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RESEARCH

Spatiotemporal variation of continentality in the mediterranean region and its connection to the Atlantic Multidecadal Oscillation

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Abstract

This study examines the spatiotemporal evolution of continentality across the Mediterranean region over the period 1950–2023 and explores the relationship between continentality and the Atlantic Multidecadal Oscillation (AMO). Using monthly data from the ERA5-Land reanalysis, three distinct continentality indices (Ivanov, Simple, and Sezer) were calculated to capture regional climate dynamics. The results show a generally insignificant increasing trend in continentality for the entire Mediterranean, driven predominantly by the faster rise in summer maximum temperatures compared to winter minimum temperatures in the western sector. In contrast, slight declines occur in parts of the eastern Mediterranean, where winter warming rates partially offset or balance summer warming. Spatial patterns indicate that continentality increases most prominently in areas such as the interior of the Iberian Peninsula and the Mediterranean islands, where intensified summer temperature anomalies contribute to larger annual temperature ranges. Conversely, the Balkan region, coastal zones of North Africa, and northeastern Türkiye exhibit decreased continentality linked to stronger winter warming. On a multidecadal scale, positive AMO phases generally coincide with higher continentality values, highlighting the influence of large-scale ocean–atmosphere interactions on temperature seasonality in the Mediterranean. Overall, the study underscores the critical role of interseasonal warming trends and atmospheric teleconnections of variability in shaping the region's continentality, with implications for future climate risk assessments and resource management.

1 Introduction

Continentality and oceanity are essential concepts in climatology, representing the influence of continental landmasses and oceans on a region's climate, respectively (Martyn 1992). Continentality and oceanity indices, quantitative measures of this influence, are crucial for understanding regional climatic variations, particularly changes in the annual and daily amplitudes of the surface temperature, humidity, cloudiness, wind speed, and atmospheric precipitation variability (Driscoll and Fong 1992; Snow, 2005).

Various continentality indices used in climatology are based on the average annual temperature amplitude scaled with the sine of latitude, as in Gorczynski (1920), Johansson (1926), Conrad (1946), Ivanov (1959), Khromov (1957), Ewert (1963), and Sezer (1990). The application of continentality indices has gained widespread acceptance in climatological research (e.g., Fobes 1954; Kopec 1965; Mikolaskova 2009; Szymanowski et al. 2018) and is used in diverse contexts, ranging from biogeographical assessments to ecological studies to agricultural, water resource management applications and even human health (Salonen et al. 2012; Torregrosa et al. 2013; Molchanova et al. 2022; Kachur et al., 2022; Ebert et al. 2022).

Many studies provide evidence that anthropogenic global climate change leads to spatiotemporal changes in the continentality index, especially depending on the amplitude of seasonal changes in surface temperature. Results based on observational or model data show that continentality values decrease in the high latitudes of the Northern Hemisphere (Hirsch et al., 2007; Qian and Zhang 2015), while increasing in Eastern Europe, the Mediterranean, and Middle East-North Africa regions (El Kenawy et al. 2016; Vlăduţ et

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al. 2018; Vlăduţ 2023). For example, Hirsch et al. (2007) demonstrated that between 1958 and 2001, continentality—the difference between the warmest and coldest months—decreased by 3.4 °C and 7.5 °C, respectively, over both the Arctic and Antarctica. Qian and Zhang (2015) found that the observations and the CMIP5 simulation models capture the weakening of the seasonality (the amplitude of the surface air temperature annual cycle) in the northern high-latitude region and East Asia and the increase in the Mediterranean region for the period of 1950–2005. El Kenawy et al. (2016) found a statistically significant increase in continental influences over the Middle East and North Africa (MENA) region, particularly in the Nile Basin and the Fertile Crescent, according to the Johansson Continentality Index and the Marsz Oceanity Index from 1960 to 2013. Vilcek et al. (2016) indicated that the continentality of Slovakia showed a statistically insignificant increasing trend in the period 1961–2013 for the reason that the temperature of the warmest month increased more rapidly than the coldest month. According to Conrad's Continentality Index, Stonevicius et al. (2018) found a statistically significant increase in Conrad's Continentality Index value across Northeastern Siberia and a decrease in said index over most of Asia and western North America for the period 1950–2015. According to Kerner's Oceanity Index, continentality increased in Northern Europe and most of North America and East Asia, while oceanity increased in the Canadian Arctic Archipelago and some parts of the Mediterranean region. This trend was associated with an increasing temperature in the coldest month due to the North Atlantic Oscillation (NAO) and East Atlantic (EA) indices. Vlăduţ et al. (2018) showed a statistically insignificant increasing trend in continentality in southern Romania and northern Bulgaria according to the Gorczyński Continentality Index and Kerner Oceanity Index between 1961 and 2015. Results also indicated that there was a positive correlation between continentality indices and the North Atlantic Oscillation Index. Vlăduţ (2023) indicated that except for the shores of the Black Sea, some locations in the western half of the Romanian Plain, and the northern part of the Eastern Carpathians, continentality displayed a statistically insignificant upward trend from 1961 to 2018 according to the simple continentality index, the Currey, the Ewert, and the Ivanov indices. The observed trend is explained by the greater temperature increase in summer compared to winter in Romania.

The interplay between oceanic and continental factors significantly influences the Mediterranean region's climate, resulting in its transitional climate characteristics (Lionello and Scarascia 2018). For several temperature indices, including sea surface temperatures and annual mean air temperatures, observed rates of climate change in the Mediterranean Region (MedR) have risen above worldwide trends (Cramer et al. 2018; Lionello and Scarascia 2018; López García 2021; Erlat and Güler 2024). Future warming in the Mediterranean region is expected to exceed global rates by 25%, with summer warming at a pace 40% larger than the global mean (Lionello and Scarascia 2018). These changes are critical to understanding the Mediterranean's susceptibility to climate-induced phenomena such as desertification and shifts in thermal continentality, marking the importance of researching this region's climate variability and trends.

Despite the extensive use of continentality indices, there is a scarcity of studies employing a multi-index approach to assess both continentality and oceanity in the Mediterranean basin over an extended period. Although North Atlantic sea surface temperatures (SST) play a critical role in driving climate variability and predictability in the Mediterranean region, less attention has been devoted to the impact of oceanic oscillations, such as the Atlantic Multidecadal Oscillation (AMO), on Mediterranean continentality. In this context, the present study aims to (1) comprehensively analyze the spatial distribution and temporal variations of thermal continentality multiple indices—including the Ivanov Index of Thermic Continentality (II), the Simple Continentality Index (SCI), and the Sezer Index of Continentality (SEZER)— with across the Mediterranean region for the period of 1950 to 2023. (2) to determine the influence of annual and decadal variability on the degree of continentality, we also assessed the relationship between the Atlantic Multidecadal Oscillation (AMO), which is particularly important for Mediterranean climate variability, and continentality indices.

2 Data and methods

2.1 Data sources

This study utilizes the ERA5-Land reanalysis dataset from the European Centre for Medium-Range Weather Forecasts (ECMWF) to investigate thermal continentality in the Mediterranean region over the 1950–2023 period (Muñoz Sabater 2019). ERA5-Land provides high-resolution monthly mean temperature data for July (the warmest month) and January (the coldest month), which serve as primary inputs for continentality indices. For the correlation analysis presented in Table 2; Fig. 6, we additionally employ ERA5-Land's monthly maximum temperatures for July (Tmax) and monthly minimum temperatures for January (Tmin). These extreme temperature metrics are mapped against the annually calculated continentality indices (Ivanov, Simple, and Sezer) over the 1950–2023 period to explore their role in driving changes in continentality across the Mediterranean region (MedR). For the Sezer Continentality Index, elevation (h) and distance to the sea (L) were calculated for each ERA5-Land grid cell. Elevation data were obtained from the Shuttle Radar Topography Mission (SRTM) dataset, while distance to the sea was computed as the Euclidean distance to the nearest coastline using geospatial tools. Additionally, the Atlantic Multidecadal Oscillation (AMO) index is used to explore large-scale climatic influences, sourced from NOAA's ERSSTv5 dataset (Enfield et al. 2001). The AMO index is an unsmoothed, area-weighted average of the Kaplan SST V2 over the North Atlantic, 0–70°N, calculated at NOAA/ESRL/PSD1: http://www.esrl.noaa.gov/psd/data/timeseries/AMO/. The AMO index was calculated as the linearly detrended, area-weighted average of SST anomalies over the North Atlantic (0–70°N) using NOAA-ERSSTv5, with annual means derived from all 12 monthly values each year.

2.2 Study area

The study area was determined in accordance with the definition of the Mediterranean Region from the 11 reference regions used in the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (Ali et al. 2022). Furthermore, to facilitate comparisons within the MedR, which is large and complicated, it is separated into the Eastern Mediterranean (EMed) and the Western Mediterranean (WMEd) by the longitude 15°E (WMO 2019) (Fig. 1). Such a spatial framework allows for an assessment of inter-regional differences in continentality and their evolution over time (Fig. 2).

2.3 Data preprocessing

Data preprocessing involves extracting monthly mean temperature values from ERA5-Land at each grid cell. For all indices considered, the primary input variables are the monthly mean temperature of the warmest (July) and coldest (January) months. Quality control procedures ensure temporal consistency and remove any missing or spurious values. Although ERA5-Land is considered one of the most advanced reanalysis datasets currently available, it should be noted that uncertainties may arise from observational data sparseness, changing observational platforms over time, and model biases. However, a recent study by Erlat and Güler (2024) validated ERA5-Land's temperature data against station observations in the Mediterranean region, confirming its reliability for capturing both mean and extreme temperatures, which are critical for continentality assessments. No other high-resolution, long-term datasets were deemed more suitable for this study's spatiotemporal needs, and as such, ERA5-Land provides a robust and comprehensive basis for the calculations performed here.

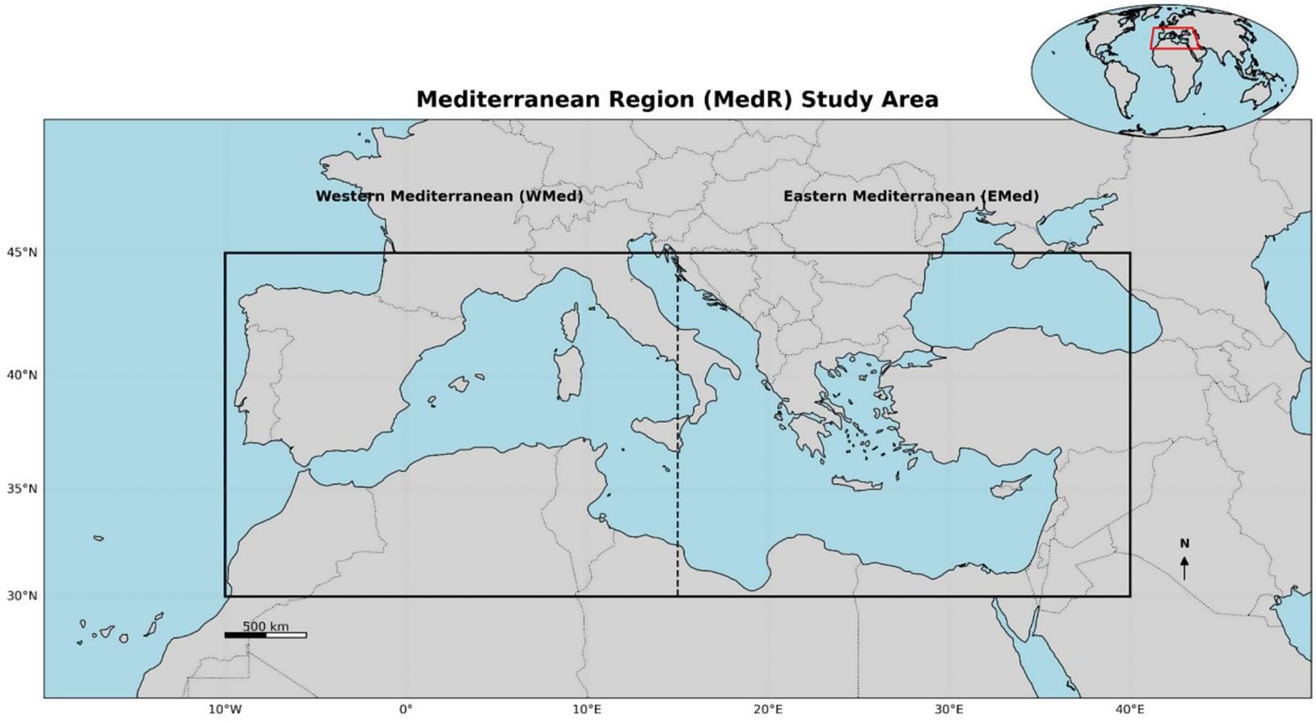


Fig. 1 The study area of the Mediterranean region (MedR), as indicated by the black rectangle and its topography. The boundaries of the Western (WMed) and Eastern Mediterranean (EMed) subdivisions are shown with dashed lines

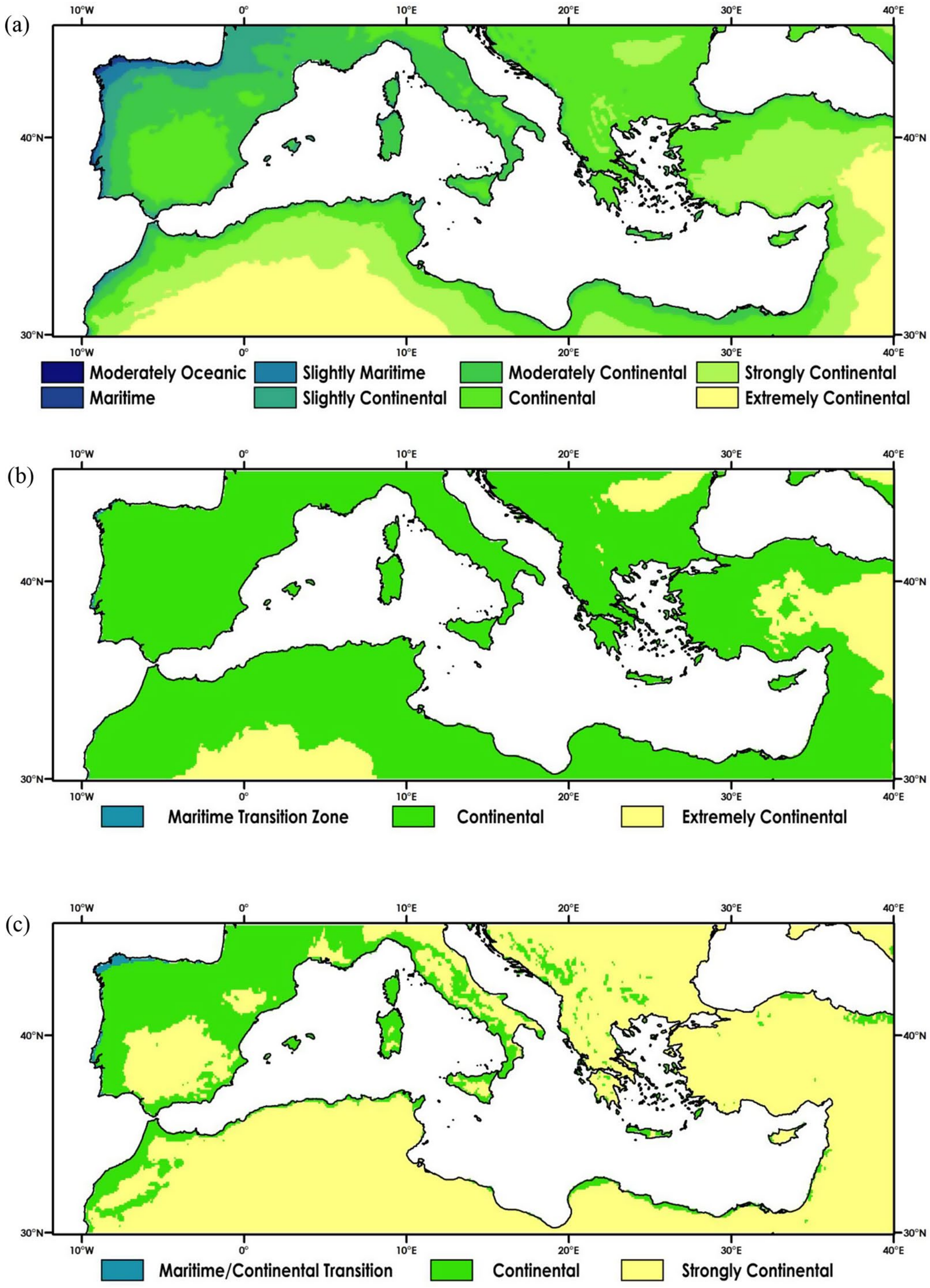


Fig. 2 Spatial distributions of (**a**) Ivanov, (**b**) Simple, and (**c**) Sezer continentality indices for the period of 1950–2023 in the Mediterranean region

2.4 Continentality indices

Three continentality indices are employed to capture a range of thermal regimes. The first is the Ivanov Index of Thermal Continentality (II), originally proposed by Ivanov (1959). The Ivanov Index is computed as:

$$II = 100 \times \frac{A}{0.33\theta}$$

where A is the annual air temperature range (°C) and θ is the geographical latitude of the considered meteorological station or grid point. According to Ivanov, there are ten categories of continentality (Table 1). This index assigns

Table 1 Continentality categories according to the Ivanov index, simple continentality index, and Sezer continentality index (Ivanov 1959; Rivas-Martinez et al. 2011; Sezer 1990)

Continentality index	Index Value	Definition
Ivanov Index	<47	Extremely oceanic
	48–56	Oceanic
	57–68	Moderately oceanic
	69–82	Maritime
	83–100	Slightly maritime
	101–121	Slightly continental
	122–146	Moderately continental
	147–177	Continental
	178–214	Strongly continental
	>214	Extremely continental
Simple Continentality Index	< 2.5 °C	Equatorial
	2.5–10 °C	Oceanic
	10–25 °C	Maritime transition zone
	25–40 °C	Continental
	>40 °C	Extremely continental
Sezer Continentality Index	00.00-10.74	Extremely oceanic
	10.75–21.49	Oceanic/maritime
	21.50-26.87	Maritime/continental transition
	26.88–43.37	Continental
	43.38–75.24	Strongly continental
	75.25–100	Extremely continental

climates along a continuum from extremely oceanic to extremely continental, offering nuanced categorization over the diverse landscapes of the Mediterranean basin.

The second index, the Simple Continentality Index (IC), is based on the formulation by Supan and adapted by Rivas-Martinez et al. (2011):

$$IC = \frac{Tmax}{Tmin}$$

where Tmax represents the monthly mean temperature (°C) of the warmest month and Tmin is the monthly mean temperature (°C) of the coldest month (Vilček et al. 2016). The simplicity and transparency of the IC facilitate direct comparisons of temperature seasonality and permit classification into broad continentality categories spanning equatorial to extremely continental conditions.

The third metric employed is the Sezer Continentality Index, introduced by Sezer (1990), which provides a nuanced approach specifically adapted to the Mediterranean climate system. In addition to categorizing climates along a gradient from extremely oceanic to strongly continental using annual temperature ranges, the Sezer Continentality Index incorporates critical regional factors such as topography and proximity to the sea. By reflecting the interplay between land-sea thermal contrasts and complex elevation gradients, the Sezer Continentality Index accommodates the diverse climatological and geographic conditions characteristic of the Mediterranean basin. This integrative design ensures that spatial heterogeneity in temperature regimes, influenced by both elevation and distance from the coastline, is captured more accurately than in more generic indices. As a result, the Sezer Continentality Index offers a more regionally sensitive measure of continentality, providing a refined and contextually appropriate assessment of thermal conditions across a landscape defined by its intricate orography and enduring maritime influences. The Sezer Continentality Index (denoted here as C) is computed as follows:

$$C = \frac{1.614 \times A}{csc\left([\phi + h/125 + L/111]\right)}$$

where:

C: The Index is expressed as a percentage, calibrated so that the degree of continentality at Oymyakon (63.46°N, 142.79°E, Siberia, Russia), an extreme continental climate reference, equals 100%.

A: Annual temperature amplitude (°C), i.e., the difference between the mean temperature of the warmest month and the coldest month.

φ (Phi): Geographic latitude in degrees of the location.

h: Elevation (height above sea level) in meters.

L: Distance from the nearest sea, expressed in kilometers, chosen to represent the most geomorphologically suitable marine boundary for the location.

csc: The cosecant function (the reciprocal of the sine function), used here to transform the combined geospatial parameters (latitude, scaled elevation, and scaled distance from sea) into a latitude-equivalent measure. The constants 125 and 111 serve as conversion factors, translating elevation and distance from the sea, respectively, into a "latitude-equivalent" unit, thus incorporating these parameters into a unified geographic term. The multiplier 1.614 is a normalization factor ensuring that Oymyakon's exceptionally continental climate yields a °C value of 100%, thus providing a reference point against which other locations' continentalities can be compared. In this way, the Sezer index integrates thermal, latitudinal, and topographic-maritime influences into a single, comprehensive index tailored for comparative continentality assessments across. Categorical thresholds for each index are summarized in Table 1.

2.5 Statistical analyses

A fourth-order Butterworth low-pass filter is applied to the continentality time series to reduce interannual variations and emphasize decadal variation. Regional averages for MedR, WMed, and EMed are computed by aggregating grid-cell data within each defined domain. This approach reveals spatial gradients in continentality responses, reflecting local geography, topography, and proximity to marine influences. The results enable an examination of whether observed changes in continentality are uniform or differ substantially between the western and eastern sectors of the Mediterranean and how these differences relate to large-scale climatic drivers and local surface energy balance components.

The statistical significance of trends in the continentality indices is assessed using the non-parametric Mann-Kendall test (Mann 1945; Kendall 1975), which is well-suited for climatological data sets due to its robustness against non-normal distributions and autocorrelation. Trend magnitudes are estimated using Sen's slope, providing a meaningful measure of the rate of change over the 1950–2023 period. To further elucidate the associations between continentality and large-scale variability, Pearson correlation coefficients are computed between each continentality index and the AMO index. Correlation analyses are performed not only on the raw annual series but also on the filtered series to distinguish immediate interannual associations from more persistent relationships emerging on decadal timescales.

Data analysis, index computation, filtering, and statistical evaluation are carried out using Python-based tools. Data manipulation and computation rely on xarray (Hoyer and Hamman 2017) and pandas (McKinney 2010), while statistical calculations and visualizations, including time series plots and correlation maps, are performed with matplotlib (Hunter 2007). These open-source libraries ensure reproducibility and transparency in the research workflow.

To better understand the physical process that causes the multidecadal and interannual variations of continentality, we examine their association with the Atlantic Multidecadal Oscillation (AMO) index (Enfield et al. 2001). Monthly values of the AMO were retrieved from NOAA's official climate data repositories, and the corresponding annual means were subsequently computed by the authors to ensure consistency with the time resolution of the continentality indices. AMO indices are linearly detrended and subjected to the same low-pass filtering as the continentality indices, ensuring comparability of signals at similar timescales.

The AMO index is an unsmoothed, area-weighted average of the Kaplan SST V2 over the North Atlantic, 0–70°N, calculated at NOAA/ESRL/PSD1: http://www.esrl.noaa.gov/psd/data/timeseries/AMO/.

3 Results

3.1 The Spatial distribution of continentality index values in the mediterranean region

The spatial distribution of the Ivanov index values is characterized by the maritime climate coast of Biscay Bay and the Atlantic coast of North Africa, while values show mainly moderate and continental in the north of the Mediterranean region. Continentality values increase towards the east and south of the region, with an extremely continental climate over the Sahara and the Syrian Desert.

Figure 3 shows the distribution of climate continentality according to the Simple Continentality Index in the Mediterranean region. In the Mediterranean region, the index value ranges between 8 °C (maritime transition zones) and 31 °C (continental). Maritime transition zones were dominant in the Atlantic coasts of the Iberian Peninsula, especially the west coast of Portugal and Galicia. Oceanic influences are particularly effective on all islands in the Mediterranean, the coast of North Africa, and the Peloponnese Peninsula. The Italian peninsula and the eastern portion of North Africa are located in a maritime transition zone (10–25 °C). Continentality values increase as one advances into the interior of the continents, and a continental regime is seen in the Sahara, the central and eastern parts of Anatolia, and the Carpathian Mountains. The Eastern Anatolia region has the highest continentality, with an annual temperature amplitude of around 31 °C.

Due to the more frequent effect of dry continental tropical or polar masses, the Sezer Continentality Index (GCI) values for the years 1950–2023 highlight the strongly continental character of the climate in EMed, especially in the majority of northern Africa, the Balkan Peninsula, and Anatolia. The Southern Sahara had the highest continentality values, particularly in the Grand Erg Oriental region (68%). The continental climate observes the northern part of the Iberian Peninsula, the Atlantic coast of North Africa, the Italian peninsula, and all islands of the Mediterranean Sea. Only the west coast of the Iberian Peninsula has a maritime climate, where the value decreases by 20%.

3.2 Spatial changes of continentality indices in the mediterranean region

According to the Ivanov index, in the last 74 years, there has been a general increase in the continentality degree in the Iberian and Italian peninsulas and the western coasts of North Africa, while a decrease has been observed in the Balkan peninsula and the east of North Africa. The statistically significant increasing trend was observed over the same part of the western coasts of North Africa, the inner part of

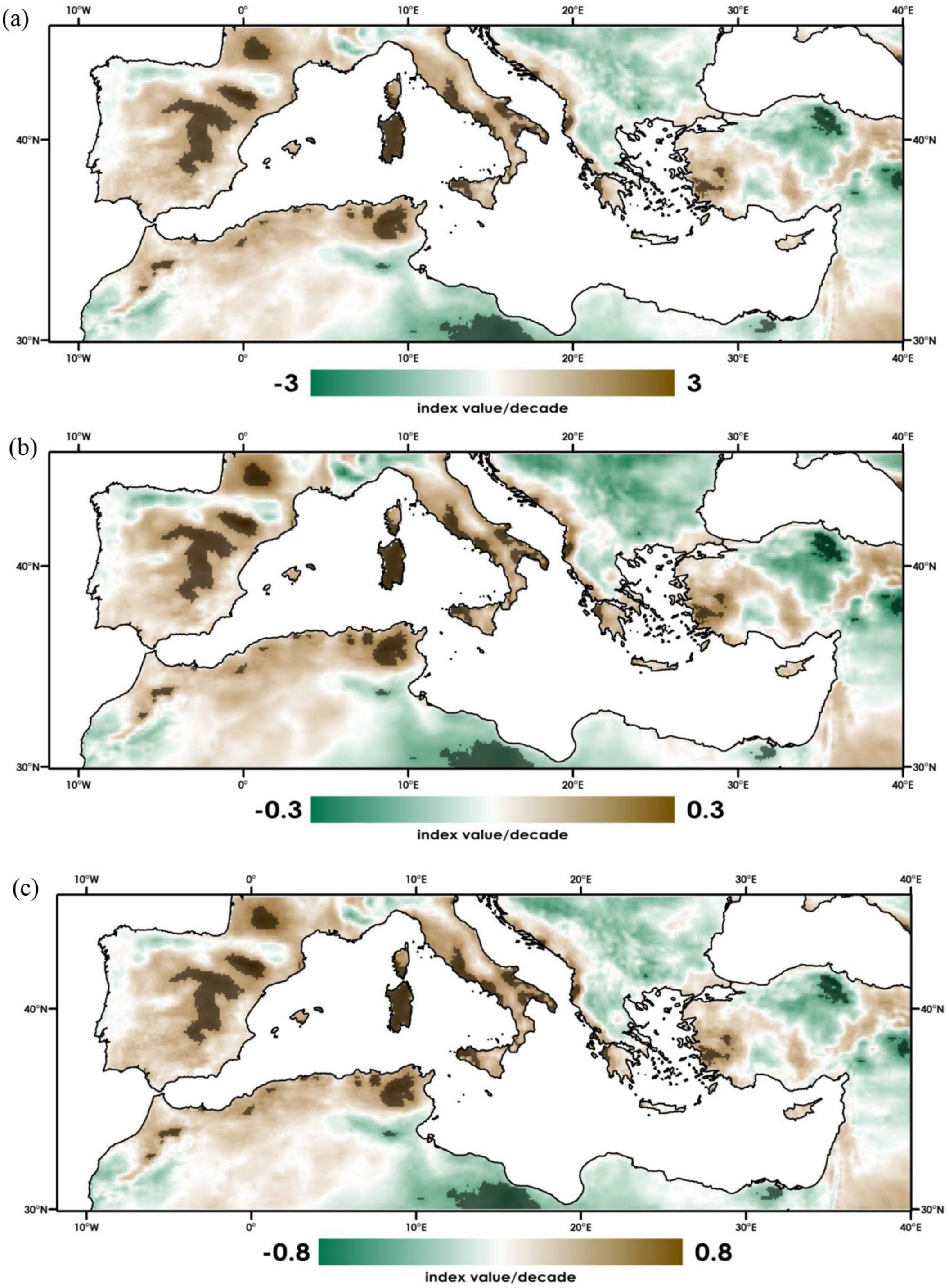


Fig. 3 Sen's slope values of Mann-Kendall trend analysis for the (**a**) Ivanov, (**b**) Simple, and (**c**) Sezer continentality indices for the period of 1950–2023

the Iberian Peninsula, the Sardinia and Corsica islands, the Italian peninsula, and the western Adriatic Sea coasts and western Anatolia, with three index values per decade for the period of 1950–2023. Conversely, the grid cells have a statistically significant declining tendency of -3 index values each decade and are primarily found in the Sirte basin in Libya and the middle Black Sea region of Tütkiye (Figure).

The spatial structure of the Simple Continentality Index overlaps with that of the Ivanov index between 1950 and 2023 over the Mediterranean region. The increasing trend in continentality values is more evident, especially in the

Western Mediterranean, with statistically significant high areas such as the Atlas Mountains and the Sistema Ibérico and Sistema Central in the Iberian Peninsula in the last 74 years. On the other hand, continentality values showed a decreasing trend along the deltaic Egyptian coastal plain and the Balkan Peninsula, which indicated a weakening of the seasonality. This is especially the case in the Sirte basin in Libya, the northern part of the Central Anatolia region of Türkiye, where trends at some grid boxes have been 0.3 °C per decade since 1950.

Similar to the trend results observed in the Ivanov and Simple continentality indices, the Sezer continentality index values have also shown an increasing trend in the western Mediterranean region over the last 73 years. Particularly statistically significant increasing trends are observed in the inner parts of the Iberian Peninsula, the Italian Peninsula, the island of Corsica, and along the northern part of the Atlas Mountains. On the other hand, a decreasing trend in continentality values was observed in the period 1950–2023 in areas such as the Balkan Peninsula, the northeast of Anatolia, Qattara, and the Western Desert in North Africa.

3.3 Temporal changes of continentality indices in the mediterranean region

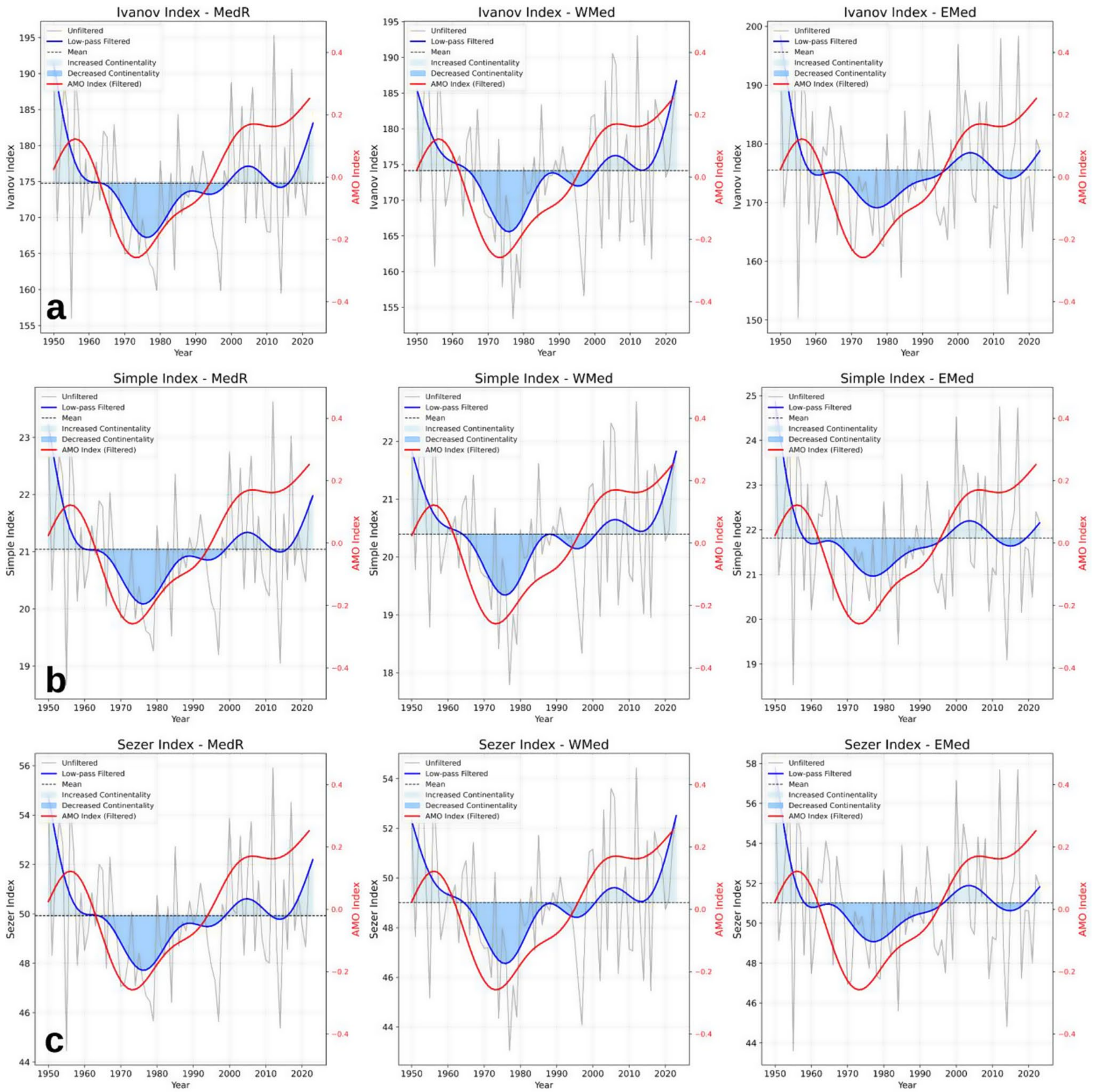
Continentality values showed multi-decadal variability that is even apparent in the detrended continentality anomalies from 1950 to 2023, and it is possible to distinguish three distinct periods in the detrended time series (Fig. 4). The three continentality indices values from 1950 to the mid-1960s were above the long-term mean and displayed remarkably high interannual variability. For example, the 1950, 1953, and 1956 were characterized by the highest continentality value for the MedR. However, 1955 has the lowest continentality value in the previous 74 years for the MedR and EMed. 1966–1997 is a period in which continentality values decreased in the Mediterranean region and more oceanic climate conditions dominated, especially in the EMed. During the end of the 1970s and early 1980s, continentality values were characterized by the lowest values since 1950. The increase in continentality values and interannual variability in the Mediterranean region after 1998 is remarkable. It is worth noticing that 2012 was the highest continentality value over the MedR and WMed from 1950 to 2023.

Mann-Kendall (M-K) and Ordinary Least Squares (OLS) trend detection of the continentality series indicates a statistically insignificant increase in continentality in the MedR and WMed, and a decrease in EMed, for the period 1950–2023 (see Table 2). The temporal change observed in continentality values according to the three indices in the Mediterranean region can be explained by the observed trends in winter and summer temperatures in the region.

The spatial distribution of mean air temperatures in winter (DJF) and summer (JJA) in the Mediterranean region reveals the difference of warming trends between seasons (Fig. 5). The most significant temperature increase during the winter season is observed in the Alps and in the northeast and southeast of Türkiye and the Balkan Peninsula, in these areas coupled with continentality values that have shown a decreasing trend over the last 74 years. On the other hand, the tendency to warm during winter is weaker in Corsica, Sicily, the west coast of North Africa, and the east coast of the Adriatic, where the continentality values show the strongest increase. In the Mediterranean region, the areas where the warming trend is strongest during the summer months are the areas where the continentality values increase, which overlap with Corsica Island of the Iberian Peninsula and the Tunisia and Atlas Mountains. On the other hand, areas where summer heating is weak, such as the Nile Delta and Libya, are parallel to areas where continentality decreases.

To assess temperature changes, we examined monthly mean temperatures for January and July, as well as monthly minimum and maximum temperatures for these months, to support our analysis of continentality and its trends. Over the last 74 years, the increase in July maximum temperature (Tmax) was more significant than changes in January minimum temperature (Tmin), suggesting an increase in the annual temperature range and thus increasing continentality in the western Mediterranean. On the other hand, in the Eastern Mediterranean, the increasing trends in maximum temperatures in July and the minimum temperatures in January are equal. This situation leads to the fact that the annual temperature amplitude does not change, and thus the degree of continentality does not tend to increase or decrease. Therefore, a very slight decreasing trend in the continentality index is observed in the Eastern Mediterranean.

Figure 6 shows the correlations between continentality indices and July mean maximum temperature (Tmax) and January mean minimum temperatures (Tmin). The Tmax in July and the three continentality indices are positively correlated with the three continentality indices in the entire Mediterranean except the Black Sea coast and the eastern part of Türkiye (Fig. 5). The highest correlation coefficients are observed in the Iberian and Italian peninsulas, especially Corsica and Sicily islands, and the western part of North Africa, where the continentality values have also increased significantly over the last 74 years. The spatial pattern of the areas where high positive correlations are observed shows that the increase in high air temperatures in July is an important parameter in the degree of continentality. The high positive correlations observed between continentality indices and maximum temperatures in July are due to the unequal warming trend observed in the hot and cold periods of the year, as mentioned above.


Ivanov Index - MedR

Ivanov Index - WMed

Ivanov Index - EMed

Simple Index - MedR

Simple Index - WMed

Simple Index - EMed

Sezer Index - MedR

Sezer Index - WMed

Sezer Index - EMed

Fig. 4 Interannual variability in the (**a**) Ivanov, (**b**) Simple, and (**c**) Sezer continentality indices in the MedR, WMed, and EMed for the period of 1950–2023, including the Atlantic Multidecadal Oscillation (AMO). The blue line represents the detrended and low-pass filtered continentality index values, while the red line indicates the low-pass filtered AMO, respectively. Positive and negative anomalies relative to the mean are highlighted to depict increased and decreased continentality phases

In the Mediterranean region, in the last 74 years, in areas where a rapid warming trend is observed in summer compared to winter, the annual temperature amplitude and continentality value are also increasing. The correlation between the continentality degree and January Tmin is high in areas where the continentality value decreases/does not change in the last 74 years. The highest correlation values are observed in the Balkan Peninsula, northeastern Anatolia, the Nile Delta, and Libya, where continentality tends to decrease. The results show that in areas where low temperatures increase rapidly in winter, continentality values have also decreased in the last 74 years. This situation can be explained by the rapid warming trend in winter compared to summer, which reduces the annual temperature amplitude and therefore continentality values.

Table 2 Trends (per decade) in July maximum temperature (°C), January minimum temperature (°C), and continentality according to Ivanov, simple, and Sezer indices between 1950 and 2023 in MedR, WMed, and EMed. Bold numbers indicate trends that are significant at the 0.01 (**) and 0.05 (*) levels

Temperatures and Indices Area/	July maximum temperature		January minimum temperature		Ivanov continentality index		Simple continentality index		Sezer continentality index	
	Sen's slope	OLS	Sen's slope	OLS	Sen's slope	OLS	Sen's slope	OLS	Sen's slope	OLS
MedR	0.027**	0.027**	0.020**	0.019**	0.008	0.009	0.002	0.001	0.004	0.003
WMedR	0.031**	0.030**	0.018*	0.017*	0.029	0.029	0.004	0.004	0.010	0.009
EMedR	0.021**	0.023**	0.022**	0.021**	-0.025	-0.015	-0.003	-0.002	-0.008	-0.005

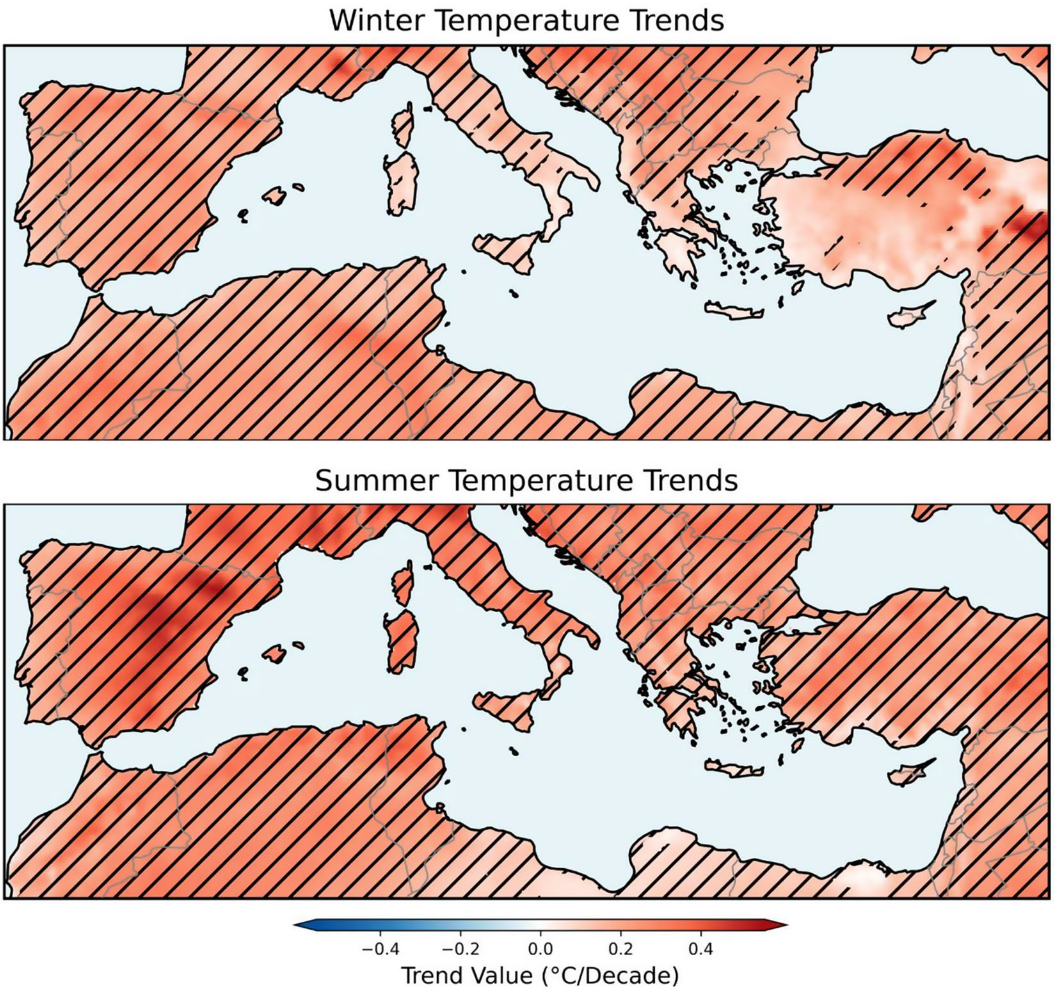


Fig. 5 Trends in winter (DJF) and summer (JJA) mean air temperatures (°C) for the period 1950–2023 across the Mediterranean region. Areas with hatching indicate regions where the Mann-Kendall trend analysis shows statistically significant trends ($p < 0.05$)

3.4 Continentality changes in the mediterranean region and their links to AMO

Teleconnection patterns are employed to assess the impact of atmospheric circulation on the temporal and spatial variations of continentality values. Indeed, previous studies have demonstrated that continentality in the Northern Hemisphere is influenced by large-scale atmospheric circulation patterns and oscillations (Stonevicius et al. 2018; Alexandrov et al. 2019; Sawaisarje and Chaudhari 2023). Although the AMO is one of the most prominent teleconnection patterns across all seasons, its role in regulating continentality variability in the Mediterranean region is less well understood compared to other teleconnection patterns such as the NAO, EA, and the Atlantic Meridional Mode. Therefore, the spatial and temporal correlation of the Atlantic Multidecadal Oscillation (AMO) and continentality values were examined.

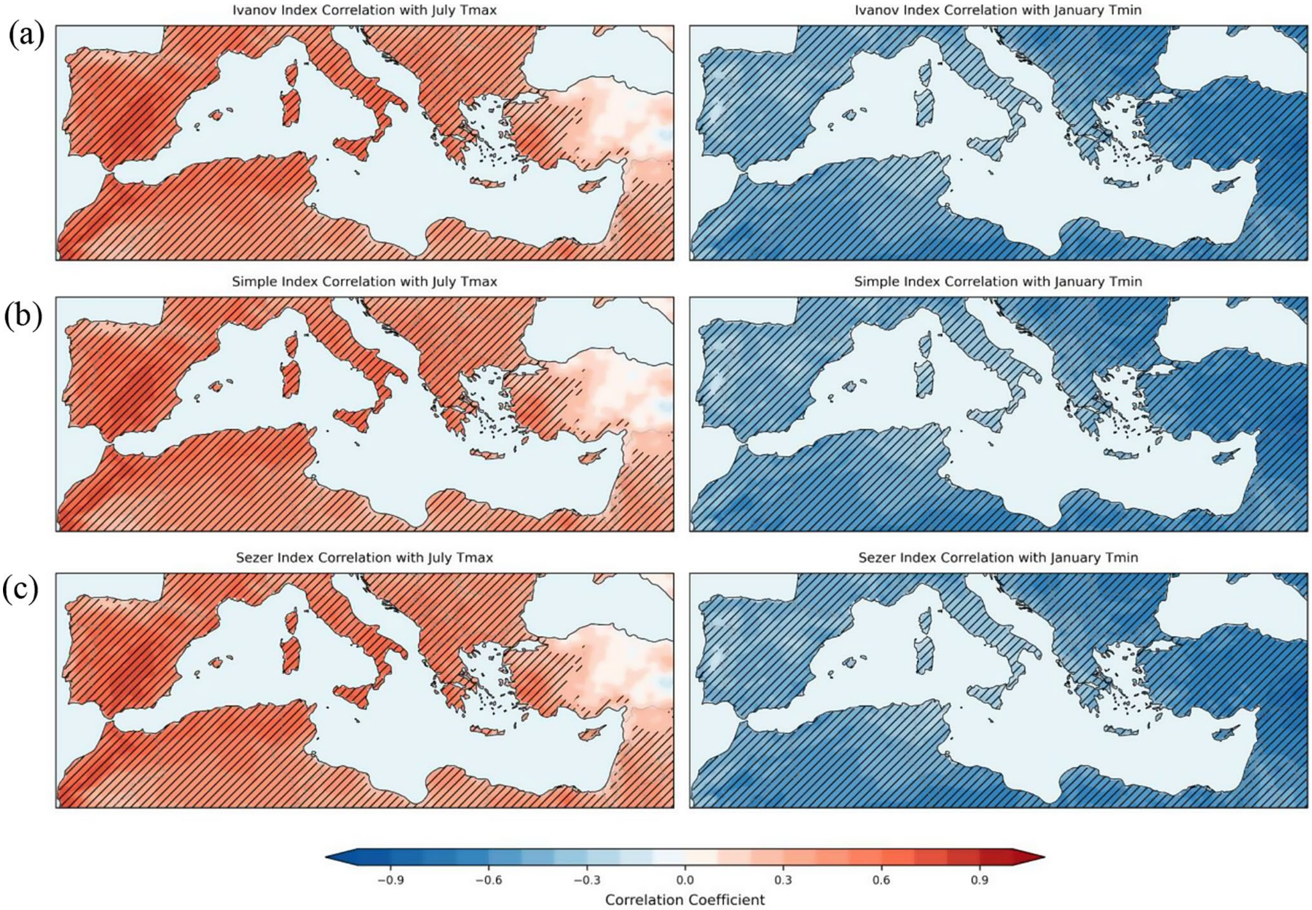


Fig. 6 Pearson's correlations between July maximum temperature (Tmax), January minimum temperatures (Tmin), and (**a**) Ivanov (**b**) Simple (**c**) Sezer continentality indices in the MedR for the period of 1950–2023

During the positive phase of the AMO (Enfield et al. 2001)—defined by quasi-periodic SST anomalies spanning 0°N to 70°N in the North Atlantic—sea surface temperatures are anomalously warm over most of the North Atlantic, while during the negative phase, opposite (cooler) conditions prevail. When the temporal change of the AMO index is examined, it is seen that the positive (warm) annual AMO phases occurred during the 1926–1963 period and the recent decades, especially a long-term strong positive phase since 1996. On the other hand, negative (cold) phases occurred during the 1964–1994 period, especially strongly negative during the period of 1971–1976 (Fig. 4). The multidecadal annual AMO index closely correlates with the decadal variations of continentality in all three regions (MedR, WMed, and EMed). In general, the close positive relationship between the AMO index and continentality indices in the Mediterranean region is observed, in which the continentality anomalies are positive during warm phases of the AMO and negative in cold phases from 1950 to 2022 in the Mediterranean region (Fig. 4). Based on detrended and low-pass filtered data, continentality in the Mediterranean region increased during the period 1950–1963 when the AMO index was positive. Conversely, during 1964–1996, when the AMO index was negative, continentality decreased. Notably, the highest positive AMO values since 1955 were recorded after 1996, coinciding with an increasing trend in continentality that was most pronounced in the Western Mediterranean. The consistency between the AMO phases and continentality values is strong evidence that the AMO was an important driver of these decadal changes in Mediterranean temperature conditions.

We calculated the spatial Pearson's correlation coefficients of the annual detrended AMO index with the gridded three continentality indices (Fig. 6). The correlations between the Ivanov, Simple, and Sezer continentality indices and the annual AMO index are positive over much of the Western Mediterranean, especially in the Iberian and Italian peninsulas, the island of Corsica, the Balkans, western Anatolia, and western North Africa, with correlations exceeding 0.7 (~95% significance level) (Fig. 7). On the other hand, the negative AMO-continentality correlations change between 0.5 and 0.7 over much of the inner part of Anatolia

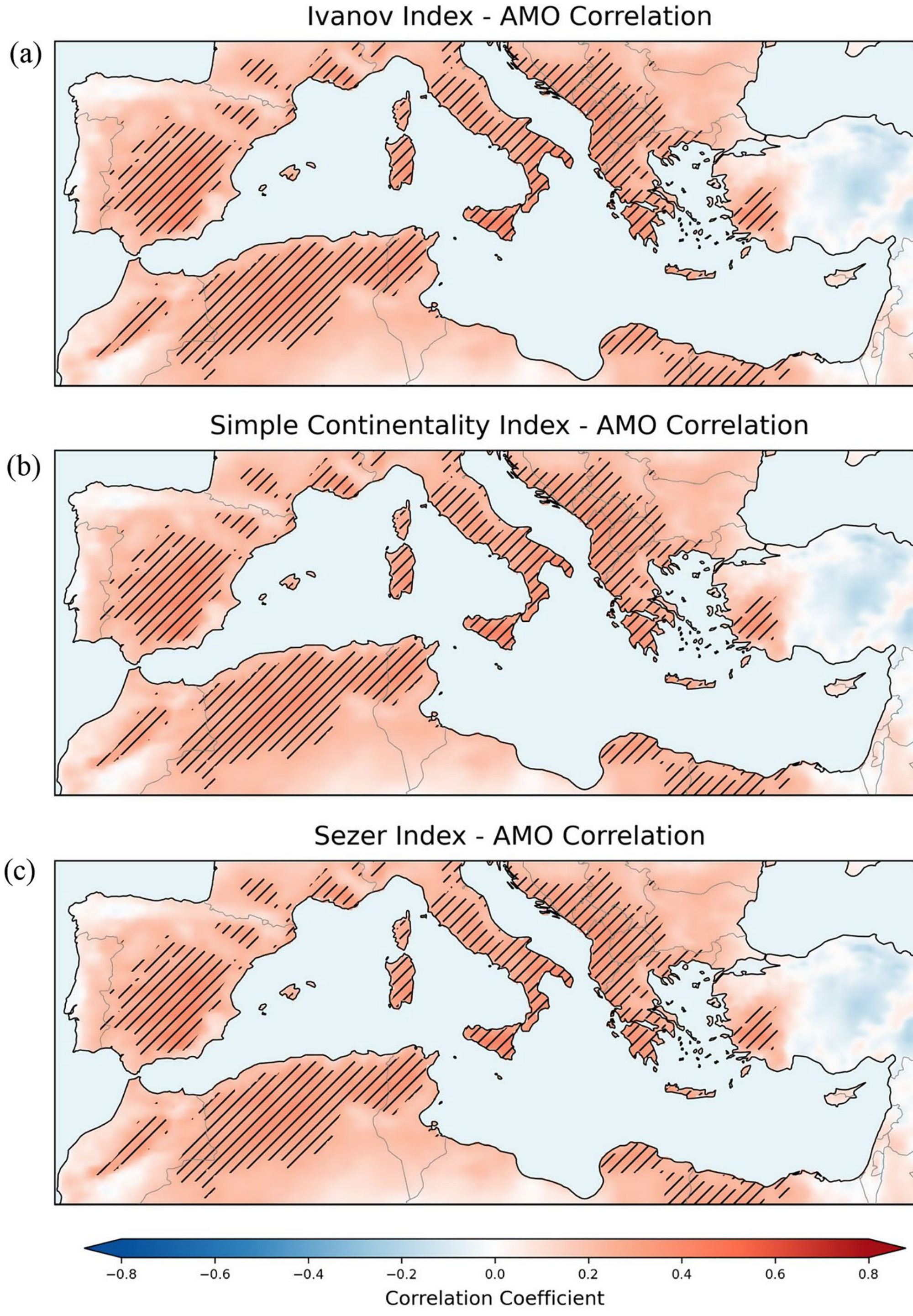


Fig. 7 Pearson's correlations between AMO and (**a**) Ivanov, (**b**) Simple, and (**C**) Sezer continentality indices in the MedR for the period of 1950–2023

and the countries of Lebanon, Syria, Palestine, and Israel in the Eastern Mediterranean region and Qattara and the Western Desert in North Africa. Indeed, the spatial pattern of correlations with the AMO annual index for the recent period of 1950–2022 is entirely consistent with trends of continentality indices.

4 Conclusions and discussion

This study presents a spatiotemporal analysis of the continentality of the Mediterranean region according to the Ivanov, Simple, and Sezer continentality indices. The research presented here contributes to a better understanding of how the AMO associated with SST over the North Atlantic influences the degree of continentality over the Mediterranean region.

Trend analyses reveal that despite considerable interannual variability, continentality showed an insignificant increasing trend in the last 74 years in the MedR and WMed. The spatially statistically significant increasing trend in continentality is observed over WMed, particularly in the inner part of the Iberian Peninsula, the southwestern part of France, the Sardinia and Corsica islands, the Italian peninsula, and Tunisia. The findings are consistent with previous studies showing that southeastern Europe is one of the few regions in the world where continentality is increasing (Hirschi et al. 2007; El Kenawy et al. 2016; Vlăduţ et al. 2018; Stonevicius et al. 2018; Vlăduţ 2023). On the other hand, continentality has decreased insignificantly in the EMed, particularly in the Sirte basin in Libya, east of the Balkan Peninsula, and the northeastern part of Türkiye, since 1950. The results also showed that AMO has a significant effect on the temporal/spatial variation of continentality in the Mediterranean region, and the decadal changes and trends observed in the degree of continentality in the Mediterranean region are related to the positive and negative phases of the AMO index. The increasing continentality over the Mediterranean region during the 1950–1963 and 1997–2023 periods occurred synchronously with an AMO warm phase, while decreasing continentality between 1964 and 1996 occurred consistently with the cold phase of the AMO index.

The spatial differences observed in the continentality trends in the Mediterranean region over the last 74 years are explained by the different trends in the maximum temperatures in the warm season and the minimum temperatures in the cold season. Although the warming trend in the summer season in the Mediterranean region has been faster than in the winter season, this trend is more pronounced in the Western Mediterranean. In WMed, during the period 1950–2023, maximum air temperatures in July increased almost twice as much as minimum temperatures in January. As shown by studies, there is a difference in seasonal warming in the Western Mediterranean, and summer temperatures in the south and central regions of Europe and the western Mediterranean region warmed most significantly since 1950 (Chen et al. 2015; Qian and Zhang 2015; Twardosz et al. 2021; Caloiero et al., 2021; Erlat and Güler 2024; Lanet et al. 2024). For example, Qian and Zhang (2015) found that summer warmed faster than winter in the Mediterranean region, and as a result, amplitudes increased slightly during 1950–2005. Similarly, an opposite trend behavior between maximum and minimum temperature series was detected between maximum and minimum temperatures in Sardinia Island, where the highest increasing trend in continentality was observed for the last 74 years. Accordingly, while maximum temperatures showed a significant positive trend, especially in spring and summer, a dominant negative trend was detected in minimum temperatures, especially in the winter season (Caloiero et al., 2021). Erlat and Güler (2024) found that since 1950, the increase in temperatures, particularly the warmest day (TXx) and coldest night (TNn), is much more pronounced in the western Mediterranean during the annual and summer seasons than in the eastern Mediterranean. Stonevicius et al. (2018) found that in southwestern Europe, the Conrad's Continentality Index increased in the areas where Tmax increased more than Tmin. The stronger warming of summer compared to winter seems to be an important factor in the increase of annual temperature amplitude and continentality.

Continentality indices can only be calculated on an annual scale, but since atmospheric oscillations are generally effective on a seasonal scale, it becomes difficult to fully determine the relationship between continentality and annual atmospheric oscillations. However, even on an annual basis, results indicate that variability in Mediterranean continentality is significantly associated with the AMO index. The increase in continentality in the Mediterranean region during the positive phase of the AMO index can be explained by the fact that the AMO index mostly affects summer temperatures over Europe. The AMO index showed a significant correlation with the surface air temperature in the westernmost parts of Europe and the Mediterranean region during spring and summer, and the warm phases of the AMO are related to high temperature anomalies across Northern Hemisphere (Mariotti and Dell'quella, 2012; Sutton and Dong 2012; Ionita et al. 2013; Gao et al. 2019). For example, Mariotti and Dell'quella (2012) showed that the AMO explains over 30% of regional decadal air temperature anomalies in JJA and no surface air–AMO connection in DJF in the Mediterranean region. Similarly, Zampieri et al. (2017) reported that during summer, positive AMO contributes to temperature increases over parts of the Iberian Peninsula. Therefore, in the positive phase of the AMO index, summer mean and maximum air temperatures in the Mediterranean tend to increase, increasing the temperature difference between winter/summer temperatures and the degree of continentality associated with it and vice versa during a negative AMO phase. In addition to atmospheric oscillations and differences in temperature increase trends in winter and summer, factors such as snow, cloud cover, and droughts should be taken into account, which will affect the degree of continentality by changing the surface energy balance. All these processes could influence the annual continentality degree by the annual temperature range. Examination of the temporal relationship between the detrended AMO index—emphasizing its multidecadal nature—and the continentality values reveals that periods marked by significant changes in continentality coincide with phase reversals in the AMO index. Notably, such transitions are observed in the mid-1960s and the late 1990s during the period 1950–2023. Numerous studies have reported that phase changes in the AMO are accompanied by alterations in mid-atmospheric circulation and shifts in North Atlantic sea surface temperature anomalies (Alheit et al. 2014; El Kenawy et al. 2016; Ellis et al., 2020). Specifically, the transition to a cold phase in the mid-1960s corresponds with a marked decrease in Mediterranean continentality, whereas the switch to a sharply warm phase from the mid-1990s onward is associated with an increase in continentality. Especially since 2015, there has been a marked increase in continentality in WMed during a period when the AMO remained in a persistently positive phase. Furthermore, research indicates that the late 1990s were characterized by significant changes in mid-atmospheric circulation, leading to a notable shift in European climate—and, by extension, in southern Europe—towards a regime of anomalously hot, dry summers (Sutton and Dong 2012; Robson et al. 2012). In summary, our results demonstrate that continentality in the Mediterranean region is strongly influenced by the multidecadal natural variability associated with the AMO.

Climate change projections all agree on the existence of significant warming trends in the 21st century, especially in the summer season in the MedR (Zittis et al. 2019; Ajjur and Al-Ghamdi 2021). Based on future projections, temperatures are expected to increase more significantly in summer than in winter. According to the projections, it is assumed that continentality will increase in MedR except in narrow areas of EMed throughout the 21st century. These changes may influence ecosystems, agriculture, and water resources across the region. Future studies could explore the application of continentality indices to regional climate models (e.g., CMIP6) or incorporate other climate variability modes (e.g., NAO, ENSO) to assess long-term projections and additional drivers of continentality changes in the Mediterranean region.

Author contributions D.D.Y. substantially contributed to the conception and design of the work, performed data collection and analysis, prepared the maps, and drafted the Methods section. E.E. substantially contributed to drafting the Introduction, Results, and Conclusion sections and critically revised important intellectual content throughout the manuscript. Both authors reviewed and approved the final version to be published and agree to be accountable for all aspects of the work, ensuring that questions related to the accuracy or integrity of any part are appropriately investigated and resolved.

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Data availability No datasets were generated or analysed during the current study.

Code availability The Python scripts used for data analysis and figure preparation are available from the corresponding author upon reasonable request.

Declarations

Ethical approval Not applicable. This study did not involve human participants or animal subjects, and therefore no ethical approval was required.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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