

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, and singular value decomposition (SVD) analysis. 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 show an evident seasonal variation. In addition, the two TEL definitions exhibit consistent correlation patterns with surface temperature (Ts), lower tropospheric temperature (Trp-1), upper tropospheric temperature (Trp-2), precipitation, and the Standardized Precipitation Evapotranspiration Index (SPEI). The results of the SVD analysis depict that although the leading mode (SVD1) explains the majority of the covariance between TELs and the examined climatic parameters, the second coupled mode (SVD2) shows more localized spatial structures, with TELs pronouncedly coupling with Ts and Trp-1 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 region, climatic parameters show an apparent spatial and temporal variation. The results confirm the linkage between climatic parameters' trends and variability 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 northward during the summer (JJA) and southward during 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). Since the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5), various research utilizing a range of metrics and reanalyses datasets have indicated that the annual mean Hadley circulation (tropics) has expanded poleward at an approximate rate of 0.1° – 0.5° latitude per decade over the last about 40 years (IPCC, 2021a), 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 (T_s) 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, and singular value decomposition (SVD). The analysis focuses on how tropical expansion relates to tropopause characteristics, T_s (considered both as a potential driver and a response to tropical belt shifts), tropospheric temperature (T_{trp}) (from the surface to the LRT level), precipitation, and SPEI as an indicator of meteorological drought. 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. The anomaly time series for tropopause parameters was created by subtracting the long-term monthly climatological means from the original observations, covering the period from 1980 to 2022. This deseasonalization procedure removes the mean annual cycle and highlights climate variability and long-term changes. LRT-H displays a maximum positive anomaly of approximately 0.41 km occurring in August 2020 and the greatest negative anomaly of approximately -0.46 km in June 1992. After November 1997, its anomaly time series shows mostly positive values, which means that the Mediterranean region has been getting warmer (Fig. 1c). In the case of LRT-T, it exhibits a maximum positive anomaly of approximately 2.01 K in January 1993 and a greatest negative anomaly of approximately -2.08 K in January 1998. It shows a dominant negative anomaly after June 1993, reflecting a predominant warming pattern over the study area (Fig. 1d). 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). 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, the TPG TEL occurrences are more poleward, with a maximum value of approximately 42.88° N, compared to the TPD TEL maximum value of approximately 42.78° N.

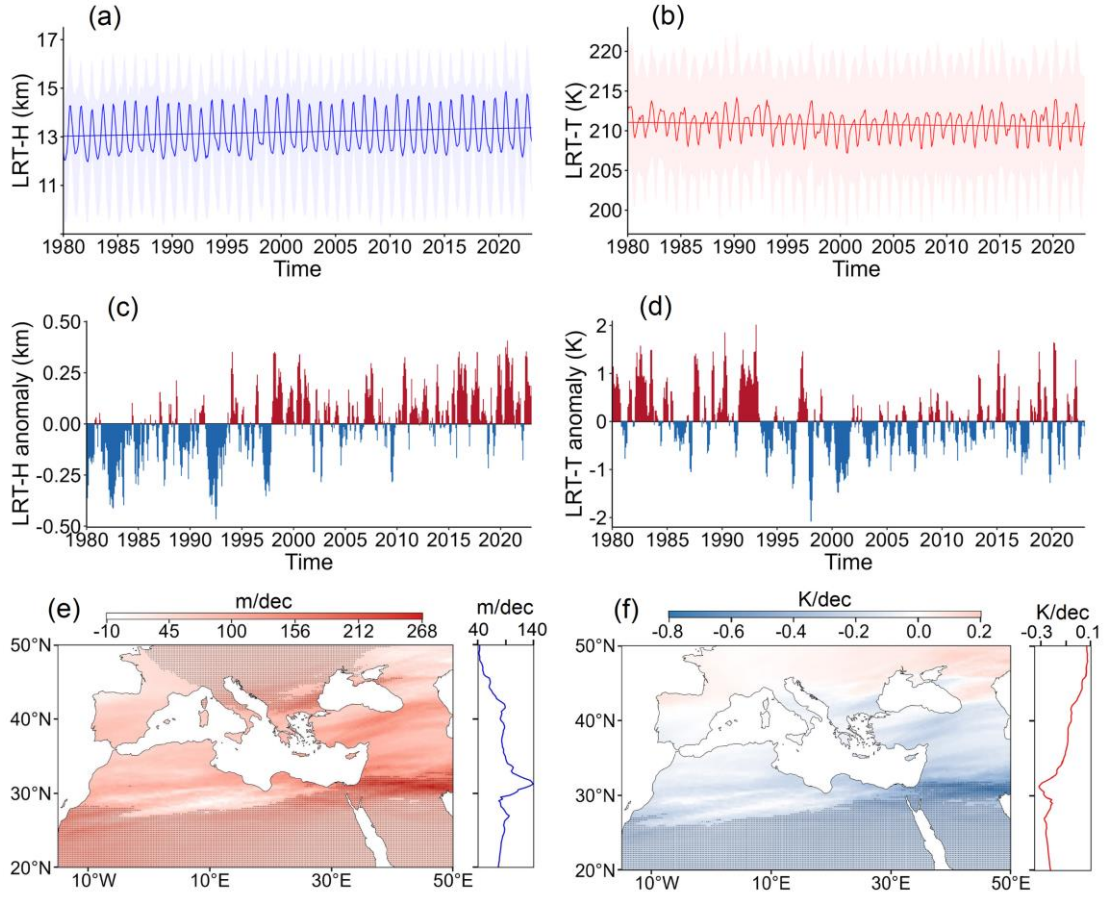


Figure 1. Monthly time series of LRT parameters in the top: (a) LRT-H and (b) LRT-T. The solid lines indicate the monthly mean values, while its surrounding light shading denotes the SD at each time step. Tropopause anomaly in the middle: (c) LRT-H anomaly time series, (d) LRT-T anomaly time series. 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.

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 results are in agreement with previous studies, which reported a pronounced seasonal cycle of the TEL, characterized by a poleward shift during JJA

and an equatorward shift during DJF, with a seasonal migration amplitude of 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

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 3 exhibits the spatial distribution of Pearson correlation coefficients between the deseasonalized anomaly time series of TPD TEL and TPG TEL with climatic parameters (Ts, Trp-1, Trp-2, precipitation, and SPEI), which were computed independently at each grid point. Ts displays abundant positive correlations with TPD TEL across the study area, with the strongest positive correlation of approximately 0.34 in the eastern Mediterranean and a weak negative correlation, which is greatest at about -0.09 in the western Mediterranean (Fig. 3a). In addition, Ts shows positive correlations with TPG TEL in the eastern Mediterranean with a maximum value of about 0.35 and negative correlations in the western Mediterranean with a greatest value of about -0.15 (Fig. 3b). The predominance of positive correlations between Ts and TEL over the Mediterranean region indicates that warmer surface conditions tend to accompany a northward displacement of the TELs. Such a relationship is physically consistent with the thermodynamic expansion of the tropospheric column under warming, which can contribute to a rise in tropopause height. The east–west contrast reflects the strong regional heterogeneity of the Mediterranean climate, including land–sea thermal contrasts and differences in the influence of continental and maritime air masses.

Trp-1 exhibits a modest correlation with both TEL definitions over all grid cells (Fig. 3c,d), with correlation values ranging from -0.06 to 0.22 and -0.15 to 0.32 for TPD TEL and TPG TEL, respectively. In the case of Trp-2, the correlation with TEL is stronger than that in the case of Trp-1, ranging from -0.42 to 0.41 and -0.52 to 0.55 for TPD TEL and TPG TEL, respectively. The positive correlation values of Trp-2 with TELs are abundant in the southeast and northwest parts of the study area, while the negative correlation values are abundant in between (Fig. 3e,f). The stronger relationship of TEL with Trp-2 signifies that variations in the upper troposphere thermal structure are more closely associated with TEL variability than changes confined to the lower troposphere. The alternating positive and negative correlation bands in Figures 3e and 3f reflect regional differences in Trp-2 variability associated with changes in large-scale circulation and the meridional distribution of the subtropical thermal structure. The precipitation shows low correlations with both TEL definitions, with abundant negative values in the eastern Mediterranean and positive values in the western Mediterranean, varying from -0.27 to 0.19 for TPD TEL and from -0.32 to 0.25 for TPG TEL (Fig. 3g,h). The negative relation of TEL locations with precipitation is dynamically consistent with the poleward migration of the descending branch of the Hadley circulation, which displaces subtropical dry zones and modifies the positions of storm tracks. The SPEI shows weak correlations with TELs (Fig. 3i,j), ranging from -0.22 to 0.14 and -0.21 to 0.15 for TPD TEL and TPG TEL, respectively. The weak linkage between TEL positions

and SPEI arises because SPEI represents an integrated hydroclimatic response that depends jointly on precipitation and atmospheric evaporative demand. Consequently, the response of SPEI to large-scale TEL variability can be partly obscured by regional variations in precipitation, temperature, soil moisture, and surface water availability. These results demonstrate that the correlation patterns of TEL from both definitions with climatic parameters are nearly identical and are in accordance with the findings of Darrag (2024).

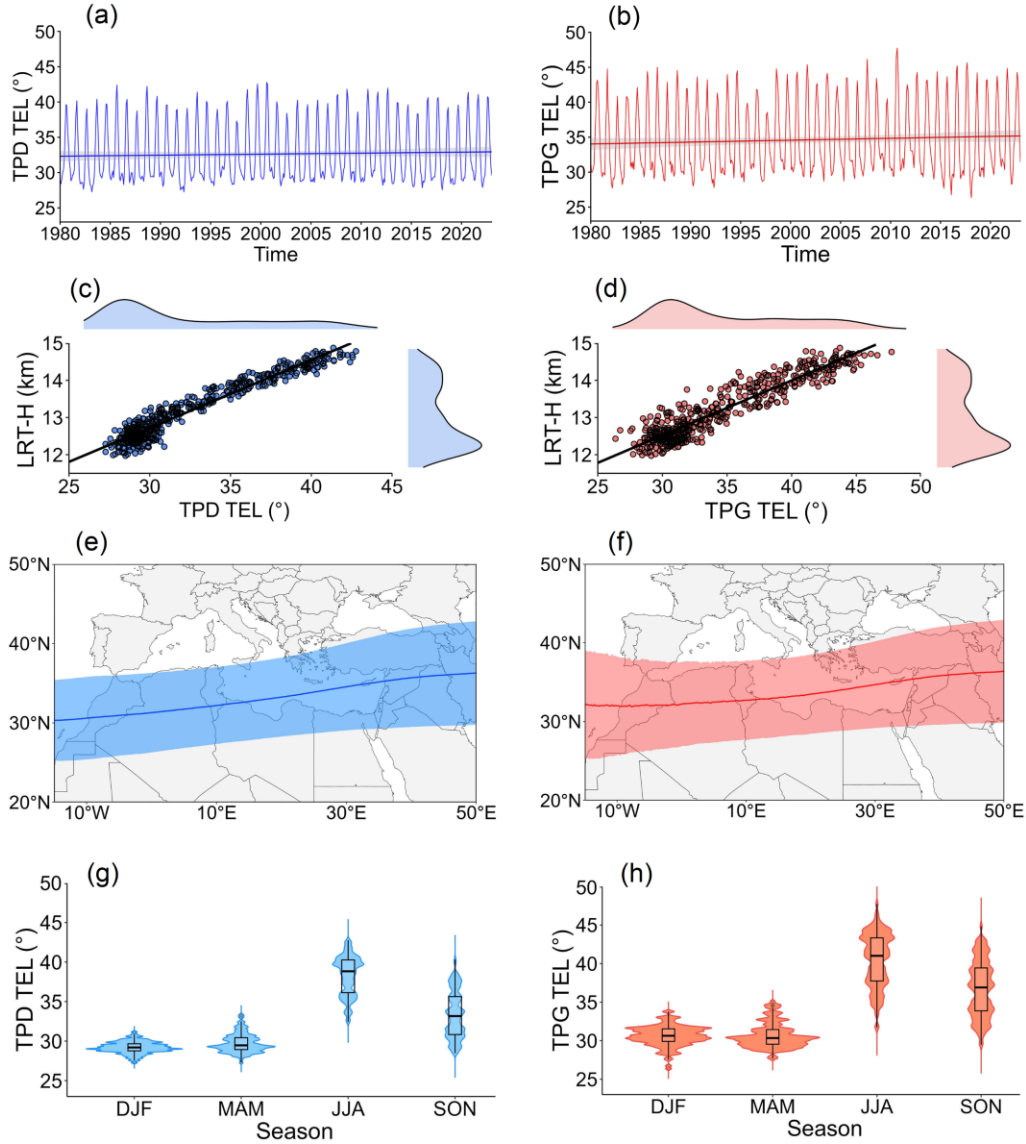


Figure 2. Monthly time series of the (a) TPD TEL method and (b) TPG TEL method, the shaded bands surrounding the trend lines denote the 95% confidence intervals of the fitted trends. The linear regression model between TPD TEL and LRT-H (c) and the linear regression model between TPG TEL and LRT-H (d), the marginal probability density functions (PDFs) of the variables are shown above and to the right of each scatter plot. 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) shown as violin plots. The width of each violin represents the probability density of the seasonal TEL values. The central box indicates the interquartile range (25th–75th percentiles); the horizontal line inside the box marks the median.

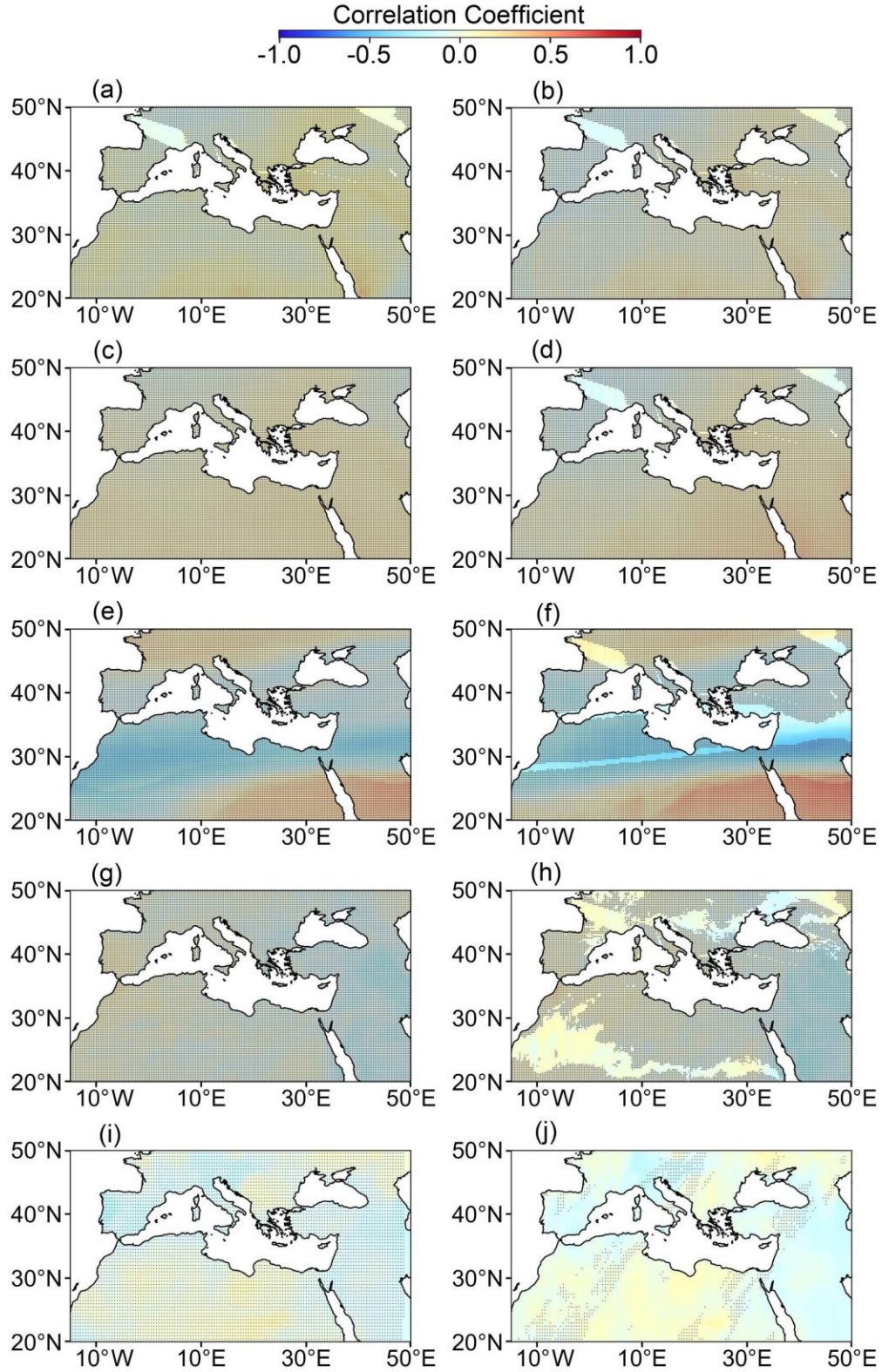


Figure 3. Correlation maps of TPD TEL (left) and TPG TEL (right) with climatic parameters, where the Pearson correlation coefficient was computed independently at each grid point. Ts (a, b), Trp-1 (c, d), Trp-2 (e, f), precipitation (g, h), and SPEI (i, j). Black stippling indicates grid points where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

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 two dominant modes of covariance. SVD1 and SVD2 depict the spatial patterns for the first and second paired modes of covariability, respectively, whereas SC1 and SC2 represent the time series of the paired expansion coefficients for the same modes. For all parameters employed in the SVD examination, their expansion coefficients' time series and related spatial variability maps are scaled to range from -1 to 1 to enable comparison and description of the paired modes of covariability (Darrag et al., 2024).

Figure 4 shows the first leading mode of covariance between the TPD TEL and climatic variables over the Mediterranean region. The left and middle panels show the SVD1 of TPD TEL and the corresponding climatic field, respectively. Whereas the right panels display their paired SC1. The squared covariance fraction (SCF) indicates the proportion of the total covariance captured by the first mode, while the correlation coefficient (r) quantifies the strength of the temporal relationship between the corresponding paired SC1. The first dominant mode explains the majority of the coupled covariance between TPD TEL and the investigated climatic parameters, accounting for 56.48–86.32% of the total covariability. This signifies that the leading mode represents the dominant large-scale pattern linking tropical belt variability with the Mediterranean climate. For the first dominant coupled mode of TPD TEL and T_s , the SCF explains 62.87% of the total covariability of both fields. The TPD TEL SVD1 exhibits a pronounced east-west gradient across the Mediterranean (Fig. 4a). The corresponding T_s SVD1 is characterized by positive covariance over western and northern regions of the study area, while it shows negative covariance over the southeastern Mediterranean and North Africa (Fig. 4b). The paired SC1 of TPD TEL and T_s displays a positive correlation of approximately 0.30. Furthermore, interannual oscillations dominate the SC1 for the temporal variability-paired mode of TPD TEL, and T_s (Fig. 4c). The spatial structure shows that the association between TEL variability and T_s is modulated by the strong land–sea thermal contrast and regional differences in surface energy exchange across the Mediterranean. In the case of the coupled fields of TPD TEL and Trp-1, the SCF of the first prevailing mode accounts for approximately 56.48% of the total covariability of both fields. The TPD TEL SVD1 displays an east-west dipole (Fig. 4d), whereas the associated SVD1 of Trp-1 reveals enhanced positive covariance over the eastern Mediterranean and North Africa. On the other hand, it shows a negative covariance over the western Mediterranean (Fig. 4e). The paired SC1 of TPD TEL and Trp-1 depicts a synchronous fluctuation and has a correlation of about 0.29, suggesting that meridional displacements of the TPD TEL are accompanied by variations in the Trp-1, although the temporal relationship remains relatively weak (Fig. 4f). The opposing fluctuations in signs between the eastern and western parts of the study region indicate that Trp-1

thermal response is spatially heterogeneous. This pattern may reflect regional differences in advection, surface forcing, and the meridional temperature gradient.

The first coupled mode of TPD TEL and Trp-2 describes approximately 86.32% of the total covariability of both fields, indicating that this mode dominates the shared variability. The TPD TEL SVD1 exhibits widespread negative covariance over the Mediterranean basin (Fig. 4g). While the Trp-2 SVD1 shows a pronounced zonal positive band extending across North Africa and the southern Mediterranean (Fig. 4h). The paired SC1 of TPD TEL and Trp-2 displays strong temporal agreement throughout the analysis period ($r = 0.67$), suggesting that variations in TPD TEL are closely linked to changes in the Trp-2 thermal structure (Fig. 4i). The tropopause and TEL are sensitive to Trp-2 variation, which can modify the meridional thermal structure and atmospheric thickness and can therefore influence the location of the subtropical tropopause and the associated transition between tropical and extratropical atmospheric regimes. In the case of the coupled fields of TPD TEL and precipitation, the SCF of the first leading mode explains approximately 68.59% of the total covariability of both fields. The SVD1 reveals a pronounced longitudinal gradient in the TPD-TEL pattern (Fig. 4j), while the precipitation SVD1 exhibits predominantly negative covariance across much of the Mediterranean basin (Fig. 4k). As depicted in Figure 4l, there is a correlation between the paired SC1 of TPD TEL and precipitation of approximately 0.42, indicating that tropical belt variability is associated with changes in Mediterranean precipitation which is controlled by regional circulation and thermodynamic processes. For the coupled fields of TPD TEL and SPEI, the SCF of the first dominant mode represents approximately 61.32% of the total covariability of both fields. The TPD TEL SVD1 is characterized by widespread positive covariance across the Mediterranean (Fig. 4m), whereas the corresponding SPEI SVD1 is characterized by alternating positive and negative zones across the Mediterranean (Fig. 4n), with a clear positive covariance in the eastern Mediterranean and negative covariance in the western Mediterranean, reflecting regional differences in drought response. The SC1 of both TPD TEL and SPEI has a correlation of about 0.37. Moreover, both show interannual and interdecadal oscillations (Fig. 4o). The heterogeneous SPEI spatial pattern, characterized by alternating positive and negative covariance across the Mediterranean, shows that the hydroclimatic response to TEL variability is spatially nonuniform. This pattern is expected because SPEI integrates the effects of precipitation and atmospheric evaporative demand, both of which exhibit substantial regional variability.

Unlike the first leading mode of covariability, the second coupled mode explains a substantially smaller fraction of the total covariance, ranging from 11.05% to 32.07%. Although this mode contributes less to the total covariability, it is characterized by more localized spatial structures, as is evident in SVD2, and the paired expansion coefficients (SC2) remain positively correlated ($r = 0.27-0.58$), indicating that the secondary mode still reflects meaningful interactions between tropical belt variability and Mediterranean climate (Fig. 5). For the coupled fields of TPD TEL and Ts, the SCF of the second dominant mode explains 26.77% of the total covariability of both fields. The second coupled mode of spatial variability, SVD2, shows that TPD TEL is characterized by

observed negative loadings over most of the study area (Fig. 5a), accompanied by Ts fluctuations of the same sign over the majority of the eastern Mediterranean and a limited zone of the western Mediterranean. On the other hand, the SVD2 of Ts shows positive fluctuations in the central Mediterranean. The Ts spatial heterogeneity may reflect the strong land–sea thermal contrast of the Mediterranean region and differences in surface energy partitioning between continental and maritime environments (Fig. 5b). The paired SC2 of TPD TEL and Ts exhibits a correlation of about 0.29 (Fig. 5c). In the case of coupled fields of TPD TEL and Trp-1, the SCF of the second dominant mode accounts for 32.07% of the total covariance of both fields, representing the largest secondary contribution among all variables. The TPD TEL SVD2 shows abundant negative fluctuations over the Mediterranean (Fig. 5d), which coincide with Trp-1 fluctuations of the same sign in most of the eastern Mediterranean and a restricted area of the western Mediterranean. Meanwhile, the SVD2 of Trp-1 displays a well-defined meridional dipole, with positive covariance centered over North Africa and negative covariance extending across the eastern Mediterranean (Fig. 5e). Such a structure may be associated with regional differences in horizontal temperature advection, surface heating, and the meridional temperature gradient. The paired temporal coefficients for TPD TEL and Trp-1 exhibit a weak correlation of approximately 0.27 (Fig. 5f).

For the coupled fields of TPD TEL and Trp-2, the SCF of the second prevailing mode represents only 11.05% of the total covariability of both fields, implying that most of the shared variability between these two variables is already captured by the first mode. Nevertheless, the paired SC2 of TPD TEL and Trp-2 remain strongly correlated ($r = 0.58$), indicating that although this secondary pattern contributes little to the overall covariance, it still represents a physically meaningful mode of coupled variability (Fig. 5i). The SVD2 of the TPD TEL displays an observed east–west gradient over the Mediterranean region (Fig. 5g), which is accompanied by Trp-2 fluctuations of opposite sign in a form of a narrow zonal band of alternating positive and negative covariance centered near 30°N, extending across North Africa and the eastern Mediterranean (Fig. 5h). Although this secondary mode of covariability between TPD TEL and Trp-2 contributes relatively little to the total covariance, it may represent regional modulation of the dominant influence of upper-tropospheric thermal variability on TEL. In the case of the coupled fields of TPD TEL and precipitation, the SCF of the second leading mode describes approximately 20.88% of the total covariability of both fields. As exhibited in Figure 5l, there is a correlation between the SC2 of TPD TEL and precipitation of approximately 0.32. The TPD TEL SVD2 shows widespread negative fluctuations over the study area (Fig. 5j). While the precipitation SVD2 depicts fragmented positive and negative covariance areas distributed throughout the Mediterranean basin (Fig. 5k), it contrasts the broad-scale precipitation pattern identified in SVD1 (Fig. 4k). The second covariability mode of TPD TEL and precipitation likely represents regional hydroclimatic modulation rather than a uniform precipitation response across the Mediterranean. For the coupled fields of TPD, TEL, and SPEI, the SCF of the second dominant mode accounts approximately 31.90% of the total covariability of both fields. As shown in Figure 5o, the correlation between the SC2 of TPD TEL and SPEI is approximately 0.44. The TPD TEL SVD2 shows an obvious east–west gradient over the Mediterranean region (Fig. 5m), while the SPEI SVD2 is characterized by

fluctuations of opposite sign to that of TPD TEL except in the western Mediterranean and the adjacent zone south of the study area (Fig. 5n). The spatial heterogeneity in SPEI likely arises from the combined effects of precipitation variability and atmospheric evaporative demand, which jointly regulate regional hydroclimatic conditions.

The SVD analyses results of TPG TEL, and climatic parameters over the Mediterranean region reveal a high degree of consistency with those of TPD TEL, and climatic parameters. The first leading mode of covariability for the coupled fields of TPG TEL and climatic variables (Fig. 6) shows coupling patterns nearly identical to those for TPD TEL and climatic variables (Fig. 4). The SVD1 for coupled fields of TPG TEL and climatic parameters explains the largest SCF (61.13–82.13%) and exhibits nearly identical large-scale spatial structures, indicating that the primary coupled signal is robust and largely independent of the TEL definition. Likewise, the paired SC1 of TPG TEL and climatic variables display similar temporal evolution, with the strongest correlation coefficient observed for Trp-2 of about 0.67. In the case of the second dominant mode of covariability, the coupled fields of TPG TEL and climatic parameters (Fig. 7) closely mirror those derived from the TPD TEL and climatic parameters (Fig. 5) with a smaller fraction of the total covariance (SCF = 13.58–25.29%) and capture more localized regional variability, characterized by enhanced spatial patterns and weak but consistent correlation between paired SC2 ($r = 0.30$ – 0.57). The differences between the SVD analyses results of both TPD TEL and TPG TEL with climatic parameters are limited to minor variations in the amplitude and local distribution of the spatial anomalies, and the correlation between paired SC2 is higher than that of paired SC1 in the case of coupled fields of TPG TEL with Ts and Trp-1, but the overall spatial and temporal covariability remains remarkably consistent.

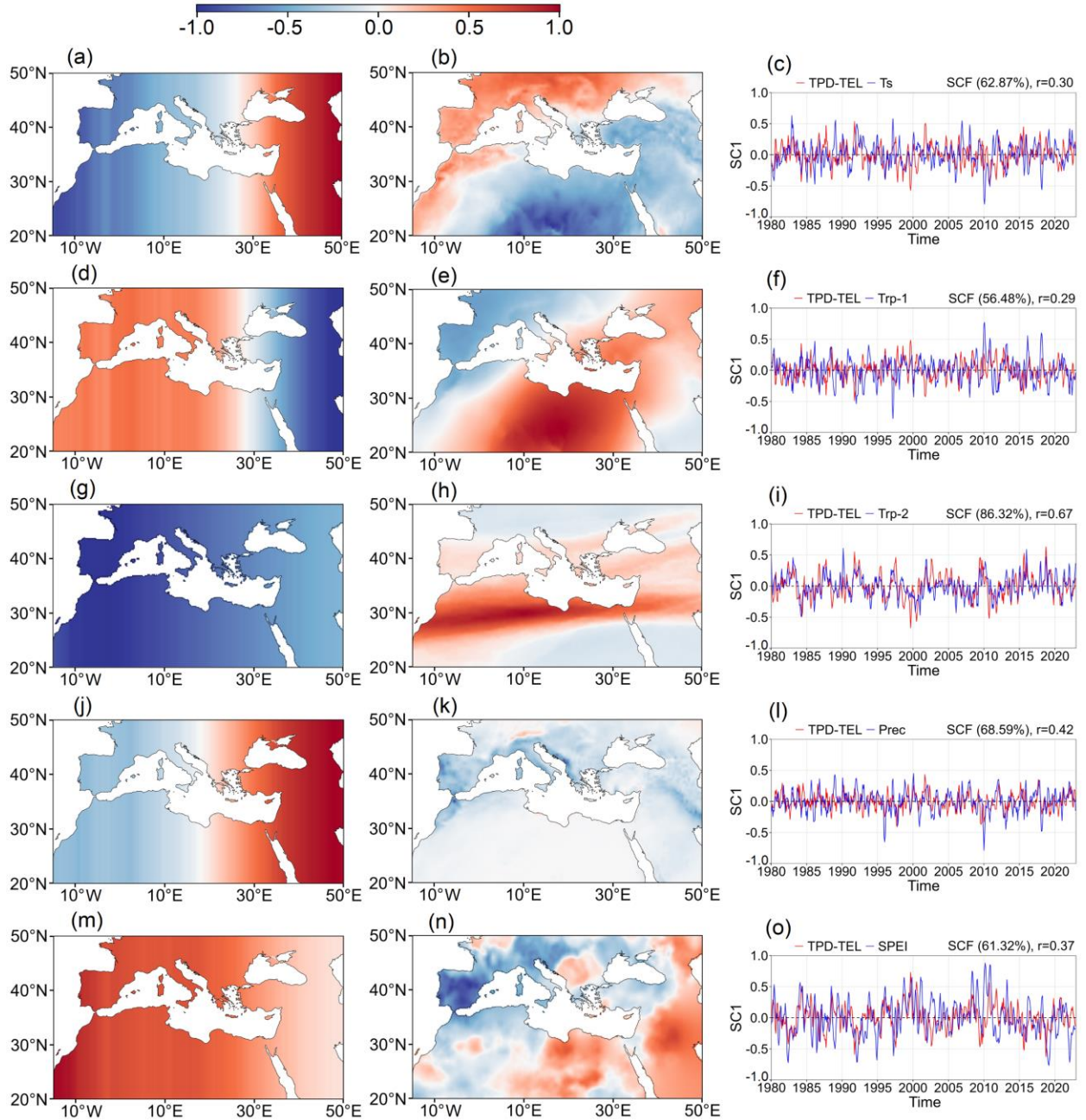


Figure 4. First leading mode of covariability for the coupled fields of TPD TEL and climatic parameters. TPD TEL and Ts (a, b, c), TPD TEL and Trp-1 (d, e, f), TPD TEL and Trp-2 (g, h, i), TPD TEL and precipitation (j, k, l), and TPD TEL and SPEI (m, n, o). The spatial patterns for the first paired mode 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).

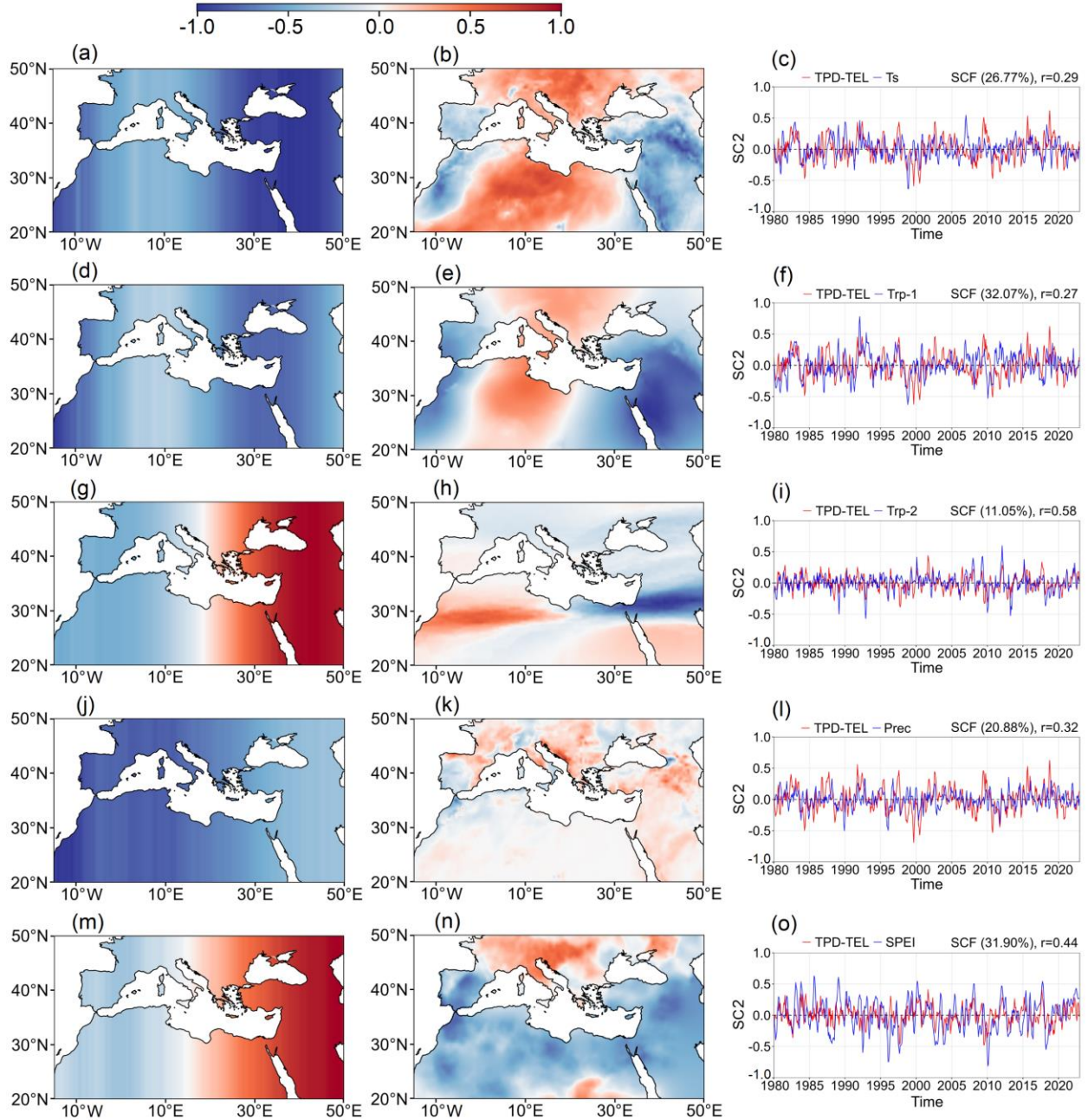


Figure 5. Second leading mode of covariability for the coupled fields of TPD TEL and climatic parameters. TPD TEL and Ts (a, b, c), TPD TEL and Trp-1 (d, e, f), TPD TEL and Trp-2 (g, h, i), TPD TEL and precipitation (j, k, l), and TPD TEL and SPEI (m, n, o). The spatial patterns for the second paired mode of covariability (SVD2) of TPD TEL (left), climatic parameter SVD2 (middle), and the time series of expansion coefficients (SC2) for the paired mode of both TPD TEL and climatic parameters (right).

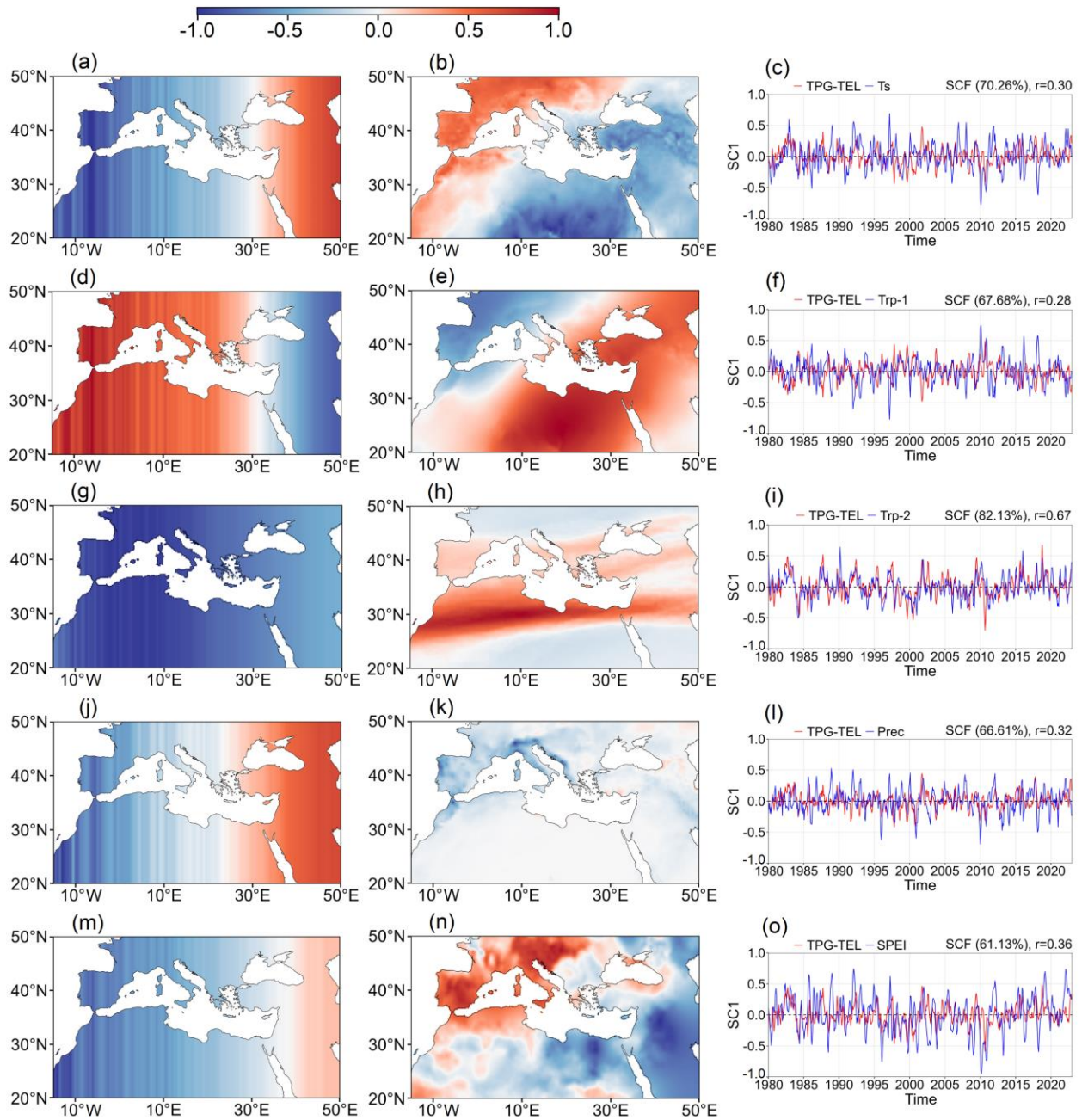


Figure 6. First leading mode of covariability as in Figure 4, but for TPG TEL and the corresponding climatic parameters.

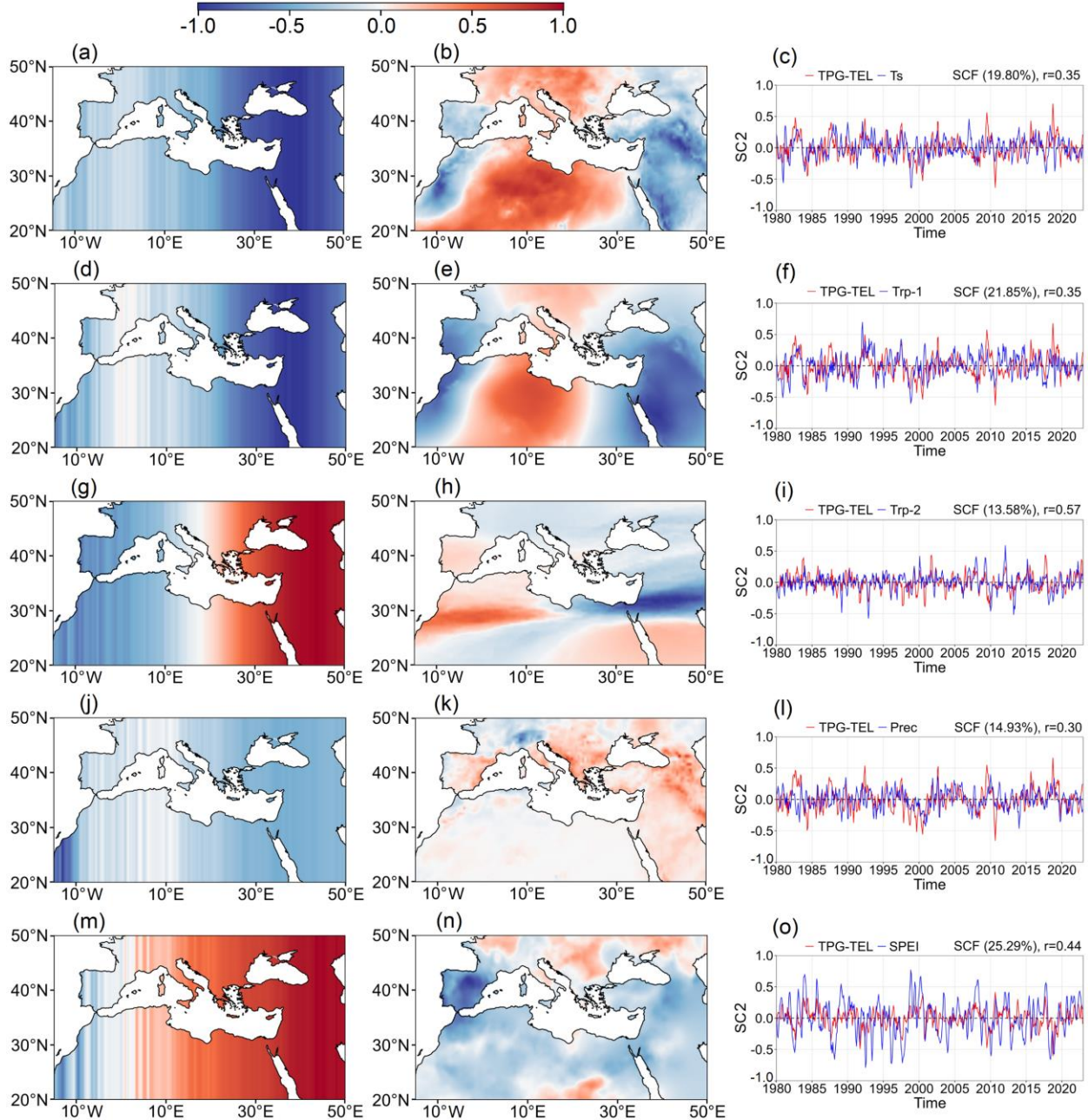


Figure 7. Second leading mode of covariability as in Figure 5, but for TPG TEL and the corresponding climatic parameters.

The Mediterranean region's monthly average Ts over the study period has increased by approximately 0.48 ± 0.03 K/dec (Fig. 8a). 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 8b. 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. This T_s spatial pattern may arise from differences in land–sea thermal contrast, surface energy balance, soil-moisture conditions, aerosol loading, and regional atmospheric circulation. Moreover, the zonal mean of the temperature linear regression map (right panel of Fig. 8b) 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. 8c). The decadal trends of Trp-1 at all grid points over the study area (Fig. 8d) 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. 8d) 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. 8e), 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. 8f). The zonal mean of Trp-2 linear regression map (right panel of Fig. 8f) 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 8g. 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 T_s , Trp-1, and Trp-2 (right panel of Fig. 8b, 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). The contrasting thermal responses of the troposphere

and lower stratosphere also modify the vertical temperature gradient near the tropopause and may therefore affect the height and spatial distribution of the LRT.

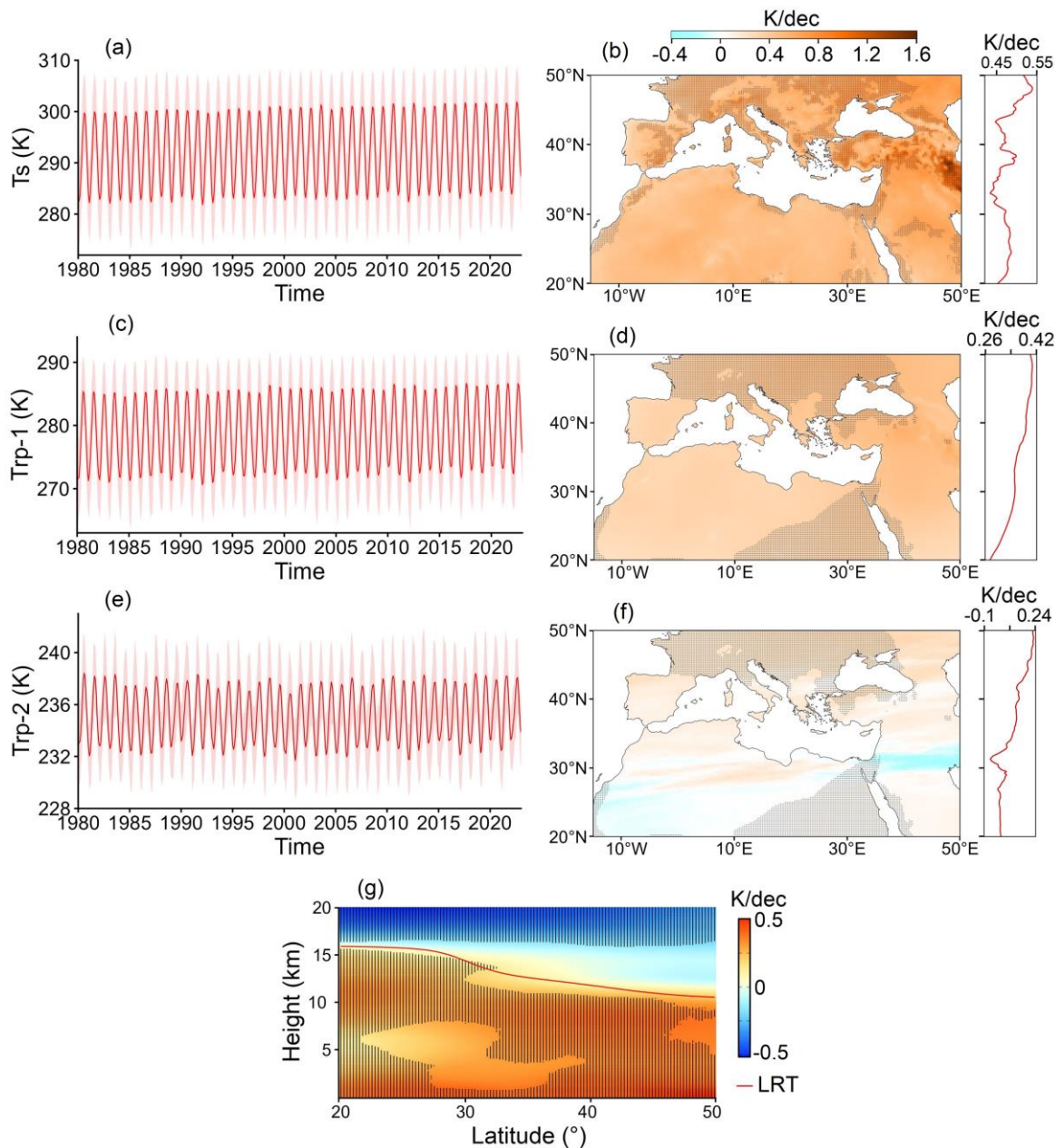


Figure 8. On the left, monthly time series of T_s (a), Trp-1 (c), and Trp-2 (e). The solid lines indicate the monthly mean values, while its surrounding light shading denotes the SD at each time step. On the right, decadal trends regression maps and their corresponding zonal mean, T_s (b), Trp-1 (d), 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. 9a). 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 9b exhibits a dominant downward trend evident in eastern and western Europe. Such drying may be associated with changes in the large-scale circulation, including the poleward expansion of the subtropical circulation and associated modifications of the Mediterranean storm tracks, which can reduce the frequency or intensity of precipitation-producing weather systems over parts of the basin. The zonal mean of the precipitation linear regression map (right panel of Fig. 9b) 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, it shows a decrease of -0.070 ± 0.001 /dec (Fig. 9c). 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. 9d), with a zonal mean (on the right panel of Figure 9d) showing a strong negative trend between 40.00° N and 50.00° N. The observed negative SPEI trend likely reflects the combined influence of precipitation deficits and increasing evaporative demand associated with regional warming.

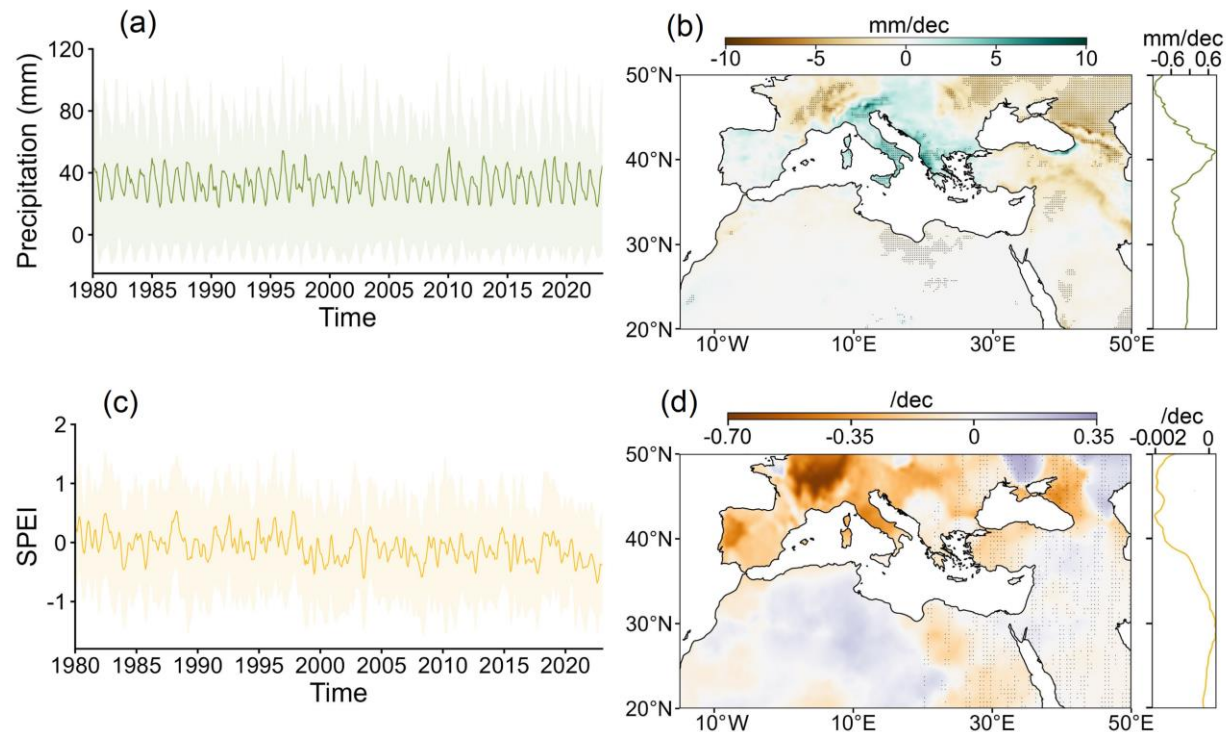


Figure 9. Monthly time series of precipitation (a) and SPEI (c). The solid lines indicate the monthly mean values, while its surrounding light shading denotes the SD at each time step. The precipitation linear regression analysis at all grid points with decadal trends and its zonal mean on the right side (b). While SPEI linear regression analysis at all grid points with decadal trends and its zonal mean 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 parameter (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, and SVD. Our findings reveal monthly average LRT-H increased by approximately 80.58 ± 3.07 m/dec, attributed to global warming caused by increasing GHG emissions (Meng et al., 2021). The predominance of positive LRT-H anomaly and negative LRT-T anomaly patterns indicates a progressive rise in the Mediterranean LRT associated with regional tropospheric warming. 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.

TEs 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). Both TEL definitions show a robust and consistent seasonal cycle that is characterized by a pronounced poleward shift during Northern Hemisphere (NH) summer and an equatorward retreat during NH winter, reflecting the seasonal migration of the tropical belt boundary in response to variations in tropospheric thermal structure. The results of the correlation analysis demonstrate that variations in the Mediterranean TELs are more closely associated with regional thermal conditions than with hydroclimatic variability. The tropical belt expansion signal is clearly reflected in Mediterranean surface warming, as evidenced by widespread positive correlations between TPD TEL and T_s , particularly over the eastern Mediterranean, with maximum correlation coefficients reaching approximately 0.34. TELs have a stronger correlation pattern with Trp-2 than that with Trp-1. Furthermore, the precipitation depicts an observed correlation pattern with TELs in both applied methods. On the other hand, SPEI has the weakest correlation pattern with TELs. Overall, both TEL definitions depict highly consistent correlation patterns with examined climatic parameters, indicating that the identified climate relationships are largely independent of the method used to define the tropical belt boundary.

The SVD analysis demonstrates that the first two SVD modes explain nearly most of the coupled variability between TELs and the investigated climatic variables. The leading mode of covariability between TELs and climatic parameters explains the majority of the shared covariance (56.48–86.32% for TPD TEL and 61.13–82.13% for TPG TEL), indicating that large-scale tropical belt variability is closely linked to regional thermal and hydroclimatic conditions. Among the investigated climatic parameters, Trp-2 depicts the strongest coupling pattern with both TEL definitions ($r = 0.67$), signifying the upper troposphere thermal structure as a climatic component associated with tropical belt fluctuations. Although the second mode of covariability for the coupled fields of TELs and climatic variables accounts for a substantially smaller fraction of the covariance (11.05–32.07% for TPD TEL and 13.58–25.29% for TPG TEL), it is distinguished by more localized spatial structures. The SVD2 of both Ts and Trp-1 depicts an evident fluctuation of the same sign as that of TPD TEL and TPG TEL in the eastern Mediterranean. The SVD analysis results of TELs from both definitions with different climatic parameters show remarkable similarities in spatial patterns, temporal evolution, and covariance fractions. 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 in 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, and trends 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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