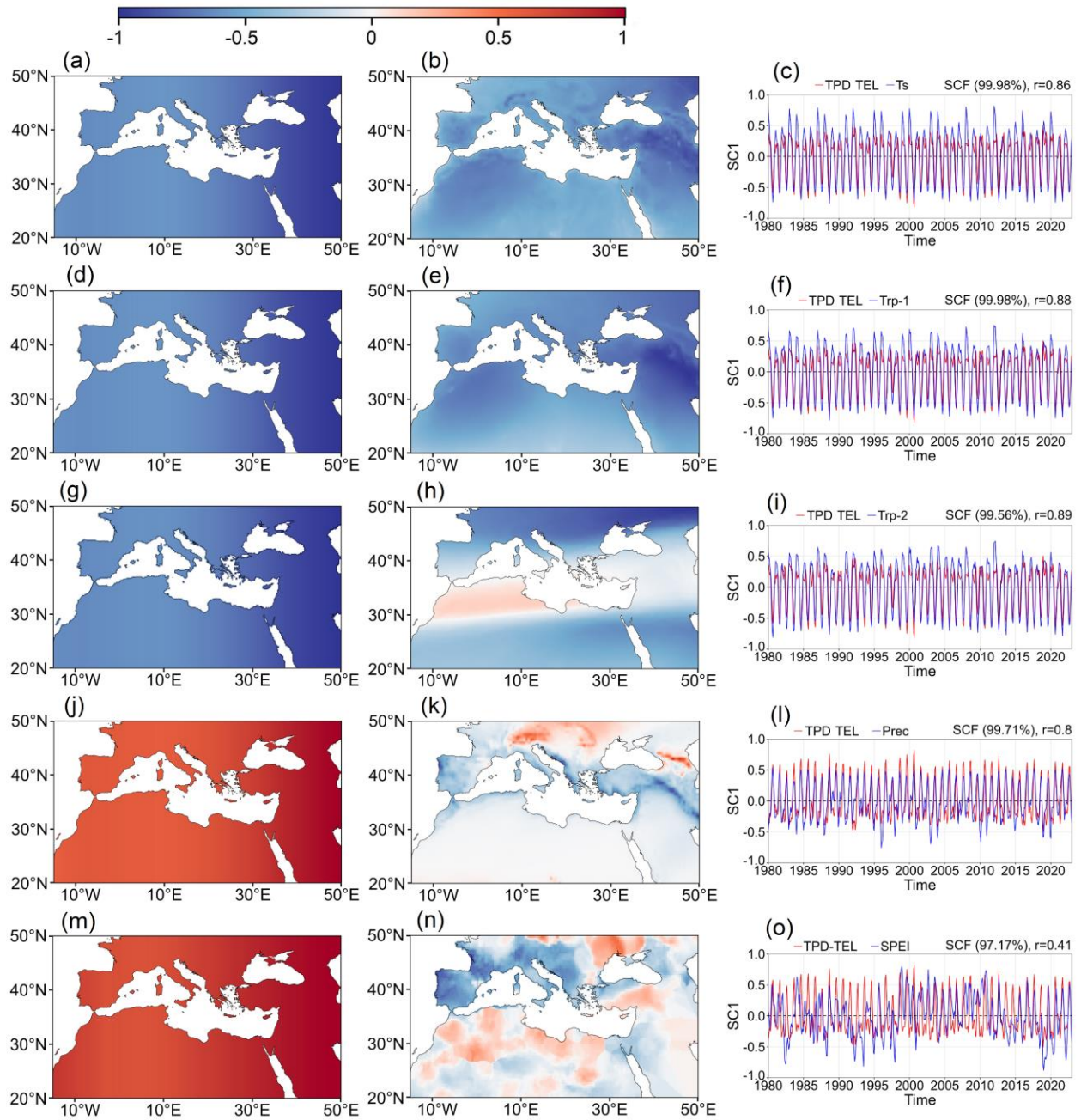


Figure 8. First leading mode of covariability for the coupled fields of TPD TEL and climatic parameters. TPD TEL and Ts (a, b, c), TPD TEL and Trp-1 (d, e, f), TPD TEL and Trp-2 (g, h, i), TPD TEL and precipitation (j, k, l), and TPD TEL and SPEI (m, n, o). The spatial patterns for the first paired mode 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).

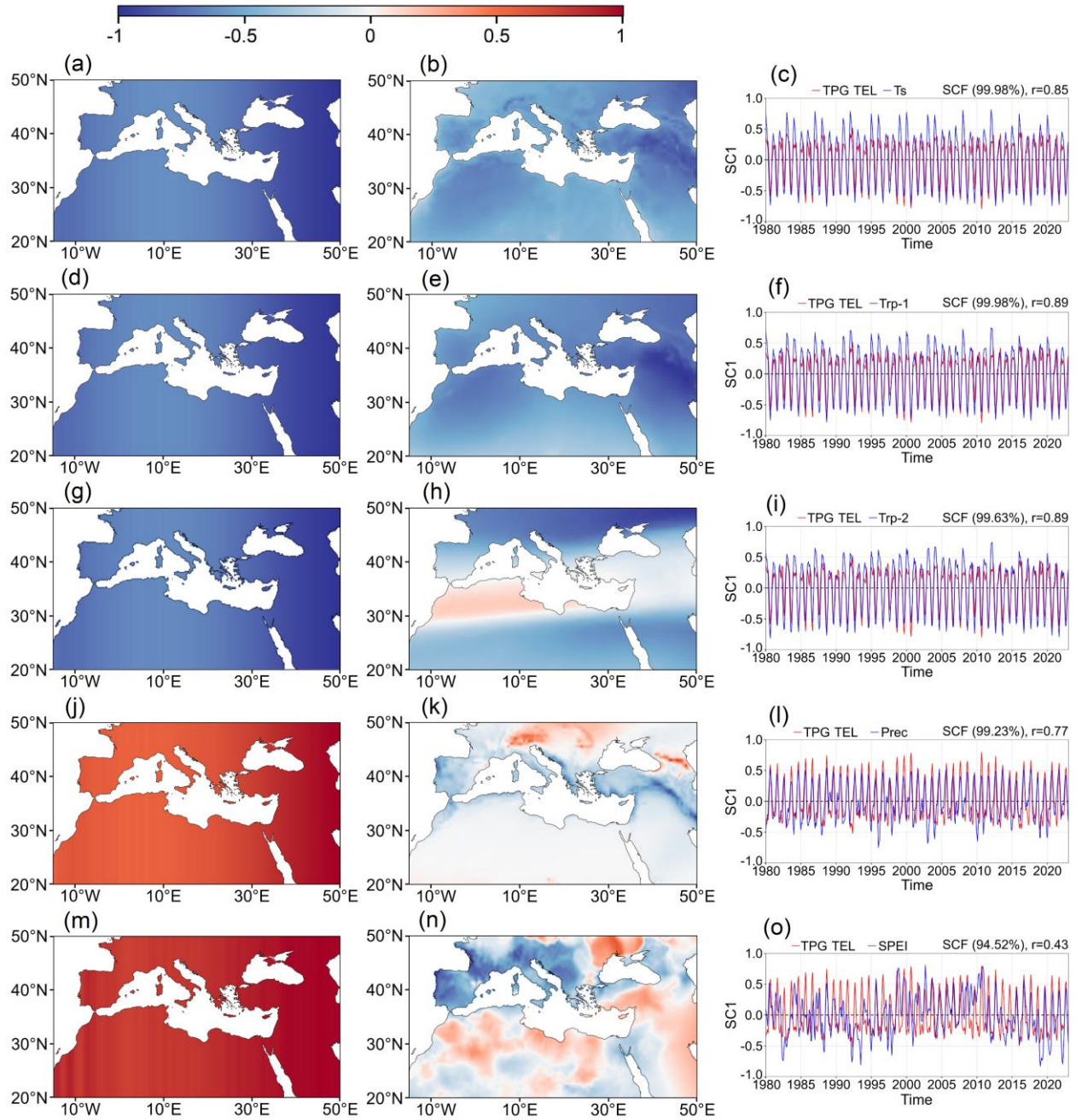


Figure 9. SVD analysis as in Figure 8, but for TPG TEL and the corresponding climatic parameters.

The Mediterranean region's monthly average Ts over the study period has increased by approximately 0.48 ± 0.03 K/dec (Fig. 10a). This is in line with the results of Castellanos et al. (2021), who found land surface air temperature was significantly rising, with yearly amplitudes ranging from 0.006 to 0.027 °C for maximum temperatures and slightly greater rates for minimum temperatures. The primary drivers of Mediterranean region warming are the rapid increase of anthropogenic greenhouse gases and the decline of aerosols and soil moisture (Kim et al., 2019; Urdiales-Flores et al., 2023). Linear regression analysis of Ts was performed at all grid points, with decadal trends plotted in Figure 10b. Ts shows a dominant upward trend across the study area. The

greatest temperature upward trends are evident in the eastern Mediterranean region, while temperature trends in the western Mediterranean are less pronounced. Moreover, the zonal mean of the temperature linear regression map (right panel of Fig. 10b) shows positive temperature trends throughout the entire study area with maximum trends in the northern zone of the Mediterranean from 46.00° N to 50.00° N. Zittis et al. (2022) reported the Eastern Mediterranean and Middle East are warming approximately twice as rapidly as the global average, indicating the Mediterranean as a whole is experiencing dramatic warming and particular locations far more drastic changes.

Trp-1 showing increasing trends of approximately 0.36 ± 0.03 K/dec (Fig. 10c). The decadal trends of Trp-1 at all grid points over the study area (Fig. 10d) depict increasing trends caused mainly by global warming. Trp-1 trends in the eastern and northern Mediterranean are stronger than those in the southern and western Mediterranean, and the zonal mean of Trp-1 linear regression map (right panel of Fig. 10d) depicts dominant positive trends throughout the entire study area with the strongest trends in the zone from 45.00° N to 50.00° N. For the monthly time series of Trp-2 (Fig. 10e), the decadal trend is 0.09 ± 0.01 K/dec, which is less than that of Trp-1. Additionally, linear regression analysis of Trp-2 performed at all grid points shows clear variation in temperature trends. In the northern Mediterranean, positive Trp-2 trends are abundant, while in the southern Mediterranean, negative trends are prevalent (Fig. 10f). The zonal mean of Trp-2 linear regression map (right panel of Fig. 10f) displays clear negative trends around the latitude of 31.25° N. Our results are compatible with Karl et al. (2006), who reported that global-average Trp have increased significantly since the late 20th century. From 1958 to the present, the global average temperature has risen at a rate of approximately 0.12°C per decade, accelerating to about 0.16°C per decade since 1979.

The decadal trends of the monthly zonal mean temperature structure during 1980-2022 over height ranges from the earth's surface to 20 km, including the troposphere and lower stratosphere, and the LRT-H zonal mean is shown in Figure 10g. As evident, there are apparent upward temperature trends in the whole troposphere, with the greatest increasing trends over the latitudinal band from around 45.00° N to 50.00° N, with a maximum value of 0.50 K/dec. As is clear from the zonal mean of linear regression trend maps of Ts, Trp-1, and Trp-2 (right panel of Fig. 10b, d, and f), there is an observed increase in temperature trends also over the latitudinal band from around 45.00° N to 50.00° N. The warming in the troposphere is associated with apparent cooling trends in the stratosphere at a greatest rate of slightly over -0.50 K/dec while the latitudinal band 20.00° N to 30.00° N is the zone of maximum stratospheric temperature declining trends. The phenomenon of tropospheric warming accompanied by stratospheric cooling is a signature fingerprint of human-induced climate change, principally driven by rising GHG emissions. These assumptions are corroborated by several studies on tropospheric warming and stratospheric cooling employing radiosonde, GNSS-RO, and satellite observations (Narayana Rao et al., 2007; Titchner et al., 2009; Haimberger et al., 2012; Steiner et al., 2020).

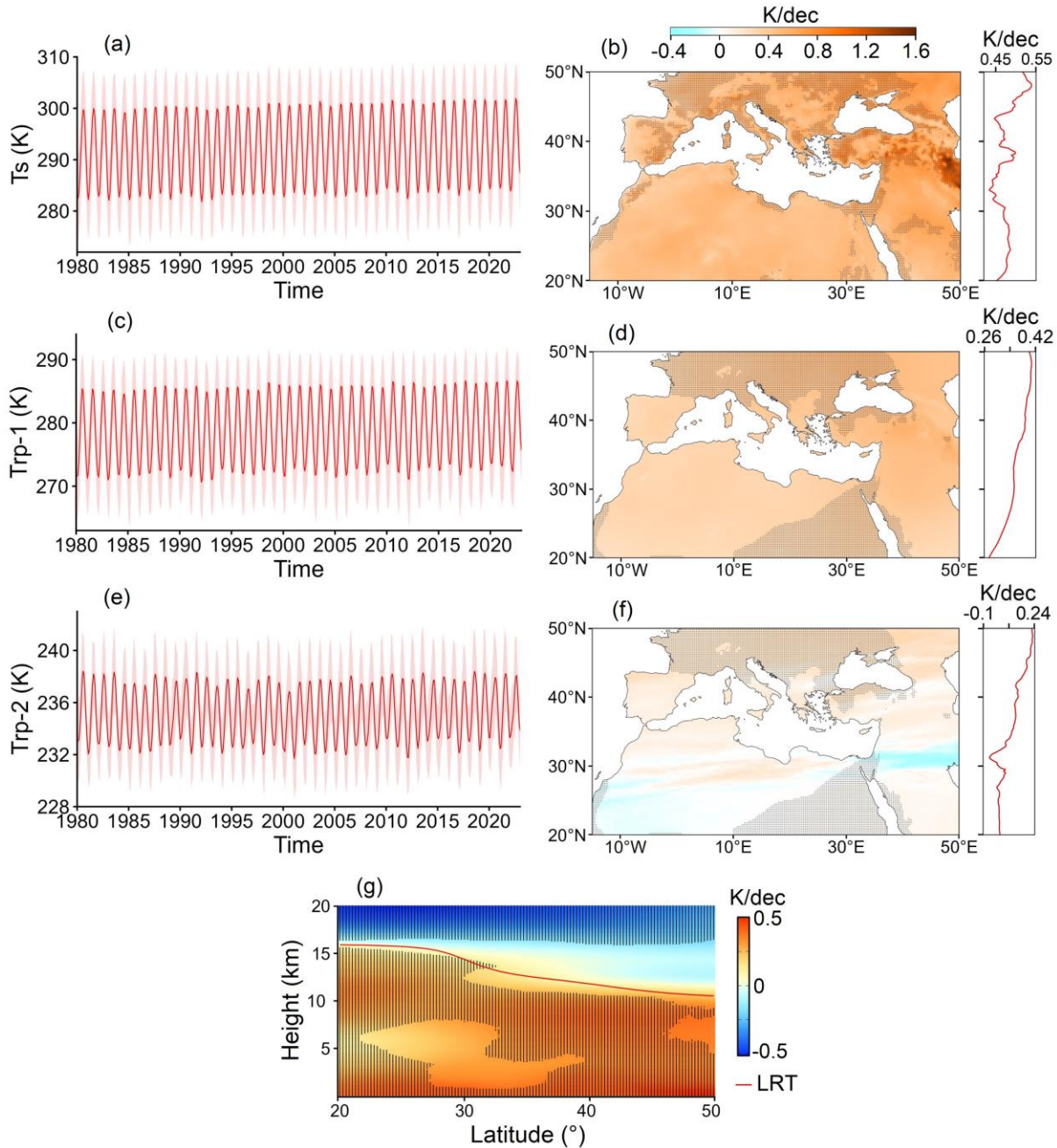


Figure 10. On the left, monthly time series of Ts (a), Trp-1 (c), and Trp-2 (e). On the right, decadal trends regression maps and their corresponding zonal mean, Ts (b), Trp-1 (d), and Trp-2 (f). Temperature trends in the troposphere and lower stratosphere (0-20 km) in addition to LRT-H represented by the red line (g). Black stippling indicates regions where the trends are statistically significant at $p < 0.05$.

Total precipitation over the Mediterranean exhibits decreasing trends of approximately -0.25 ± 0.05 mm/dec (Fig. 11a). This is in accordance with previous studies reporting significant changes in precipitation patterns driven by climate change as reflected by observational data and climate model projections indicate 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). Linear regression analysis of total precipitation in Figure 11b exhibits a dominant downward trend evident in eastern and western Europe. The zonal mean of the precipitation linear regression map (right panel of Fig. 11b) exhibits evident positive trends at approximately latitude 41.00° N while depicting a strong negative trend between 47.00° N and 50.00° N. SPEI is commonly used to monitor meteorological drought status showing in Figure 11c a decrease of -0.070 ± 0.001 /dec. Recent studies have highlighted significant trends in drought occurrences and characteristics across the Mediterranean Basin (Essa et al., 2023) and historical analyses using SPEI from 1980 to 2014 reveal a significant upward trend in drought frequency (Choutri and Hussien, 2024; Kesgin et al., 2024). SPEI linear regression analysis exhibits evident decreasing trends, especially in the northern Mediterranean (Fig. 11d) with a zonal mean (on the right panel of Figure 11d)) showing strong negative trend between 40.00° N and 50.00° N.

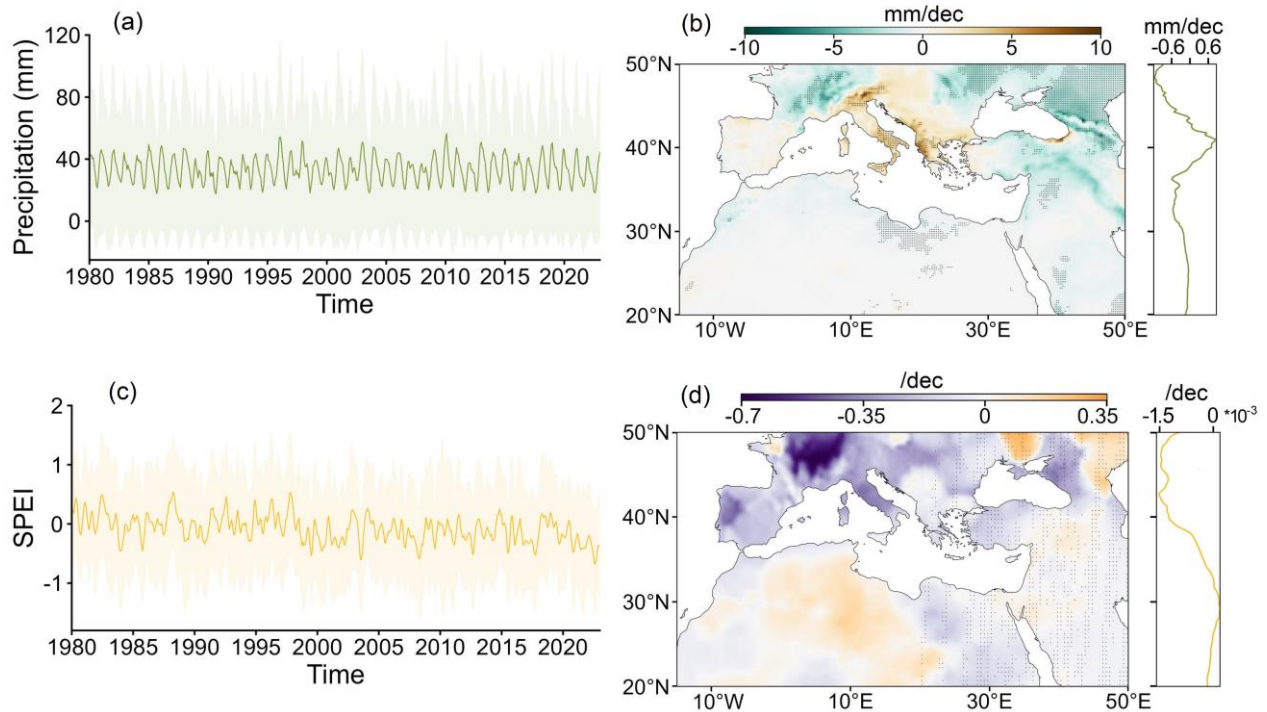


Figure 11. Monthly time series of precipitation (a) and its linear regression analysis at all grid points with decadal trends, with the zonal mean of the regression map on the right side (b). Monthly time series of SPEI (c) and its linear regression analysis at all grid points with decadal trends, with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

4 Conclusions

The Mediterranean region is recognized as a climate change hotspot, where the combined impacts of global warming and tropical belt expansion are contributing to significant alterations in climatic patterns. We have investigated the relationship between tropical belt expansion over the Mediterranean region and climatic parameters (tropopause, temperature, precipitation, and SPEI)

variations using observational and reanalysis data from January 1980 to December 2022. We employ a comprehensive analysis applying correlation, linear regression, SVD, WTC, and PCA. Our findings reveal monthly average LRT-H increased by approximately 80.58 ± 3.07 m/dec, attributed to global warming from increasing GHG emissions (Meng et al., 2021). LRT-H shows stronger positive anomalies than negative ones, while LRT-T displays higher negative anomalies than positive. Moreover, LRT-H shows dominant upward trends over the study area, with maximum values of approximately 266.50 m/dec in the eastern Mediterranean, reflecting intensifying warming conditions. These results corroborate previous research based on GNSS-RO, radiosonde, and reanalysis datasets that have documented rising tropopause height (Sausen and Santer, 2003; Schmidt et al., 2004; Seidel and Randel, 2006; Pisoft et al., 2021). Based on the two tropopause height metrics, the tropical belt expanded poleward at rates of approximately 0.14 ± 0.05 °/dec and 0.27 ± 0.06 °/dec for TPD and TPG methods, respectively. The tropical belt expansion has long been connected to changes in atmospheric structure caused by global warming; as temperatures increase, enhanced tropospheric warming causes thermal expansion of the troposphere, resulting in a rise in tropopause height. This vertical expansion is accompanied by poleward growth of the area covered by the tropical belt.

TELs exhibit an evident longitudinal variation, as the eastern Mediterranean shows enhanced poleward TEL occurrences compared to that over the western Mediterranean. This east–west contrast is consistent with the strong influence of Atlantic storm tracks in the western Mediterranean (Lionello et al., 2006), while variability in upper-tropospheric jet dynamics may also play an important role in the eastern Mediterranean (Manney et al., 2011). TELs from both methods exhibit strong positive correlations with LRT-H, Ts, and Trp, while showing strong negative correlations with precipitation. WTC analysis confirms that both TEL definitions are in phase with high coherence to LRT-H, Ts, and Trp, but out of phase with precipitation. However, no significant relationship exists for SPEI with TELs or other climatic parameters due 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. Spatial correlation analysis reveals that both Ts and Trp-1 show positive correlations with TELs across the study area, with the highest values in the eastern Mediterranean. Trp-2 displays predominantly positive spatial correlations with TELs throughout most of the Mediterranean except within the latitudinal band where TELs undergo poleward expansion and equatorward contraction. Precipitation exhibits strong negative correlations with TELs in the eastern Mediterranean while showing positive correlations over northern and southernmost parts of the study area.

SVD analysis demonstrates the first mode of temporal variability for paired modes of TELs and all climatic parameters is dominated by inter-annual oscillations. SC1 of TELs shows strong positive correlations with all climatic factors but less in the case of SPEI. The first spatial mode (SVD1) reveals clear coupling between Ts and Trp-1 with TELs in the eastern Mediterranean. For Trp-2, SVD1 shows linkage with TELs in the southernmost and northernmost zones of the study

area, while displaying opposite-sign oscillations in southern Europe, northern Africa, and the middle zone of the eastern Mediterranean. Precipitation SVD1 exhibits two strong fluctuation signals (one in the eastern Mediterranean and another in southern Europe) accompanied by opposite-sign TEL fluctuations over the same regions and another two covariability zones northward of the previous ones but accompanied by TEL fluctuations of the same sign over the same regions. SPEI SVD1 displays clear coupling of the same sign with TELs in major areas of the eastern Mediterranean and northern Africa regions, while in western Europe, both depict opposite sign fluctuations. The stronger coupling between TELs and climatic parameters in the eastern Mediterranean indicates the strong effect of the TEL pattern in this region compared to the broader study area. Ts over the Mediterranean region increased at 0.48 ± 0.03 K/dec, with the most significant rises in the eastern Mediterranean and less dramatic increases in the western Mediterranean. Trp-1 and Trp-2 show increasing trends of approximately 0.36 ± 0.03 K/dec and 0.09 ± 0.01 K/dec, respectively, with positive trends most abundant in the eastern and northern Mediterranean for Trp-1 and the northern Mediterranean for Trp-2. The temperature structure across the Mediterranean has the greatest magnitudes and trends near the surface, which gradually drop with altitude and exhibit a strong height-dependent spatial pattern. Total precipitation and SPEI exhibit decreasing trends of approximately -0.25 ± 0.05 mm/dec and -0.070 ± 0.001 /dec, respectively, in agreement with previous studies reporting pronounced aridification and more frequent droughts over the Mediterranean region (Essa et al., 2023; André et al., 2024).

The results presented in this study confirm climatic parameter variability, coherence, and coupling are linked to TELs variability throughout the Mediterranean region, with apparent interaction and coupling between climatic parameter patterns and TELs over the eastern Mediterranean. Our findings advance the understanding of the long-term variability of key climatic parameters over the Mediterranean, as well as their relationships and interactions with large-scale tropical belt dynamics.

Author contribution. Conceptualization: MD and SJ; Methodology: MD; Software: MD; Validation: SJ and MD; Formal analysis: MD; Investigation: SJ and MD; Resources: MD; Data curation: MD; Writing—original draft preparation: MD; Visualization: MD; Writing—review and editing: SJ, MD, AC, AS, IR and AMR; Supervision: SJ.

Competing interests. The authors declare no competing interests.

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