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RESEARCH ARTICLE

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Tropical nights in the Mediterranean: A spatiotemporal analysis of trends from 1950 to 2022

Doğukan Doğu Yavaşlı[1] | Ecmel Erlat[2]

[1]Department of Geography, Kırşehir Ahi Evran University, Kırşehir, Türkiye

[2]Department of Geography, Ege University, Bornova, Türkiye

Correspondence
Ecmel Erlat, Department of Geography, Ege University, 35100 Bornova, Izmir, Türkiye.
Email: ecmel.erlat@ege.edu.tr

Abstract

The Mediterranean region, noted for its climatic uniqueness and rapid urban expansion, is a critical area for climate change studies. This research investigates the increase in extreme temperatures, particularly focusing on tropical nights and their socio-economic implications. Our aim was to analyse the spatiotemporal changes, including long-term variation and trends in the tropical night indices in the Mediterranean region over 73 years (1950–2022). To achieve this, we utilized ERA5-Land reanalysis data, conducting a comparative analysis to highlight the differential impacts of urbanization on tropical nights in urban and non-urban areas. The study reveals a significant rise in the frequency of tropical nights region-wide. Specifically, the onset of the tropical night season is occurring earlier, with an advancement of approximately 17.3 days per decade, while the season's end is delayed by about 17.1 days per decade, effectively prolonging the duration of tropical nights. This change is most pronounced in urban areas, where tropical nights have increased more significantly compared to non-urban regions, highlighting the exacerbating effect of urbanization on nocturnal temperature trends. Overall, our findings underline the combined effects of anthropogenic climate change and urban development on the increased occurrence and intensity of tropical nights in the Mediterranean region.

KEYWORDS

climate change, hot extreme temperatures, Mediterranean climate, tropical nights

1 | INTRODUCTION

It has long since been reported that due to anthropogenic climate change and land cover changes, the daily minimum temperature has risen faster than the daily maximum temperature, leading to more hot and tropical nights, especially in high-density cities (Davy et al., 2017; Vose et al., 2005; Wang et al., 2017). Hot or tropical nights have significant implications for human health, especially for vulnerable populations, ecosystems, agriculture and energy consumption in affected areas. Changes in the frequency of tropical nights, which result in discomfort and heat-related illnesses due to insufficient nocturnal rest, are an illustration of a pertinent human health concern. Especially, days with high temperatures frequently precede these warm nights, preventing the human body from recovering from diurnal thermal stress and leading to episodes of temperature-induced discomfort (Hajat et al., 2002;

Ragetti et al., 2017; Rippstein et al., 2023; Royé, 2017; Royé et al., 2021). A study conducted in Barcelona, Spain, underscored an augmented mortality risk from natural, respiratory and cardiovascular causes during hot nights where temperatures surpassed 23°C (Royé, 2017). Tropical nights also increase energy demand for cooling in urban areas. The sensitivity of night-time electricity consumption to temperature variations surpasses that of daytime, with a correlation coefficient of 0.7 between night-time usage and daily minimum temperature. This consumption intensifies further when Tmin breaches 24°C (Wang et al., 2023). Rising night-time air temperatures also modulate the distribution and activity of vectors of diseases, given that summers hotter-than-average summers have stronger effects on vector traits than warmer-than-average winters (Endo & Amarasekare, 2022). Furthermore, tropical nights, marked by heightened night-time temperatures, influence a myriad of biological processes, from physiological functions and growth to productivity and food security. This is attributed to the fact that minimum air temperatures modulate night-time plant respiration rates, potentially reducing biomass accumulation and crop yields (Hatfield & Prueger, 2015; Kumudini et al., 2014; Sadok & Jagadish, 2020). For instance, night temperature plays an important role in soybean protein and oil accumulation, and high night temperatures result in a significant reduction in yield due to smaller seed size, lower seed weight and a reduced number of effective pods and seeds per plant (Song et al., 2016; Yang et al., 2023). Wheat, which is one of the leading agricultural products in the world, is most adversely affected by even short episodes of high night temperatures during the grain-filling period, resulting in a significantly reduced yield (Mamrutha et al., 2020).

Numerous studies have consistently demonstrated that the frequency, duration, and spatial extent of warm/hot extremes, including tropical nights, change in parallel with the increase in minimum temperatures regionally or globally (e.g., Abatan et al., 2019; Alexander et al., 2006; Donat & Alexander, 2012; Elizbarashvili et al., 2017). For example, Alexander et al. (2006) determined significant positive trends in the annual number of tropical nights over central and southwest Asia, the northern part of Africa, and southern Brazil between 1951 and 2003, suggesting a global upward shift in the distribution of daily minimum temperatures throughout the globe. Elizbarashvili et al. (2017) reported an increase in tropical nights in Georgia, particularly along the Black Sea coast and the Kolkheti lowland, by 4–6 days per decade from 1936 to 2013. Abatan et al. (2019) highlighted significant upward trends in tropical nights across three Nigerian regions (Guinea 0.39, Savanna 0.52 and Sahel 0.60 days per decade annually) between 1971 and 2012.

The Mediterranean region, undergoing warming at a rate faster than global averages, is also observing an increase in the frequency of hot extremes. Observational data collected from meteorological stations throughout the Mediterranean have served as the basis for several studies investigating indices of climatic extremes, notably focusing on tropical nights (Cantos et al., 2019; El Kenawy et al., 2011; Erlat & Türkeş, 2017; Fioravanti et al., 2016; Founda et al., 2019; Scorzini et al., 2018). For example, El Kenawy et al. (2011), analysing data for the period 1990–2006, indicated a significant increase in the frequency and intensity of most of the hot temperature extremes in northeastern Spain. In the 47-year timeframe, a 0.6-day decade increase in tropical nights was noted. Geographically, coastal regions adjacent to the Mediterranean and Cantabrian Seas exhibited more pronounced warming than their inland counterparts. Fioravanti et al. (2016) found that increasing trends for tropical nights (TR20) were 7–9 days per decade. The mean number of tropical nights has shown positive anomalies since 1982, except for 1984 and 1996. The highest TR20 anomalies (+42 days, respectively) were recorded in 2003. Erlat and Türkeş (2017) showed that the number of tropical nights indicated a persistently increasing trend statistically, especially after the year 1985 at the majority of the stations (87 of 92) in Cantos et al. (2019) noted an escalation in the frequency, duration, and intensity of tropical nights between 1950 and 2014 in the Valencia and Murcia regions of Spain's Mediterranean coast, attributing this to global warming and enhanced sea surface temperatures in the central Western Mediterranean. Founda et al. (2019) found that significant changes in the seasonality of hot extreme temperatures especially the number of tropical nights, were identified in the Eastern Mediterranean in the period 1896–2017. Some stations have reported shifts in the start and end dates of tropical nights by over 10 days per decade since the mid-1970s.

Urbanization and urban heat islands (UHI) which describe the difference between suburban and urban temperatures are one of the main factors leading to artificially elevated air temperatures, especially at night around the world (e.g., Benas et al., 2017; Hu & Li, 2022; Roth et al., 2022). Urban building materials have high heat capacities and high thermal admittance, resulting in slow cooling rates in built-up areas during the late afternoon and evening. Therefore, UHIs are primarily nocturnal events and, depending on location and local weather conditions, can produce average temperature differences between urban and rural areas of 2°C and, in some cases peak at more than 10°C and increased temperature extremes (IPCC, 2014). For example, an analysis revealed strong UHI intensities reaching values up to 6.0°C with a mean intensity of 3.8°C during nocturnal hours of August in a small Mediterranean city of Agrinio (Vardoulakis et al., 2013). Observations of the maximum urban heat island intensity range from 2 to 4°C during the warm part of the year, respectively, showing a smaller variability during the summer months than in the winter in Thessaloniki (Giannaros & Melas, 2012). A study has shown that urbanization contributes to 30%–50% of nocturnal heatwaves in China. The urbanization effect increased the frequency of night-time extreme warm events by 4.85 days in Liaoning Province for the period 1959–2018 (Hu & Li, 2022).

Climate model projections indicate that the frequency and intensity of hot extreme temperatures will increase for the rest of the 21st century under all emission scenarios due to continuing anthropogenic climate change (Cardoso et al., 2019; Carvalho et al., 2021; Dosio & Fischer, 2018; Jordan & Brierley, 2022; Nastos & Kapsomenakis, 2015). For instance, simulations from six Regional Climate Models (RCMs) for Greece, spanning reference (1961–1990), near-future (2031–2050) and distant-future (2071–2100) periods, project an increase in tropical night occurrences (ranging from 9–39 to 28–60 days) across the majority of the country, barring certain highland areas (Nastos & Kapsomenakis, 2015). Compared to a 1.5°C world, a further 0.5°C warming results in a more than 60% increase in the number of tropical nights over southern Europe, in particular parts of the Mediterranean, with a robust change in the minimum summer temperature (Dosio & Fischer, 2018). High-resolution EURO-CORDEX regional climate simulations for the RCP8.5 scenario predict that tropical nights during the extended summer season (MJJAS) will reach 60 days by the century's end, a stark contrast to the current average of 7 days observed in Portugal (Cardoso et al., 2019). Under the SSP2-4.5 scenario, projections indicate that by 2046–2065, tropical nights in the Mediterranean will increase by 20–40 nights annually, escalating to 40–60 nights by the end of the century in regions like the Iberian Peninsula's south-central area, Italy, Greece, and parts of southern Türkiye (Carvalho et al., 2021). CMIP6 model simulations, when assessing exposure to extreme heat events across various future scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5), project that global annual exposure to tropical nights could soar by 814%–1055% from pre-industrial levels by the 21st century's conclusion, depending on the specific emission trajectory (Jordan & Brierley, 2022).

The Mediterranean region stands out as a significant climate "hotspot," exhibiting heightened sensitivity to global climate shifts. Remarkably, its warming rate surpasses global averages by approximately 20%, with summer temperatures even reaching a staggering 50% above global warming rates (Lionello & Scarascia, 2018). Temperature extremes in the Mediterranean region have undergone significant shifts, marked by a notable rise in warm days and a concurrent decrease in cold nights (Lelieveld et al., 2016). Among the various extreme climate indices, tropical nights emerge as a particular indicator of these shifts. While numerous studies have focused on the changes in tropical nights at country levels within the Mediterranean, a comprehensive analysis spanning the entire region remains conspicuously absent. Comprehending the change in tropical nights within the Mediterranean basin, a region distinctly sensitive to climate change is crucial. This understanding is essential for assessing potential impacts on human health and ecological systems, and it offers valuable insights for devising effective climate adaptation and mitigation strategies in the region. In light of these considerations, our study embarks on a comprehensive analysis of tropical nights across the Mediterranean region. Our primary objectives are to reveal the observed changes and trends concerning (1) the number of tropical nights, (2) dates of the first, (3) the last occurrence of tropical nights, (4) variations in their seasonal duration, (5) the maximum consecutive tropical nights, (6) their intensity, and (7) maximum intensity, all since 1950. In addition to analysing the general trends of tropical nights in the Mediterranean region, this study aims to specifically investigate the impacts of urbanization on these trends. We assess how urban and non-urban areas differ in terms of changes in tropical nights, providing insight into the influence of human settlement patterns on local climate conditions. Our analysis leverages gridded datasets encompassing the entire Mediterranean region, ensuring a comprehensive and region-wide perspective.

2 | DATA AND METHODS

The primary dataset utilized in this study is the historical reanalyzed data sourced from the European Centre for Medium-Range Weather Forecasts (ECMWF) fifth-generation global atmospheric reanalysis dataset, known as ERA5-Land. This dataset stands out due to its comprehensive coverage, offering a total of 50 variables that describe the water and energy cycles over land surfaces. It provides data on a global scale, at an hourly frequency, and boasts a spatial resolution of approximately 9 km. Furthermore, its temporal coverage spans from 1950 onwards, making it an invaluable resource for climate studies. The consistency, long-term coverage, and high spatial resolution of ERA5-Land ensure that it offers a high-quality dataset of land surface variables. This data was accessed through the Copernicus Climate Change

FIGURE 1 Study area in the Mediterranean Region. This map outlines the specific area of focus for our analysis of tropical night trends from 1950 to 2022, as indicated by the black rectangle. The map provides a geographic context for our study, covering key locations across the Mediterranean that were included in our assessment of tropical nights.

Service (C3S) (Muñoz-Sabater et al., 2021). In this study, we concentrated on the geographical bounds of 10°W–40°E and 30°–45°N, thereby encapsulating the entirety of the Mediterranean region, exclusive of marine areas (Figure 1). Data for 26,299 days covering the period 1950–2022 were processed. The hourly 2 m air temperature data, initially in Kelvin, was converted to degrees Celsius by subtracting 273.15.

In the study, tropical night (TR) was defined as the number of days when the minimum temperature (TN) exceeded 20°C, as proposed by ETCCDI (2023). To comprehensively understand the spatial and temporal variations in tropical nights, we analysed the seven indices of TR (Table 1).

Following the derivation of these indices, we embarked on a trend analysis to discern the temporal changes in these seven indices. Our methodology incorporated nonparametric, robust procedures renowned for their efficacy in detecting significant trends. Initially, the modified Mann–Kendall statistic was employed for the seven indices (Hamed & Rao, 1998; Kendall, 1975; Mann, 1945). This tool, with its widespread application in hydrological, meteorological, and agrometeorological

TABLE 1 Definition of tropical night indices used in the study.

Short name	Definition	Units
TRsum	The annual frequency (total sum of daily cases) of tropical nights	days
TRfirst	The Julian Day of the first TR occurrence	dates
TRlast	Julian Day of the last TR occurrence	dates
TRlength	The number of days that contribute to tropical night event spanning three or more consecutive nights identified through a 3-day rolling window	days
TRmaxlength	The annual maximum length of tropical nights (consecutive tropical nights)	days
TRintensity	The annual mean intensity of TN (the difference between minimum temperature and the TN threshold of 20°C)	°C
TRmaxintensity	The maximum intensity of tropical nights **(**the peak daily value in the hottest tropical nights in a year)	°C

studies, was used to detect and assess the statistical significance of the trends at a 1% level. Subsequently, to quantify the magnitude of observed trends, we applied Sen's slope (Salmi et al., 2002; Sen, 1968; Zhang et al., 2015). Given its robustness to outliers and non-normal distributions, Sen's slope analysis is a preferred choice in climate studies. The direction of the slope (positive or negative) indicates the trend's direction, while its magnitude provides insights into the rate of change over time. To ensure robustness in our findings, we masked significance levels for p-values greater than 0.01 from the Mann–Kendall test, thereby maintaining a 99% confidence interval. In our analysis, we utilized the entire historical series to determine the anomalies of tropical nights, providing a more comprehensive view of the trends and variations from 1950 to 2022. We have used ESRI's Sentinel-2 Land Use/Land Cover data from Living Atlas (ArcGIS Living Atlas of the World, 2023) to delineate urban and non-urban areas to assess the impacts of urbanization on tropical nights. In delineating urban and non-urban areas for the purposes of this study, the "build area" classification within the dataset was designated to represent urban regions. Conversely, all remaining land use/land cover classifications were collectively utilized to define non-urban areas.

3 | RESULTS

3.1 | The annual mean number of tropical nights

The Mediterranean region boasts a diverse range of climate types, stretching from the African desert in the south to the temperate zones of European countries in the north. In addition, climatic conditions vary for short distances depending on the physical geography conditions such as the altitude, the orography, and the land–sea interactions. Consequently, the spatial distribution of tropical night occurrences exhibits significant subregional variability within the Mediterranean. This results in number of tropical nights (TRsum) values ranging from 0 to 250 days (Figure 2a). TRsum showed a clear longitudinal and elevation gradient in the region. The highest values, approaching 200 days annually, are found in the hot semi-arid and arid zones of northern Africa, notably in northern Algeria, northeastern Cyprus, and the deserts of Syria and the Negev. Mainly along the coastline of Gulf of Gabès (Tunisia), Gulf of Sidra, the Nile River delta and the Levantine Sea, small areas in the south of Anatolia, especially in the Çukurova plain and the Southern Aegean islands, the Puglia region (Italy), and around the Balearic Islands, south of the Iberian Peninsula, lower Danube plain and east of the Greek peninsula TRsum values are between 50 and 100 days. The markedly high number of tropical nights in a narrow zone along the entire Mediterranean coast is noteworthy. In the coastal zone, the number of tropical nights varies between 40 and 100, regardless of latitude. In contrast, most inland and elevated regions report fewer tropical nights, typically under 10 days annually. Similarly, the Atlantic coasts have seen a notable reduction in the annual average of tropical nights, dropping to fewer than 10 days.

Analysing the temporal evolution of tropical nights in the Mediterranean region reveals two distinct periods (Figure 3). From 1950 to 1986, the recorded values predominantly stayed below the long-term average, indicating a decreasing trend. 1976 (−2.5) has the lowest negative Tsum anomaly since 1950 in the Mediterranean region. Studies show that the mid-1970s corresponded to a period in which the global climate system underwent a dramatic shift to a climate regime all over the world. The shift in the climate regime now is known to have coincided with a shift due to the changes in the phase of the Pacific Decadal Oscillation (PDO). The PDO index shifted in 1976 from dominantly negative values for the 25-year time period 1951–1975 to dominantly positive values for the period 1977–2001, which was manifested by climate anomalies all over the world in the mid-1970s (Hartmann & Wendler, 2005; Jacques-Coper & Garreaud, 2015; Meehl et al., 2014). TRsum has exhibited an increasing trend for the period since the mid-1980s. Standardized TRsum anomalies illustrate a predominantly positive anomaly from 2005 to 2022 compared with the reference period. According to the region-based averaged time series of the Mediterranean region, the highest number of tropical nights was observed in 2022 and 2021 since the year 1950 (Figure 3a). According to the regional average, for the first time in the last 73 years, the number of tropical days has exceeded 1 month in 2021 and 2022. In 2022, the TRsum was 9.6 days higher than the reference period, and the TRsum differed by +3.2 standard deviation from the reference period. The year 2022, when TRsum values reached the highest value in the last 73 years, also coincides with the date when marine heat waves (MHW) lasted the longest in the Mediterranean. The MHW event, which affected the entire Mediterranean basin, occurred almost continuously in the period between May and August 2022. In the summer of 2022 (including June, July and August), 3-month average sea surface temperature anomalies reached locally high values of 4.6°C (Mercator Ocean International, 2023).

Figure 4a illustrates the spatial distribution of the Sen slope values for TRsum spanning the period from 1950 to 2022. The trend is noticeably greater in the hot semi-arid and arid areas of northern Africa and the coastline of the Mediterranean Sea, with values reaching 7.0 days per

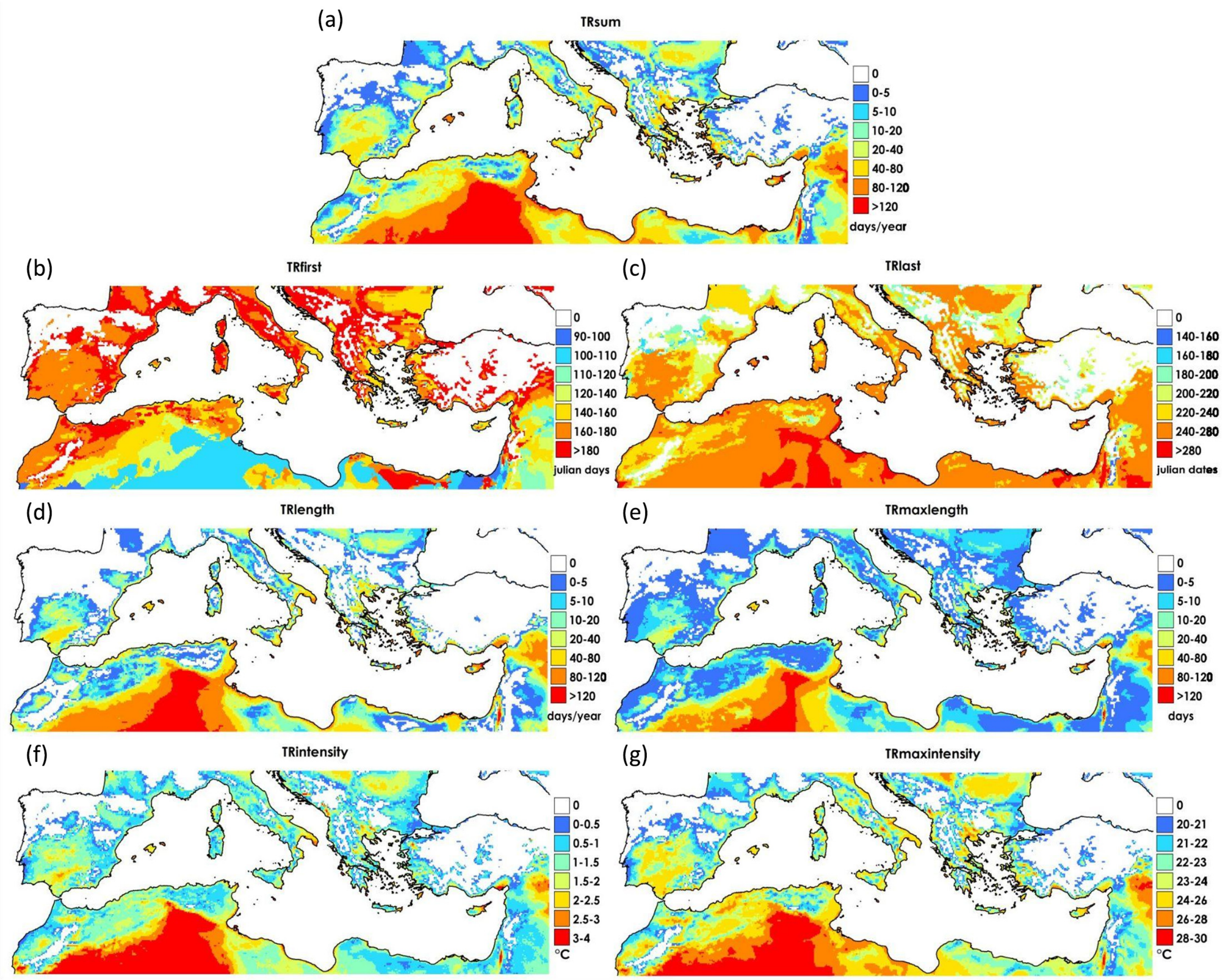

FIGURE 2 Spatial distribution of the annual mean (a) frequency, (b) first occurrence, (c) last occurrence, (d) length, (e) maximum length, (f) intensity, (g) maximum intensity of tropical night for 1950–2022 over the Mediterranean region.

decade. Similarly, significant trends, ranging between 5.0 and 6.0 days per decade, are evident in basins within the Iberian Peninsula, such as the Ebro and Guadalquivir, the Po Basin in Italy and the plains of Western Anatolia. For the rest of the Mediterranean region, which generally corresponds to high-elevation sites like the Alps, Dinaric Alps and Pyrenees, the trends in TRsum are not significant, showing that the annual number of tropical nights in these regions did not create a measurable change between 1950 and 2022.

3.2 | The annual mean first occurrence of tropical nights

The complex topography and coastlines in the Mediterranean region create great differences in the spatial distribution of the first (TRfirst) and last occurrences of tropical nights. As a result, tropical nights in the Mediterranean region begin on average on the 90th day (late March) in the arid regions of northern parts of Africa; on the other side, this date shifts to the 150th day (late May) in the inner part of the land. In the Mediterranean region, tropical nights at high altitudes begin to occur in late July (Figure 2b).

The mean first occurrence of tropical nights in the period 1950–2022, like with other index values, can be divided into two different subperiods (Figure 3b). The first period, which spans from 1950 to 1997, is typically characterized by positive anomaly values, in which the first tropical nights occur on average during the 164th Julian day. 1992 had the highest positive anomaly value during this time, when the frequency of tropical nights began later (174th Julian days) compared to the reference

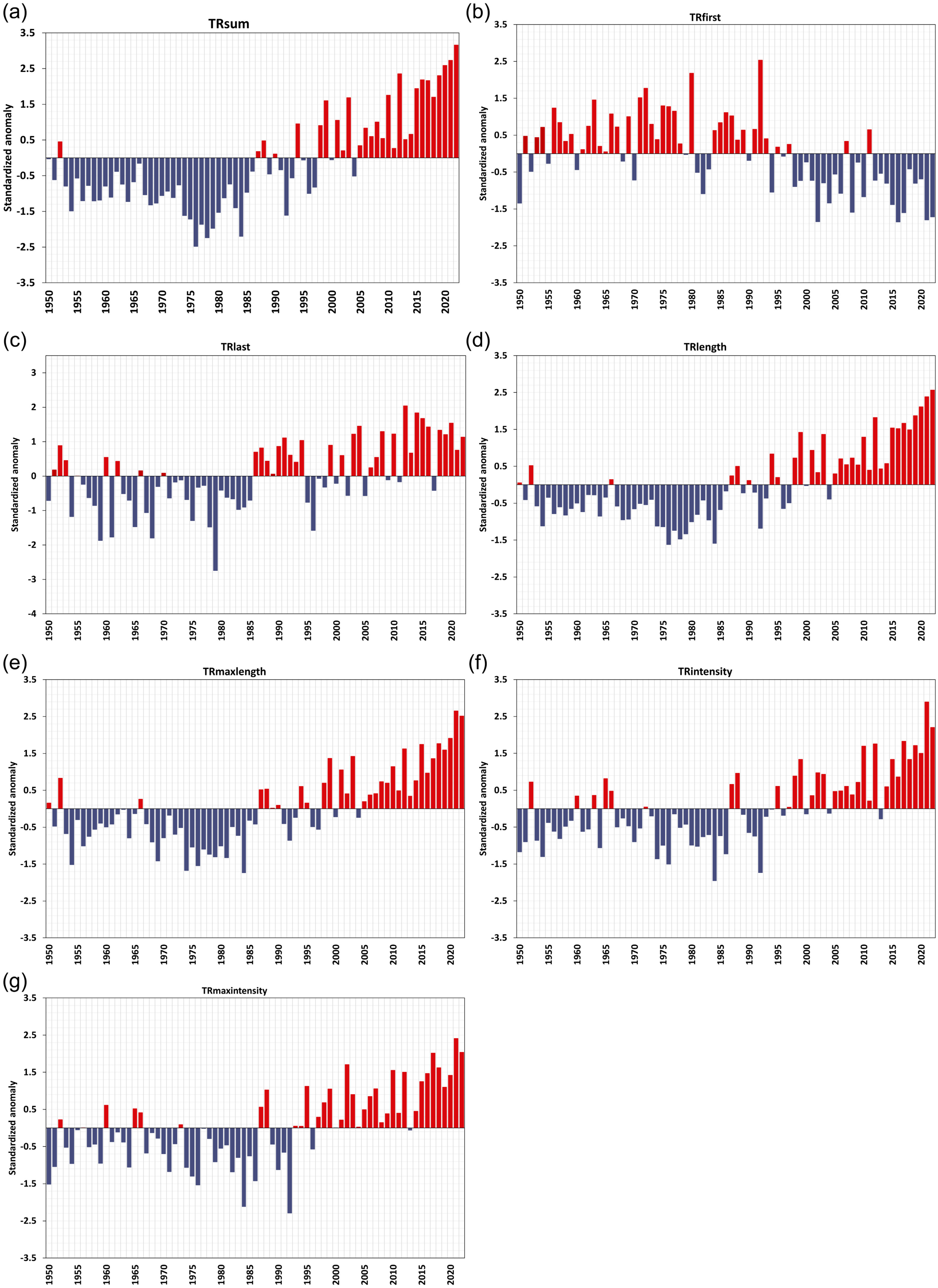

FIGURE 3 Standardized anomalies of (a) frequency (days), (b) first occurrence (dates), (c) last occurrence (dates), (d) length (days), (e) maximum length (days), (f) intensity (°C), (g) maximum intensity of tropical nights (°C) according to regional averaged time series in the Mediterranean region with respect to the reference period 1950–2022.

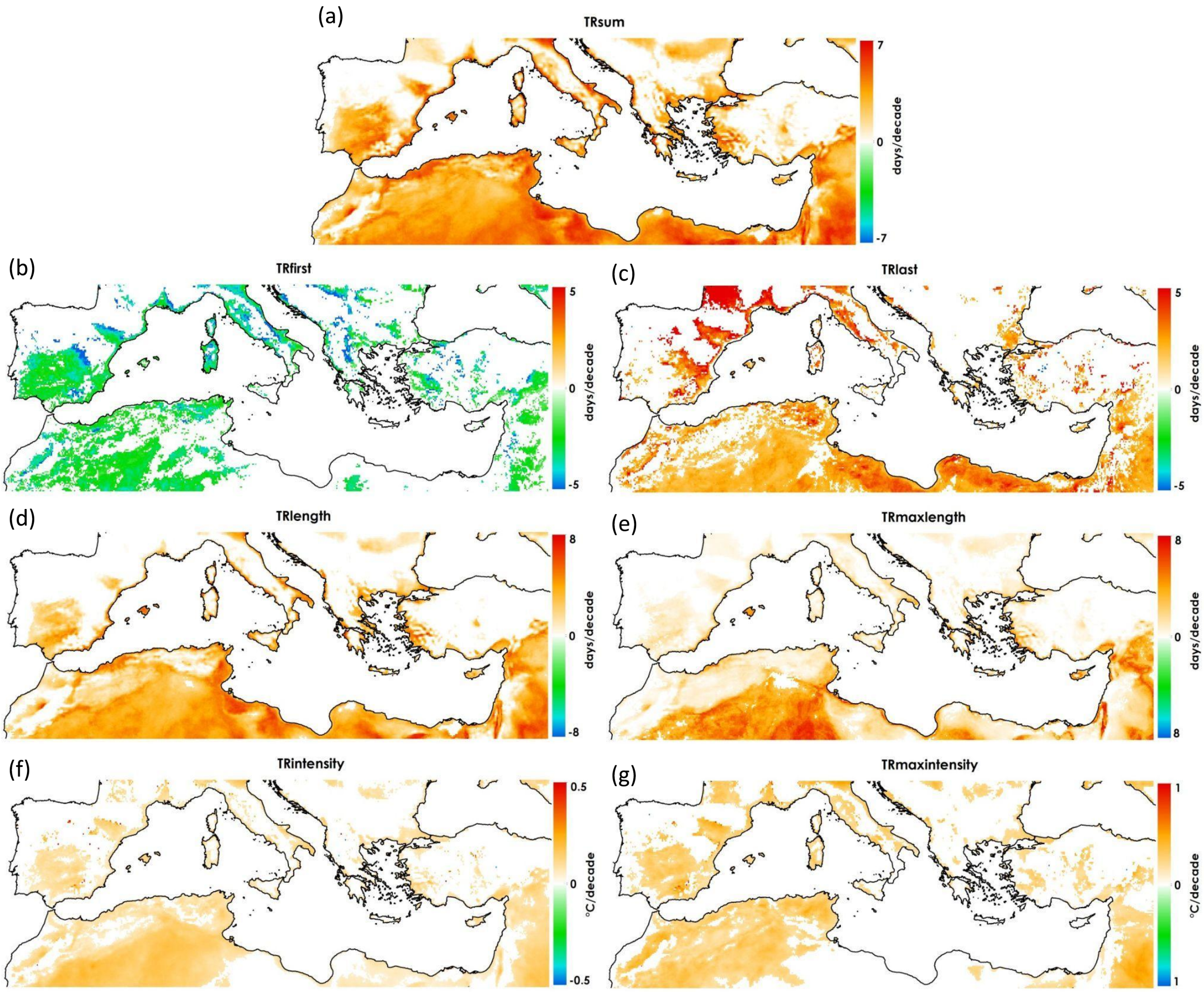

FIGURE 4 Spatial distribution of Sen's slope values of the (a) frequency, (b) first occurrence, (c) last occurrence, (d) length, (e) maximum length, (f) intensity, (g) maximum intensity of tropical nights for the period of 1950–2022 over the Mediterranean region. Colourized areas where trends are significantly different from zero (p-values greater than 0.01), as determined by a Mann–Kendall test. Areas with no data, zero values and/or statistically insignificant are masked with white colour.

period in the Mediterranean region. Studies show that Pinatubo's eruption in 1991 led to a significant cooling in European temperatures in the two summers following the eruptions (Man et al., 2014; Robock & Mao, 1995). The earlier onset of tropical nights has been evident since the end of the 1990s. Especially, the onset of tropical nights in the Mediterranean region has shifted significantly to earlier dates, except for 2007 and 2011 since 1998. The earliest onset of tropical nights appeared in 2016 (152nd Julian day), with negative anomaly values of −1.76. As a matter of fact, it was determined that night temperatures in June 2016 reached their highest levels at an all-time high (WMO, 2023).

Negative long-term trends in the dates of TRfirst are observed in many parts of the Mediterranean region except a few grid points in Anatolia, implying a statistically significant earlier beginning of the season of tropical nights (Figure 4b). Negative trends (earlier shifts) in the timing of TRfirst are 5 days per decade at the south of the Iberian Peninsula, along the coastline of the Gulf of Lion Bay, Sardinia, and Corsica islands, along the coastline of Peninsula Italy, west and southeastern Anatolia, and in some places, the Balkan Peninsula. Similar trends were also found in the western and northern parts of Africa. Consequently, it can be inferred that the commencement of tropical nights across most of the Mediterranean region has advanced by approximately 35 days since the mid-20th century.

3.3 | The annual mean last occurrence of tropical nights

In the semi-arid regions of the northern sections of Africa, tropical nights persist until mid-October. For instance, in the Negev desert, the average date of the end of the TR season is 320 days (mid-November). The last date of tropical nights in the south of the Iberian and Italian peninsulas, the Po Plain, west, and southeastern Anatolia, Cyprus Island, and some places in the Balkan region, along the coastline of the Peloponnese peninsula in the Mediterranean region, extends until mid-September. On the other hand, the last date when tropical nights are observed in high-altitude regions is the end of June (Figure 2c).

Over the span from 1950 to 2022, the Mediterranean Region has witnessed considerable temporal change in the annual mean values of last occurrence of tropical nights (TRlast). The annual mean value of TRlast showed a negative anomaly from 1950 to 1985, except for a few years, with the lowest value in 1979 (240th Julian day) (Figure 3c). However, since the mid-1980s, strong positive anomalies have emerged, indicating that nearly the entire Mediterranean Region has seen an extension in the tropical night season, with the last occurrence being notably delayed. Among the past 73 years, 2012 stands out as the year when tropical nights later ended (263rd Julian days). The shift in the last date of tropical nights in the Mediterranean in 2012 can be linked to that year's heatwave and higher average air temperatures. In fact, the summer mean temperature time series constructed with the best estimate of the CRUTEM4 observational data set shows that the 2003 record was subsequently broken in 2012. However, the heatwave effects in 2012 were less noticeable than those in 2003 (Christidis et al., 2015).

The Mann–Kendall analysis reveals a shift in the timing of last tropical nights, although substantial differences in trends were apparent among regions (Figure 4c). The most noteworthy TRlast trends, which show a 5.0 day/decade later ending to the tropical nights, were seen in basins in the Iberian Peninsula, along the Gulf of Lion coast, and in northern parts of Africa and east of the Biscay Bay. Conversely, in Central Anatolia, the Balkans and northern parts of the Iberian Peninsula, there is less tendency to shift to later dates for the final occurrence of tropical nights. Thus, there is a clear signal across the Mediterranean region of changing TRfirst and TRlast.

3.4 | The annual mean tropical night length

The annual mean tropical night length (TRlength) is characterized as the yearly count of tropical night spells lasting 3 days or more. Figure 2d illustrates the spatial distribution of TRlength spanning the years 1950–2022. Regions with higher values (>120 days) are mostly evident in the arid and semi-arid terrains of northern parts of Africa, the Negev and part of the Syrian Desert. TRlength is progressively decreasing to the north of the region, with the annual frequency of tropical night length varying from 60 to 100 days in the narrow belt of the Mediterranean Sea, the Aegean Sea islands, the northeast of Cyprus, the plain in Anatolia, around the Balearic Islands, the Andalusia region in Spain, the Po Basin, and the Halkidiki Peninsula in Greece.

Relative to the reference period, tropical night length predominantly exhibited negative anomalies between 1950 and 1986, with only 2 years as exceptions (as depicted in Figure 3d). On the other hand, from 1987 onwards, there has been a discernible increase in the length of tropical nights across the Mediterranean region. Over the past 73 years, 2022 marked the peak in TRlength, registering a positive anomaly value of 3.26 compared to the reference period. These positive anomalies indicate a double increase in the duration of tropical nights in the Mediterranean region since 2005.

The TRlength trends are statistically significant at the $p < 0.01$ level across the majority of the Mediterranean region, as illustrated in Figure 4d. Prominent increases in the length of TR are observed around the Gulf of Sidra, the arid lands of Egypt and Syria, and around the Balearic Islands, with rates reaching 8 days per decade. Similarly, Cyprus, southern and western Turkey, the lower Danube basin, Italy's Puglia region, and Spain's Andalusia region have also witnessed a pronounced positive trend, amounting to 4 days per decade. These positive trends suggest that the season with tropical nights has been prolonged in the Mediterranean region since the middle of the 20th century.

3.5 | The annual mean maximum length of tropical nights

The spatial distribution of the maximum length (TRmaxlength) of successive tropical night numbers in the Mediterranean region shows significant regional differences (Figure 2e). Similar to other indices, the highest values for uninterrupted tropical nights belong to the semi-arid and arid areas of northern parts of Africa. For instance, in the Negev desert and the lowlands of northeast Algeria, this duration extends to 170 days, roughly equivalent to five and a half months. Another area where the maximum length of tropical nights in the Mediterranean region is the highest is the northeast of Cyprus, the semi-arid lands of Syria, and the eastern coastline of the Mediterranean, with 80 days. The maximum length of tropical nights is between 30 and 20 days on the north coast of the Mediterranean.

Figure 3e illustrates the temporal variability of TRmaxlength, averaged regionally. Although an overall increasing trend in TRmaxlength is detected for the period 1950–2022 in the Mediterranean region, the entire study period may be roughly divided into two subperiods. The first subperiod lasted from the beginning of the study period until the mid-1980s and was characterized by continued negative anomalies of TRmaxlength except in 1950, 1952 and 1966, with little variance from year to year. It is worth noticing that 1984 was the lowest negative anomaly of TRmaxlength over the whole study period from 1950 to 2022. Conversely, the subsequent subperiod, extending from 1987 to 2022, was characterized by predominantly positive anomalies, signifying extended tropical nights. These positive anomalies became particularly pronounced post-2005, indicating stronger warming night-time temperatures. The highest TRmaxlength values in the last 73 years were reached in 2021 and 2022, respectively. The lowest value of TRlength in 1984 can be associated with the El Chichón eruption in 1982. Studies revealed a severe summer temperature cooling 2 years after stratospheric volcanic clouds in Europe (Erlat & Türkeş, 2019; Esper et al., 2013). For instance, after the 1982 El Chichon eruption, Turkey experienced its most significant negative anomalies in summer minimum temperatures, in contrast to the impacts of the 1963 Agung and 1991 Pinatubo eruptions (Erlat & Türkeş, 2019). On the other hand, the highest values observed in TRmaxlength values after the 2000s confirm the trend of a rapid increase in summer minimum air temperatures in recent years. The maximum length of tropical nights in the Mediterranean region was observed in 2021. According to the heat wave magnitude index, among the 16 most severe heat waves experienced in Europe since 1950, the heatwave in 2021 is the longest heatwave observed with 60 days (13.5 days on average) (Lhotka & Kyselý, 2022). The continuous positive anomalies observed in TRmaxlength values after 2005 are parallel to the human-induced global temperature increase and the resulting increase in seawater temperatures in recent years.

Over the past 73 years, the trend in TRmaxlength has indicated a significant increase in the tropical night season across the Mediterranean region. A significant lengthening of tropical nights was observed over a large part of northern parts of Africa, especially south of the Saharan Atlas range, as well as the Negev desert and semi-arid parts of Syria, with a 9.0-day increase per decade (Figure 4e). Concurrently, along the Mediterranean Sea coastline, the southern Iberian Peninsula, the Italian peninsula, the islands of Corsica and Sardinia, and both the western and southeastern regions of Anatolia, there has been a significant increase in the maximum length of tropical nights. Here, the estimated rate of extension ranges between 2.0 to 3.0 days per decade.

3.6 | The annual mean intensity of tropical nights

The intensity of tropical nights (TRintensity), characterized by the deviation of the minimum temperature from the TR threshold of 20°C, exhibits a range between 0 and 4°C across the Mediterranean region (Figure 2f). Similar to the other indices, the semi-arid and arid regions of West Africa and the Negev Desert have the highest values, where the mean temperature on tropical nights is above 24°C. In regions such as the semi-arid tracts of Syria, the northeastern portion of Cyprus, the Çukurova plain in southern Anatolia, the Halkidiki Peninsula in Greece, Italy's Puglia region, the vicinity of the Balearic Islands and Spain's Huelva province, the intensity of tropical nights hovers around 3°C.

Area-averaged TRintesity anomalies across the Mediterranean region relative to 1981–2010 are generally negative for the period of 1950 to the middle of the 1990s (Figure 3f). The lowest values of TRintesity coincide with the cooling effects of post-volcanic eruptions, such as 1984 and 1992. By contrast, a marked increase in the intensity of tropical nights since 1995 was shown, with a peak value of 2021. Continuous positive anomaly values in the past decades document a rapid shift toward higher night-time temperatures in the Mediterranean. The significant increase in the intensity of tropical nights in the summer of 2021 can be associated with the heatwave event that set new records, especially in the Eastern Mediterranean (Lhotka & Kyselý, 2022).

Trends in TRintensity spanning the period from 1950 to 2022 are illustrated in Figure 4f. Trends reveal significant long-term warming in tropical nights over most of the region. The increasing intensity of tropical nights is clearly manifested in northern Africa, especially south of the Saharan Atlas range, and parts of the semi-arid lands of Syria, with warming reaching 0.5°C per decade. On the other side, the general tropical night intensity at the coastline of the Mediterranean Sea and in basins in the Iberian, such as the Ebro and Guadalquivir, the Po Basin, and the West Anatolian plains, and around the

Marmara Sea, increased significantly (0.01 significance level) at a rate of 0.3°C per decade, respectively, in the last 73 years. The regions where weak trends are seen are the inland and highlands, where tropical nights are uncommon, and their occurrence varies greatly from year to year.

3.7 | The annual mean maximum intensity of tropical nights

The maximum intensity of tropical nights (TRmaxintensity) is defined as the mean of peak daily value in the hottest tropical nights in a year. The annual mean value of TRmaxintensity exhibits pronounced spatial variability across the region, with values ranging from 20 to 30°C. The major hotspots of TRmaxintensity are located in fields of sand dunes in the Sahara Desert as Grand Erg Occidental and The Grand Erg Oriental with the mean peak daily value of tropical nights exceeding 30°C. Similarly, the highest values were observed in the Negev desert and some parts of the Syrian desert. TRmaxintensity values typically lie between 26 and 28°C in areas such as the Antalya Bay and the Çukurova plain in Turkey, along the southern coasts of the Aegean Sea, the Halkidiki Peninsula in Greece, and in basins of the Iberian Peninsula, notably the Guadiana and Guadalquivir, as well as the lower Danube region (Figure 2g).

As illustrated in Figure 3g, the anomaly trends for TRmaxintensity across the Mediterranean region display distinct variations between the periods of 1950–1992 and 1993–2022. TRmaxintensity anomalies generally show negative anomaly values for the period 1950–1992, and the lowest values were observed in 1992 (−2.3) and 1984 (−2.1). Strong negative anomalies in TRmaxintensity in 1992 and 1984 can be associated with the El Chichón (1983) and Pinatubo (1991) volcanic eruptions. In contrast, the period 1993–2022 was characterized as the period with the highest temperatures measured on tropical nights in the entire Mediterranean region since 1950. In particular, 2021 was the period when the amplitude of tropical nights was the highest, with an anomaly value of +2.14. In fact, summer 2021 is described as an unprecedented year over the Mediterranean in terms of the record-breaking temperatures and the earliest start of a major heatwave (19 June) (Lhotka & Kyselý, 2022).

Figure 4g illustrates the spatial trend of change in the peak daily value on the hottest tropical nights of the year. The result reveals a significant warming trend over most of the dryland areas in the northern parts of Africa, south of the Iberian and Italian peninsulas, Corsica and Sardinia islands, parts of Syria, and western and southeastern Anatolia, while small cooling trends were observed over the Saharan Atlas Range and a very small part of the Nile delta, Central Anatolia and Thrace, the Puglia region, and the southwest of France.

3.8 | Comparative analysis of tropical nights: Urban versus non-urban areas

Urban areas typically exhibit higher night-time temperatures than their rural counterparts, a phenomenon attributed to variations in the urban/rural energy balance. These variations arise from changes in land cover, alterations in radiative and heat fluxes due to modified land cover, and human activities (Chapman et al., 2017; Oke et al., 1981). For example, a significant increase in nocturnal urban heat island intensity (up to 3°C) was detected in Athens, Greece, during exceptionally hot weather (Founda et al., 2015).

The Mediterranean region, particularly its southern and eastern parts, ranks among the world's most rapidly urbanizing areas. It was determined that 163 million of the 190 million people added to the population in the region between 1970 and 2010 lived in cities, and the urban population (towns with a population of more than 10,000) increased by 1.9% annually during this period, from 152 million to 315 million (GRID-Arendal, 2023). All these findings indicate that urban areas in the Mediterranean Region may contribute to the observed trends in tropical night indices.

To delve deeper into this, our study probed the disparities in tropical night indices between urban and rural settings. The M-K results show that there are significant differences in tropical night indices in urban areas in the Mediterranean region compared to non-urban areas, with a statistical significance of 0.01% (Table 2). This suggests that over the past 73 years, urban locales have experienced more accelerated nocturnal warming, largely attributed to urban heat island effects. Specifically, the TRsum surged by 24.2 days per decade in urban settings, compared to a 15.4-day increase in non-urban areas.

Across the Mediterranean region, in both urban and non-urban areas, the occurrence of the first TR event tends to be earlier, although this trend is much stronger in urban areas. In urban areas, the date of the first tropical night has shifted 19 days earlier per decade since 1950, while in non-urban areas, this figure has been 15.6 days. Similarly, the last date of tropical days shifted later by 17.9 days per decade in urban areas, while a change of 16.2 days per decade was observed in non-urban areas. In the Mediterranean region, the largest difference in terms of TR between urban and non-urban areas in the last 73 years has been observed in the length of tropical nights. The increasing trend in TRlengh is

TABLE 2 Trend analysis results for tropical night indices (frequency, first and last occurrence date, length, intensity and maximum intensity) in urban and non-urban areas of the Mediterranean region, 1950–2022.

	Urban area		Non-urban area	
Indices	**M–K test *Z***	**Sen's slope *Q***	**M–K test *Z***	**Sen's slope *Q***
TRsum (day)	5.35**	2.42	5.67**	1.54
TRfirst (day)	−3.12**	−1.90	−4.08**	−1.56
TRlast (day)	4.71**	1.79	5.03**	1.62
TRlength (day)	5.35**	2.32	5.56**	1.28
TRmaxlength (day)	5.77**	1.90	5.67**	1.09
TRintensity (°C)	3.44**	0.09	4.50**	0.06
TRmaxintensity (°C)	3.65**	0.17	4.61**	0.13

Note: Analysis was conducted using Mann–Kendall (M-K) tests with Sen's slope values expressed in units of change per year. Results are marked for statistical significance at (*) 0.05 and (**) 0.01 levels.

almost twice as large in urban areas (23.2 days per decade) than in rural areas (12.8 days per decade). Similarly, significant differences are observed in the TRmaxlength index between urban and non-urban areas at the 0.01 significance level.

Although air temperatures measured during tropical nights have shown an increasing trend in both urban and non-urban areas since 1950, as expected, this trend has been stronger in urban areas (0.9°C per decade) than in non-urban areas (0.6°C per decade). The peak daily value of the hottest tropical nights in a year between urban and non-urban areas also showed a statistically significant difference at the 0.01 level. In essence, our findings underscore the profound impact of urbanization on tropical night indices, with the Mediterranean region's urbanization from 1950 to 2022 distinctly reflected in these indices.

4 | CONCLUSIONS AND DISCUSSION

This work analyses the long-term variations and trends in the characteristics of tropical nights in the Mediterranean region for the period 1950–2022. The Mediterranean Region has experienced a general change in tropical night characteristics during the period 1950–2022, against non-uniform trends both spatially and temporally, which is consistent with the concurrent increase in hot extremes over several regions of the world (IPCC, 2022; Perkins et al., 2012). Our findings indicate statistically significant increases in the number of tropical nights and the length of the season due to tropical nights starting earlier and ending later in the Mediterranean region in the last 73 years. It is seen that the intensity of tropical days significantly increases in the Mediterranean region.

This change observed in the indices of tropical night numbers in the Mediterranean region can be attributed to anthropogenic warming. In most land regions, including Europe and the Middle East, the probability of extreme temperatures at least doubled, with an increase of about 2 W·m^{-2} by 2018 in anthropogenic forcing (Estrada et al., 2023). Increasing tropical nights is consistent with night-time low temperatures increasing about twice as rapidly as daytime highs over northern hemisphere mid-latitudes in response to anthropogenic forcing (Donat & Alexander, 2012; Dwyer et al., 2012). As a result, larger increases in night-time hot extremes than daytime have been observed since 1980.

A closer examination of the temporal distribution of tropical nights from 1950 to 2022 reveals a significant change in the TR indices since the mid-1990s, particularly in the last decade. Generally, the highest values observed in the time series can be associated with heat wave events such as 2021 and hot years, and the lowest values can be associated with the 1983 El Chichón and the 1991 Pinatubo volcanic eruptions.

The most noteworthy trends at tropical nights were observed in the arid and semi-arid lands of the Mediterranean region, like northern Africa, the Negev, and Syria. Some recent studies have shown that arid and semi-arid regions made an even greater contribution to global warming in the last century, accounting for almost half of continental warming (Huang et al., 2017; Ji et al., 2014). This amplified warming in arid regions, termed the "desert amplification effect," is attributed to increased long-wave radiation due to a warmer and more humid atmosphere. Because as the air temperature increases in these regions, the air gets warmer and the amount of water vapour in the air increases, but latent heat is not released because the descending air prevents condensation. This process manifests itself as a downward increase in long-wave radiation (Cook & Vizy, 2015; Evan et al., 2015; Zhou et al., 2016). For instance, Cook and Vizy (2015) found that from 1979 to 2012, the Sahara Desert warmed 2–4 times more than all tropical areas. The seasonality of the amplified warming is maximum during July–October, with a minimum during June. Zhou et al. (2016) investigated the T2m warming trends in 50°S and 50°N for the years 1979–2012 and discovered that warming rates increased significantly with increasing surface aridity, with the Sahara Desert and the Arabian Peninsula experiencing the strongest recent warming. These results suggest that the desert amplification effect (DA) is a fundamental feature of changing tropical night characteristics over the arid and semi-arid lands of the Mediterranean region.

It can be thought that "diurnal asymmetric warming" also plays an important role in the change in the number of tropical nights in the Mediterranean Basin. Indeed, the land surface air temperature observations showed that evidently nights have been warming much faster than days, and daily minimum temperatures have increased about 40% faster than daily maximum temperatures due to changes in the cloud cover, solar radiation, aerosols, precipitation, planetary boundary layer depth, land use change and deforestation in the latter half of the twentieth century (Davy et al., 2017; Doan et al., 2022; Zhong et al., 2023; Zhou, 2021). The asymmetry is most substantial at the surface, gradually decreases with height, and disappears above approximately 1 km from the ground. For example, Zhou (2021) revealed that in the Arabian Peninsula, the warming trend in the lower troposphere at 0000 UTC is consistently greater than the value at 1200 UTC, and the day-night warming difference increases with pressure and reaches a maximum at the surface. Data from 21 surface stations revealed warming rates of 0.56 for Tmax and 0.72°C per decade for Tmin. Studies conducted for the Mediterranean basin also show that night temperatures rise faster and therefore DTR values tend to decrease (e.g., Bilbao et al., 2019; Katavoutas et al., 2023; Türkeş & Sümer, 2004). Katavoutas et al. (2023) have reported that climatic anomalies and long-term decline in DTR due to faster increasing rates in night-time than in daytime air temperature in 16 European cities based on long-term observational data (1961–2019). Results also showed that the DTR during both hot days and HW days is higher compared to the DTR during summer normal days in all cities.

Trend analysis revealed that the number of tropical nights and the temperature values recorded during tropical nights increased faster along the coasts than inland. This has shown the potential effect of SST on tropical nights along the coastline in the Mediterranean region. According to recent studies from satellite data, the Mediterranean SST has also experienced significant warming, estimated to be 3.7 times higher than the global ocean trend (Mohamed et al., 2019; Pastor et al., 2020; Pisano et al., 2020). In addition, despite regional differences in the Mediterranean during the period 1982–2021, an increasing trend in terms of frequency, duration, and intensity was found in MHWs, which has accelerated since 2000 and especially in the last decade (Pastor & Khodayar, 2023). Studies show the increasing SST, especially at coasts, is one of the possible factors in enhancing the high extreme temperatures and heatwaves worldwide (Feudale & Shukla, 2011; Lima & Wethey, 2012; Mohamed et al., 2022). Coastal SST changes have been determined to be larger than the changes of the global mean and open ocean, resulting in a fast increase in extreme hot/cold days (Liao et al., 2015). For example, it has been found that the spatial and temporal distribution of tropical nights along the Mediterranean coast of Spain is directly linked to the Western Mediterranean SST (Cantos et al., 2019). HadGEM3 global climate model indicates that changes in sea surface temperature (SST)/sea ice extent (SIE) explain 62.2 ± 13.0% of the area-averaged seasonal mean warming signal over Western Europe (Dong et al., 2017). Between 1982 and 2010, SST increased by an average of 0.25°C per decade in ~71.6% of the world's coastal areas, while the number of yearly extremely hot days significantly increased in 38.1% of the world's coastal areas, at a mean rate of 13.8 days per decade (Lima & Wethey, 2012). As in the Mediterranean, SST in the Black Sea increased by approximately 0.65 ± 0.07°C per decade between 1982 and 2020. More than two-thirds of all MHW events were recorded in the last decade (2010–2020) (Mohamed et al., 2022).

The UHI effect constitutes an additional contributing factor to the observed changes in tropical nights. The tropical night trends are larger in urban areas, increasing the area-averaged statistics in the Mediterranean region. Studies showed that warm nights are more frequent and intense in urban areas than in rural environments (Schatz & Kucharik, 2015; Sun et al., 2019; Zhang et al., 2021). The analysis results reveal that there have been statistically significant differences between urban and non-urban areas in all TR indices in the last 73 years. When urban and non-urban areas are compared, as expected, the frequency, length and intensity of tropical nights increase in urban areas compared to non-urban areas, while the first date of tropical nights occurs earlier and the last date of tropical nights occurs later. The increase in the duration of tropical nights, quantified as the average lengthening of these events each year, exhibits the most significant upward trend in urban areas compared to non-urban areas within the Mediterranean region.

While this study provides a comprehensive analysis of tropical nights in the Mediterranean region from 1950 to 2022, there are inherent limitations to consider. The data utilized spans over seven decades, which might encompass periods of data scarcity, especially in earlier years or in less populated rural areas. This can introduce uncertainties, particularly when comparing urban and non-urban regions, given the potential for observational biases. The regional scale of this study, while offering a broad perspective, might mask microscale variations. For instance, specific urban areas or narrow coastal strips might exhibit unique tropical night characteristics that are not fully captured in a broader regional analysis. Furthermore, our analysis is grounded in observed records without researching specific modelling or future scenario projections. While this ensures a robust understanding of past and present trends, it does not provide insights into potential future changes under varying climate scenarios. urban heat island (UHI) effects, though considered, might have more detailed impacts at the city level, influenced by factors like urban planning, vegetation cover, and architectural designs, which were beyond the scope of this study.

In terms of future research, it would be beneficial to research deeper into the microscale variations of tropical nights, especially in rapidly urbanizing areas. Additionally, incorporating climate model projections can offer insights into the potential future of tropical nights in the Mediterranean under different global warming scenarios. Given the significant socio-economic and health implications of increased tropical nights, understanding these future trajectories is crucial for regional planning and mitigation strategies.

AUTHOR CONTRIBUTIONS

Doğukan Doğu Yavaşlı: Methodology; visualization; data curation; formal analysis; writing – review and editing. **Ecmel Erlat:** Supervision; conceptualization; project administration; writing – original draft.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

ORCID

Doğukan Doğu Yavaşlı https://orcid.org/0000-0002-0150-867X
Ecmel Erlat https://orcid.org/0000-0001-7576-9445

REFERENCES

Abatan, A.A., Abiodun, B.J., Adefisan, E.A. & Gutowski, W.J. (2019) Hot days and tropical nights in Nigeria: trends and associated large-scale features. *Theoretical and Applied Climatology*, 137, 2077–2093. Available from: https://doi.org/10.1007/s00704-018-2713-0

Alexander, L.V., Zhang, X., Peterson, T.C., Caesar, J., Gleason, B., Klein Tank, A.M.G. et al. (2006) Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research: Atmospheres*, 111(D5), D05109. Available from: https://doi.org/10.1029/2005JD006290

ArcGIS Living Atlas of the World. (2023) The global human settlement layer urban centres database. Available from: https://livingatlas.arcgis.com/en/home/ [Accessed on 10th September 2023]

Benas, N., Chrysoulakis, N. & Cartalis, C. (2017) Trends of urban surface temperature and heat Island characteristics in the Mediterranean. *Theoretical Applied Climatology*, 130, 807–816. Available from: https://doi.org/10.1007/s00704-016-1905-8

Bilbao, J., Román, R. & De Miguel, A. (2019) Temporal and spatial variability in surface air temperature and diurnal temperature range in Spain over the period 1950–2011. *Climate*, 7(1), 16. Available from: https://doi.org/10.3390/cli7010016

Cantos, J.O., Serrano-Notivoli, R., Miró, J. & Meseguer-Ruiz, O. (2019) Tropical nights on the Spanish Mediterranean coast, 1950–2014. *Climate Research*, 78(3), 225–236. Available from: https://doi.org/10.3354/cr01569

Cardoso, R.M., Soares, P.M.M., Lima, D.C.A. & Miranda, P.M.A. (2019) Mean and extreme temperatures in a warming climate: EURO CORDEX and WRF regional climate high-resolution projections for Portugal. *Climate Dynamics*, 52, 129–157. Available from: https://doi.org/10.1007/s00382-018-4124-4

Carvalho, D., Cardoso Pereira, S., & Rocha, A. (2021) Future surface temperatures over Europe according to CMIP6 climate projections: an analysis with original and bias-corrected data. *Climatic Change*, 167, 1–17. https://doi.org/10.1007/s10584-021-03159-0

Chapman, S., Watson, J.E.M., Salazar, A., Thatcher, M. & McAlpine, C.A. (2017) The impact of urbanization and climate change on urban temperatures: a systematic review. *Landscape Ecology*, 32, 1921–1935. Available from: https://doi.org/10.1007/s10980-017-0561-4

Christidis, N., Jones, G.S. & Stott, P.A. (2015) Dramatically increasing chance of extremely hot summers since the 2003 European heatwave. *Nature Climate Change*, 5(1), 46–50. Available from: https://doi.org/10.1038/nclimate2468

Cook, K.H. & Vizy, E.K. (2015) Detection and analysis of an amplified warming of the Sahara Desert. *Journal of Climate*, 28, 6560–6580. Available from: https://doi.org/10.1175/JCLI-D-14-00230.1

Davy, R., Esau, I., Chernokulsky, A., Outten, S. & Zilitinkevich, S. (2017) Diurnal asymmetry to the observed global warming. *International Journal of Climatology*, 37(1), 79–93. Available from: https://doi.org/10.1002/joc.4688

Doan, Q.V., Chen, F., Asano, Y., Gu, Y., Nishi, A., Kusaka, H. et al. (2022) Causes for asymmetric warming of sub-diurnal temperature responding to global warming. *Geophysical Research Letters*, 49(20), e2022GL100029. Available from: https://doi.org/10.1029/2022GL100029

Donat, M.G. & Alexander, L.V. (2012) The shifting probability distribution of global daytime and night-time temperatures.

Geophysical Research Letters, 39(14), L14707. Available from: https://doi.org/10.1029/2012GL052459

Dong, B., Sutton, R.T. & Shaffrey, L. (2017) Understanding the rapid summer warming and changes in temperature extremes since the mid-1990s over Western Europe. *Climate Dynamics*, 48, 1537–1554. Available from: https://doi.org/10.1007/s00382-016-3158-8

Dosio, A. & Fischer, E.M. (2018) Will half a degree make a difference? Robust projections of indices of mean and extreme climate in Europe under 1.5°C, 2°C, and 3°C global warming. *Geophysical Research Letters*, 45(2), 935–944. Available from: https://doi.org/10.1002/2017GL076222

Dwyer, J.G., Biasutti, M. & Sobel, A.H. (2012) Projected changes in the seasonal cycle of surface temperature. *Journal of Climate*, 25(18), 6359–6374. Available from: https://doi.org/10.1175/JCLI-D-11-00741.1

El Kenawy, A., López-Moreno, J.I. & Vicente-Serrano, S.M. (2011) Recent trends in daily temperature extremes over northeastern Spain (1960–2006). *Natural Hazards and Earth System Sciences*, 11, 2583–2603. Available from: https://doi.org/10.5194/nhess-11-2583-2011

Elizbarashvili, M., Elizbarashvili, E., Kutaladze, N., Elizbarashvili, S., Maisuradze, R., Eradze, T. et al. (2017) Climatology and historical trends in tropical nights over the Georgian Territory. *Earth Science*, 6(5-1), 23–30 (Special issue: new challenge for geography: landscape dimensions of sustainable development). Available from: https://doi.org/10.11648/j.earth.s.2017060501.14

Endo, A. & Amarasekare, P. (2022) Predicting the spread of vector-borne diseases in a warming world. *Frontiers in Ecology and Evolution*, 10, 758277. Available from: https://doi.org/10.3389/fevo.2022.758277

Erlat, E. & Türkeş, M. (2017) Observed variations and trends in number of tropical nights in Turkey. *Aegean Geographical Journal*, 26(2), 95–106 (in Turkish with English abstract).

Erlat, E. & Türkeş, M. (2019) Temperature responses of Turkey's climate to the tropical volcanic eruptions over second half of the twentieth century. *Theoretical and Applied Climatology*, 137, 2369–2379. Available from: https://doi.org/10.1007/s00704-018-2711-2

Esper, J., Schneider, L., Krusic, P.J., Luterbacher, J., Büntgen, U., Timonen, M. et al. (2013) European summer temperature response to annually dated volcanic eruptions over the past nine centuries. *Bulletin of Volcanology*, 75, 1–14. Available from: https://doi.org/10.1007/s00445-013-0736-z

Estrada, F., Perron, P. & Yamamoto, Y. (2023) Anthropogenic influence on extremes and risk hotspots. *Scientific Reports*, 13(1), 35. Available from: https://doi.org/10.1038/s41598-022-27220-9

ETCCDI. (2023) Climate change indices. Available from: http://etccdi.pacificclimate.org/indices.shtml [Accessed on 8th August 2023]

Evan, A.T., Flamant, C., Lavaysse, C., Kocha, C. & Saci, A. (2015) Water vapor–forced greenhouse warming over the Sahara Desert and the recent recovery from the Sahelian drought. *Journal of Climate*, 28, 108–123. Available from: https://doi.org/10.1175/JCLI-D-14-00039.1

Feudale, L. & Shukla, J. (2011) Influence of sea surface temperature on the European heat wave of 2003 summer. Part I: an observational study. *Climate Dynamics*, 36, 1691–1703. Available from: https://doi.org/10.1007/s00382-010-0788-0

Fioravanti, G., Piervitali, E. & Desiato, F. (2016) Recent changes of temperature extremes over Italy: an index-based analysis. *Theoretical Applied Climatology*, 123, 473–486. Available from: https://doi.org/10.1007/s00704-014-1362-1

Founda, D., Pierros, F., Petrakis, M. & Zerefos, C. (2015) Interdecadal variations and trends of the urban heat island in Athens (Greece) and its response to heat waves. *Atmospheric Research*, 161, 1–13. Available from: https://doi.org/10.1016/j.atmosres.2015.03.016

Founda, D., Varotsos, K.V., Pierros, F. & Giannakopoulos, C. (2019) Observed and projected shifts in hot extremes' season in the eastern Mediterranean. *Global and Planetary Change*, 175, 190–200. Available from: https://doi.org/10.1016/j.gloplacha.2019.02.012

Giannaros, T.M. & Melas, D. (2012) Study of the urban heat island in a coastal Mediterranean City: the case study of Thessaloniki, Greece. *Atmospheric Research*, 118, 103–120. Available from: https://doi.org/10.1016/j.atmosres.2012.06.006

GRID-Arendal. (2023) Urban population in the Mediterranean countries. Available from: https://www.grida.no/resources/5932 [Accessed on 15th September 2023]

Hajat, S., Kovats, R.S., Atkinson, R.W. & Haines, A. (2002) Impact of hot temperatures on death in London: a time series approach. *Journal of Epidemiology and Community Health*, 56, 367–372. Available from: https://doi.org/10.1136/jech.56.5.367

Hamed, K.H. & Rao, A.R. (1998) A modified Mann–Kendall trend test for autocorrelated data. *Journal of Hydrology*, 204, 182–196. Available from: https://doi.org/10.1016/S0022-1694(97)00125-X

Hartmann, B. & Wendler, G. (2005) The significance of the 1976 Pacific climate shift in the climatology of Alaska. *Journal of Climate*, 18(22), 4824–4839. Available from: https://doi.org/10.1175/JCLI3532.1

Hatfield, J.L. & Prueger, J.H. (2015) Temperature extremes: effect on plant growth and development. *Weather and Climate Extremes*, 10, 4–10. Available from: https://doi.org/10.1016/j.wace.2015.08.001

Hu, Z. & Li, Y. (2022) Effect of urbanization on extreme temperature events in Liaoning Province, China, from a spatiotemporal perspective. *Urban Climate*, 41, 101025. Available from: https://doi.org/10.1016/j.uclim.2021.101025

Huang, J., Li, Y., Fu, C., Chen, F., Fu, Q., Dai, A. et al. (2017) Dryland climate change: recent progress and challenges. *Reviews of Geophysics*, 55(3), 719–778. Available from: https://doi.org/10.1002/2016RG000550

IPCC. (2014) In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E. et al. (Eds.) *Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. Contribution of working group II to the fifth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge and New York, NY: Cambridge University Press.

IPCC. (2022) In: Shukla, P.R., Skea, J., Slade, R., Al Khourdajie, A., van Diemen, R., McCollum, D. et al. (Eds.) *Climate change 2022: mitigation of climate change. Contribution of working group III to the sixth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge and New York, NY: Cambridge University Press. Available from: https://doi.org/10.1017/9781009157926

Jacques-Coper, M. & Garreaud, R.D. (2015) Characterization of the 1970s climate shift in South America. *International Journal of*

Climatology, 35(8), 2164–2179. Available from: https://doi.org/10.1002/joc.4120

Ji, F., Wu, Z., Huang, J. & Eric, P. (2014) Evolution of land surface air temperature trend. *Nature Climate Change*, 4(6), 462–466. Available from: https://doi.org/10.1038/nclimate2223

Jordan, G. & Brierley, C.M. (2022) Future global and regional human exposure to tropical night heat events. Authorea Preprints.

Katavoutas, G., Founda, D., Varotsos, K.V. & Giannakopoulos, C. (2023) Diurnal temperature range and its response to heat waves in 16 European cities—current and future trends. *Sustainability*, 15(17), 12715. Available from: https://doi.org/10.3390/su151712715

Kendall, M.G. (1975) *Rank correlation methods*. London: Griffin.

Kumudini, S., Andrade, F.H., Boote, K.J., Brown, G.A., Dzotsi, K.A., Edmeades, G.O. et al. (2014) Predicting maize phenology: intercomparison of functions for developmental response to temperature. *Agronomy Journal*, 106, 2087–2097. Available from: https://doi.org/10.2134/agronj14.0200

Lelieveld, J., Proestos, Y., Hadjinicolaou, P., Tanarhte, M., Tyrlis, E. & Zittis, G. (2016) Strongly increasing heat extremes in the Middle East and North Africa (MENA) in the 21st century. *Climate Change*, 137, 245–260. Available from: https://doi.org/10.1007/s10584-016-1665-6

Lhotka, O. & Kyselý, J. (2022) The 2021 European heat wave in the context of past major heat waves. *Earth and Space Science*, 9(11), e2022EA002567. Available from: https://doi.org/10.1029/2022EA002567

Liao, E., Lu, W., Yan, X.-H., Jiang, Y. & Kidwell, A. (2015) The coastal ocean response to the global warming acceleration and hiatus. *Scientific Reports*, 5, 16630. Available from: https://doi.org/10.1038/srep16630

Lima, F.P. & Wethey, D.S. (2012) Three decades of high-resolution coastal sea surface temperatures reveal more than warming. *Nature Communications*, 3(1), 704. Available from: https://doi.org/10.1038/ncomms1713

Lionello, P. & Scarascia, L. (2018) The relation between climate change in the Mediterranean region and global warming. *Regional Environmental Change*, 18, 1481–1493. Available from: https://doi.org/10.1007/s10113-018-1290-1

Mamrutha, H.M., Rinki, K., Venkatesh, K., Gopalareddy, K., Khan, H., Mishra, C.N. et al. (2020) Impact of high night temperature stress on different growth stages of wheat. *Plant Physiology Reports*, 25, 707–715. Available from: https://doi.org/10.1007/s40502-020-00558-w

Man, W., Zhou, T. & Jungclaus, J.H. (2014) Effects of large volcanic eruptions on global summer climate and East Asian monsoon changes during the last millennium: analysis of MPI-ESM simulations. *Journal of Climate*, 27, 7394–7409. Available from: https://doi.org/10.1175/JCLI-D-13-00739.1

Mann, H.B. (1945) Nonparametric tests against trend. *Econometrica*, 13, 245–259.

Meehl, G.A., Goddard, L., Boer, G., Burgman, R., Branstator, G., Cassou, C. et al. (2014) Decadal climate prediction: an update from the trenches. *Bulletin of the American Meteorological Society*, 95(2), 243–267. Available from: https://doi.org/10.1175/BAMS-D-12-00241.1

Mercator Ocean International. (2023) Record-high marine heatwaves in the Mediterranean Sea, summer 2022. Available from: https://www.mercator-ocean.eu/en/news/marine-heatwaves-mediterranean-summer-2022/ [Accessed on 9th August 2023]

Mohamed, B., Abdallah, A.M., Alam El-Din, K., Nagy, H. & Shaltout, M. (2019) Inter-annual variability and trends of sea level and sea surface temperature in the Mediterranean Sea over the last 25 years. *Pure and Applied Geophysics*, 176, 3787–3810. Available from: https://doi.org/10.1007/s00024-019-02156-w

Mohamed, B., Ibrahim, O. & Nagy, H. (2022) Sea surface temperature variability and marine heatwaves in the Black Sea. *Remote Sensing*, 14(10), 2383. Available from: https://doi.org/10.3390/rs14102383

Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G. et al. (2021) ERA5-Land: a state-of-the-art global reanalysis dataset for land applications. *Earth System Science Data*, 13(9), 4349–4383. Available from: https://doi.org/10.5194/essd-13-4349-2021

Nastos, P.T. & Kapsomenakis, J. (2015) Regional climate model simulations of extreme air temperature in Greece. Abnormal or common records in the future climate? *Atmospheric Research*, 152, 43–60. Available from: https://doi.org/10.1016/j.atmosres.2014.02.005

Oke, T.R., Kalanda, B.D. & Steyn, D.G. (1981) Parameterization of heat storage in urban areas. *Urban Ecology*, 5(1), 45–54. Available from: https://doi.org/10.1016/0304-4009(81)90020-6

Pastor, F. & Khodayar, S. (2023) Marine heat waves: characterizing a major climate impact in the Mediterranean. *Science of the Total Environment*, 861, 160621. Available from: https://doi.org/10.1016/j.scitotenv.2022.160621

Pastor, F., Valiente, J.A. & Khodayar, S. (2020) A warming Mediterranean: 38 years of increasing sea surface temperature. *Remote Sensing*, 12(17), 2687. Available from: https://doi.org/10.3390/rs12172687

Perkins, S.E., Alexander, L.V. & Nairn, J.R. (2012) Increasing frequency, intensity and duration of observed global heatwaves and warm spells. *Geophysical Research Letters*, 39(20), L20714. Available from: https://doi.org/10.1029/2012GL053361

Pisano, A., Marullo, S., Artale, V., Falcini, F., Yang, C., Leonelli, F.E. et al. (2020) New evidence of Mediterranean climate change and variability from sea surface temperature observations. *Remote Sensing*, 12(1), 132. Available from: https://doi.org/10.3390/rs12010132

Ragettli, M.S., Vicedo-Cabrera, A.M., Schindler, C. & Röösli, M. (2017) Exploring the association between heat and mortality in Switzerland between 1995 and 2013. *Environmental Research*, 158, 703–709. Available from: https://doi.org/10.1016/j.envres.2017.07.021

Rippstein, V., de Schrijver, E., Eckert, S. & Vicedo-Cabrera, A.M. (2023) Trends in tropical nights and their effects on mortality in Switzerland across 50 years. *PLOS Climate*, 2(4), e0000162. Available from: https://doi.org/10.1371/journal.pclm.0000162

Robock, A. & Mao, J. (1995) The volcanic signal in surface temperature observations. *Journal of Climate*, 8(5), 1086–1103. Available from: https://doi.org/10.1175/1520-0442(1995)008<1086:TVSIST>2.0.CO;2

Roth, M., Sanchez, B., Li, R. & Velasco, E. (2022) Spatial and temporal characteristics of near-surface air temperature across local climate zones in a tropical city. *International Journal of Climatology*, 42(16), 9730–9752. Available from: https://doi.org/10.1002/joc.7862

Royé, D. (2017) The effects of hot nights on mortality in Barcelona. *International Journal of Biometeorology*, 61, 2127–2140. Available from: https://doi.org/10.1007/s00484-017-1416-z

Royé, D., Sera, F., Tobías, A., Lowe, R., Gasparrini, A., Pascal, M. et al. (2021) Effects of hot nights on mortality in southern Europe. *Epidemiology*, 32(4), 487–498. Available from: https://doi.org/10.1097/EDE.0000000000001359

Sadok, W. & Jagadish, S.K. (2020) The hidden costs of nighttime warming on yields. *Trends in Plant Science*, 25(7), 644–651. Available from: https://doi.org/10.1016/j.tplants.2020.02.003

Salmi, T., Maatta, A., Anttila, P., Ruoho-Airola, T. & Amnell, T. (2002) *Detecting trends of annual values of atmospheric pollutants by the Mann–Kendall test and Sen's slope estimates—The Excel template application MAKESENS*, Vol. 31. Helsinki: Finnish Meteorological Institute, Publications on Air Quality.

Schatz, J. & Kucharik, C.J. (2015) Urban climate effects on extreme temperatures in Madison, Wisconsin, USA. *Environmental Research Letters*, 10(9), 094024. Available from: https://doi.org/10.1088/1748-9326/10/9/094024

Scorzini, A.R., Di Bacco, M. & Leopardi, M. (2018) Recent trends in daily temperature extremes over the central Adriatic region of Italy in a Mediterranean climatic context. *International Journal of Climatology*, 38, e741–e757. Available from: https://doi.org/10.1002/joc.5403

Sen, P.K. (1968) Estimates of the regression coefficient based on Kendall's tau. *Journal of the American Statistical Association*, 63(324), 1379–1389.

Song, W., Yang, R., Wu, T., Wu, C., Sun, S., Zhang, S. et al. (2016) Analyzing the effects of climate factors on soybean protein, oil contents, and composition by extensive and high-density sampling in China. *Journal of Agricultural and Food Chemistry*, 64(20), 4121–4130. Available from: https://doi.org/10.1021/acs.jafc.6b00008

Sun, Y., Hu, T., Zhang, X., Li, C., Lu, C., Ren, G. et al. (2019) Contribution of global warming and urbanization to changes in temperature extremes in eastern China. *Geophysical Research Letters*, 46(20), 11426–11434. Available from: https://doi.org/10.1029/2019GL084281

Türkeş, M., & Sümer, U.M. (2004) Spatial and temporal patterns of trends and variability in diurnal temperature ranges of Turkey. *Theoretical and Applied Climatology*, 77, 195–227. https://doi.org/10.1007/s00704-003-0024-5

Vardoulakis, E., Karamanis, D., Fotiadi, A. & Mihalakakou, G. (2013) The urban heat island effect in a small Mediterranean city of high summer temperatures and cooling energy demands. *Solar Energy*, 94, 128–144. Available from: https://doi.org/10.1016/j.solener.2013.04.016

Vose, R.S., Easterling, D.R. & Gleason, B. (2005) Maximum and minimum temperature trends for the globe: an update through 2004. *Geophysical Research Letters*, 32, L23822. Available from: https://doi.org/10.1029/2005GL024379

Wang, K., Li, Y., Wang, Y. & Yang, X. (2017) On the asymmetry of the urban daily air temperature cycle. *Journal of Geophysical Research: Atmospheres*, 122(11), 5625–5635. Available from: https://doi.org/10.1002/2017JD026589

Wang, Y., Lu, B. & Han, Z. (2023) Rapid increase of the nighttime electricity demand in Beijing due to compound heatwaves. *Urban Climate*, 50, 101595. Available from: https://doi.org/10.1016/j.uclim.2023.101595

WMO. (2023) European climate in 2016 marked by warm nights and major floods. Available from: https://public.wmo.int/en/media/news/european-climate-2016-marked-warm-nights-and-major-floods [Accessed on 1th September 2023]

Yang, L., Song, W., Xu, C., Sapey, E., Jiang, D. & Wu, C. (2023) Effects of high night temperature on soybean yield and compositions. *Frontiers in Plant Science*, 14, 1065604. Available from: https://doi.org/10.3389/fpls.2023.1065604

Zhang, P., Ren, G., Qin, Y., Zhai, Y., Zhai, T., Tysa, S.K. et al. (2021) Urbanization effects on estimates of global trends in mean and extreme air temperature. *Journal of Climate*, 34(5), 1923–1945. Available from: https://doi.org/10.1175/JCLI-D-20-0389.1

Zhang, Q., Xu, C.Y., Zhang, Z.X. & Chen, Y.D. (2015) Observed trends of annual maximum daily precipitation in the Yangtze River basin during 1960–2013. *Water Resources Management*, 29(8), 2761–2775. Available from: https://doi.org/10.1016/j.jhydrol.2005.09.023

Zhong, Z., He, B., Chen, H.W., Chen, D., Zhou, T., Dong, W. et al. (2023) Reversed asymmetric warming of sub-diurnal temperature over land during recent decades. *Nature Communications*, 14(1), 7189. Available from: https://doi.org/10.1038/s41467-023-43007-6

Zhou, L. (2021) Diurnal asymmetry of desert amplification and its possible connections to planetary boundary layer height: a case study for the Arabian Peninsula. *Climate Dynamics*, 56(9–10), 3131–3156. Available from: https://doi.org/10.1007/s00382-021-05634-x

Zhou, L., Chen, H., Hua, W., Dai, Y. & Wei, N. (2016) Mechanisms for stronger warming over drier ecoregions observed since 1979. *Climate Dynamics*, 47, 2955–2974. Available from: https://doi.org/10.1007/s00382-016-3007-9

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