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Trend analysis of air temperature in a megacity between two continents: the synoptic weather station in İstanbul Atatürk Airport

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Abstract
İstanbul is the largest city located in the Mediterranean Basin and has a medium to high risk of climate change and future climate risks. Changes in temperature and other weather variables have had significant impacts on İstanbul. In this context, there is a need for studies on the issues of climate monitoring and climate change vulnerability to reduce the adverse impacts. The aim of this study is to investigate the temperature trends of synoptic weather station in İstanbul Atatürk Airport between 1973 and 2023 to have a general idea about how the temperature has changed over the last half-century and to establish statistically whether a trend is significant or not. The values of minimum (Tmin), maximum (Tmax) and mean (Tmean) temperature related parameters were estimated. Annual, monthly and seasonal temperature trends are also analyzed. The findings of this study indicate a significant ($p < 0.001$) rise in the mean air temperature (Tmean) of İstanbul over the past 51 years (1973–2023), with an annual warming trend of 0.06 °C. The strongest increasing trend in seasonal mean air temperatures has been observed in the summer season, with an increase of 0.08 °C per year. The trend analysis also shows a statistically non-significant increase in yearly average minimum temperature (Tmin) between 1973 and 2023, with a rate of 0.04 °C per year. However, the annual maximum temperature (Tmax) has shown no changes.

Keywords Climate change, Temperature, Trend analysis, Annual, Seasonal, İstanbul

Introduction

Climate change refers to the gradual change of the typical weather patterns that characterize the local, regional, and worldwide climates of Earth over an extended period. According to climate data records, the world's climate has shown a rapid warming trend in recent years. The past nine years, 2015–2023, was the nine warmest years on record in the world and 2023 is confirmed as the warmest calendar year in global temperature with 1.48 °C degrees Celsius (°C) above the pre-industrial 1850–1900 baseline (Copernicus 2024). Every decade since the 1990s has been hotter than all the decades preceding it in the world (WMO, 2022). Changes observed in Earth's climate since the mid-20th century are driven mainly by human activities, particularly fossil fuel burning, which increases heat-trapping greenhouse gas levels in Earth's atmosphere, raising Earth's average surface temperature. Natural processes can also play a role in climate change. These include internal variations such as cyclical ocean patterns like El Niño, La Niña, and the Pacific Decadal

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Oscillation, as well as external influences like volcanic eruptions, fluctuations in the Sun's energy emissions, and alterations in Earth's orbit.

The Mediterranean region is recognized as one of the world's regions particularly sensitive to climate change (Cramer et al. 2018; IPCC 2022). Annual mean temperatures on land and sea across the Mediterranean Basin are warming faster than the global averages (MedECC 2020). There are several reasons explaining this high sensitivity to climate change. Firstly, the Mediterranean basin is located in a transitional zone between the temperate climate of mid-latitudes and the hotter and drier climate of North Africa. Another explanatory factor comes from its geographical features, i.e., a semi-closed sea surrounded by mountains and highly urbanized coastal regions (Thiébault and Moatti 2016). These climatic, geographical and, anthropogenic factors contribute to the strong spatial and temporal variability of climate encountered in the Mediterranean. According to a recent study, the Eastern Mediterranean region is experiencing a warming trend nearly twice as rapid as the global average and compared to other populated areas worldwide (Zittis et al. 2022).

Located in the Eastern Mediterranean, Türkiye and İstanbul are affected by climate change at increasing rates. The analysis of observed trends in annual averages over the last century shows an overall increase in temperatures and extreme events (Lelieveld et al. 2012; Ozdemir et al. 2012; Toros et al. 2017; Abbasnia and Toros 2018, 2020; Hadi and Tombul 2018; Yurtseven 2023; Yılmaz et al. 2023, Ciftci and Sahin 2023). Climate projections from global or regional climate models indicate that this warming trend will continue, with the magnitude of these changes primarily depending on the emission scenario after 2050 (Özturk et al. 2015; Todaro et al. 2022). Climate projections also indicate an increase in the frequency and intensity of heatwaves (Zittis et al. 2022). However, the detailed spatial distribution of temperature changes remains uncertain.

The purpose of this study is to analyze the temperature trends of synoptic weather station in İstanbul Atatürk Airport between 1973 and 2023 to understand how the temperature has changed over the last half-century and to find if there is a statistically significant trend or not. First, the values of minimum (Tmin), maximum (Tmax) and mean (Tmean) temperature related parameters were estimated. Second, annual, monthly and seasonal temperature trends are analyzed. Finally, the 50-year evolution of the air temperature in relation to the larger European and Mediterranean context were discussed. The climate trends were detected by employing the Theil-Sen non-parametric test (Theil 1950; Sen 1968) for different confidence levels ($\alpha = 0.001$, 0.01, 0.05 and 0.1).

Materials and methods

Study area

İstanbul is located in the Marmara region of Türkiye which is in the northwestern part of the country connecting Europe to Asia. This metropolis located on the both sides of the entrance to 30-km-long Bosporus Strait connecting the Mediterranean and Sea of Marmara (south) to the Black Sea (north). The city has Mediterranean climate with hot and dry summers and cold winters. In 1973, İstanbul was primarily centered around the Golden Horn, the estuary flowing southwest into the Bosporus Strait. Over the past five decades, İstanbul's population has increased, leading to the city's expansion to accommodate its inhabitants. By 2023, the city had sprawled several kilometers to the east and west. By the end of 2023, İstanbul housed 17 million people, constituting 20% of Turkey's population.

İstanbul Atatürk Airport is located in the southwest of İstanbul near the Marmara Sea, in the European part of the city (Fig. 1). The airport was opened in 1924 and was initially named Yeşilköy Airport and it was renamed Atatürk International Airport in 1980. Atatürk International Airport, formerly the primary international airport of İstanbul, ceased commercial passenger flights on April 6, 2019, and all commercial flight operations were relocated to the new İstanbul Airport. It is now only in use for private jets and governmental flights. Temperature data used of this study were obtained from the meteorological station of İstanbul Atatürk Airport (40,976 N, 28,821 E, 33 m above sea level). The station belongs to the General Directorate of Meteorology of Türkiye. It is integrated (ID: 17,060) into the climatic network of the World Meteorological Organization (WMO). The main reason for choosing this station was that it represents the Mediterranean climate better than the northern parts of İstanbul.

Changes in temperature and other weather variables have had significant impacts on İstanbul. Over the course of the last century, there has been an elevation in the daily average temperature in İstanbul. The most substantial increase in seasonal daily average temperatures occurred during the summer months (Toros et al. 2017). Other observations were the decrease in annual total amount of precipitation, increase in the frequency of the intense rain, the rise in the annual average temperature and the extension of the warm periods in a year (Turoğlu 2014). A study investigating the impact of heat on mortality in cities across Europe and the Eastern–Southern Mediterranean, including Istanbul, reveals that a temperature increase of 1 °C above a specific threshold leads to a 2.4% rise in mortality across all age groups (Leone et al. 2013) and mortality rates rises during heat waves in İstanbul (Çulpan et al. 2022). In this context, there is a need for

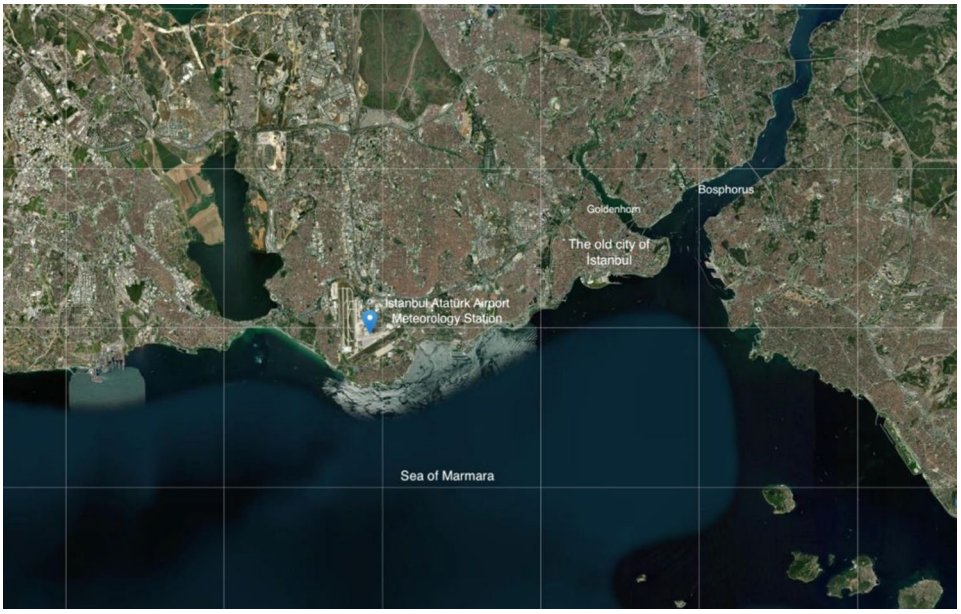

Fig. 1 Map of İstanbul. Synoptic weather station of İstanbul Atatürk Airport is shown with a blue sign

studies on the issues of climate monitoring and climate change vulnerability to reduce the adverse impacts.

Data and methodology

The data used in this work cover the period 1973–2023, without gaps. Hourly temperature data of İstanbul Atatürk Airport meteorological station was imported from the NOAA Integrated Surface Database (ISD) (NOAA, 2024). Data analysis was conducted on a monthly, seasonal, and yearly basis. The minimum (Tmin), maximum (Tmax) and mean (Tmean) temperature related parameters were estimated. Climate trends were identified using the Theil-Sen non-parametric test (Theil 1950; Sen 1968) for different confidence levels (0.001, 0.01, 0.05 and 0.1). Theil- Sen method is commonly employed for the analysis of climatic and environmental time series, as well as for evaluating trends (Hadi and Tombul 2018; Proutsos et al. 2020; Alemu and Dioha 2020; Mainuddin et al. 2022; Bey et al. 2024), because of its reliability to ascertain the magnitude of trends in climate datasets. Theil-Sen function determines the maximum possible number of point-to-point slopes that can be calculated from the complete observations. Then, it calculates the median of slopes from the slopes of each pair of points in the dataset. This median slope is known as the Theil-Sen estimate of the relationship. Theil-Sen estimation can produce accurate estimates in the face of extreme observations because median of slopes is robust against the influence of extreme values (University of Virgina 2023).

Worldmet package of the R software was used to import climate data from NOAA ISD. Openair package of the R software was used for the Theil-Sen trend identification under different levels of confidence and the estimation of the slopes (R Development Core Team 2024). The symbols shown next to each trend estimate relate to how statistically significant the trend estimate is: $p<0.001$=***, $p<0.01$=**, $p<0.05$=* and $p<0.1$ = +.

Results

Temperature and related parameters

The mean annual temperature for the study area, calculated from 51 years of data spanning 1973–2023, is 15.0 °C, as indicated in Table 1 which presents the average annual values of mean, minimum and maximum air temperatures of the meteorological station. Figure 2(a) shows that the warmest temperature (17.0 °C) occurred in 2018, followed by 2019 and 2023. Figure 2(b) shows the climate stripes for 51 years. Every stripe corresponds to the average temperature of a single year compared to the overall average temperature (15.0 °C) across the entire period. Blue shades represent years that were cooler than average, whereas red indicates years that were hotter than average. As this figure shows, there has been a strong warming trend over the past 50 years. Indicatively, the temperature changes appear to follow different patterns before and after 1993. By dividing the dataset into two climatic periods (the 1st climatic period from 1973 to 1993, comprising 21 years, and the 2nd climatic period from 1993 to 2023, comprising 31 years) and analyzing trends for each period, it was seen that there are two different temperature periods.

Figure 3 show that July and August stand out as the warmest months with a mean temperature of 24.7 °C, whereas January is the coldest, recording 6.1 °C. The variations in mean temperature across seasons align with the

Table 1 Monthly, seasonal and annual values of mean (Tmean), maximum (tmax) and minimum (tmin) temperatures of different time periods (1973–1993, 1993–2023, 1973–2023) from the climatic station of İstanbul Atatürk Airport

	1973–1993	1993–2023	1973–2023
Month	$T_{mean}(T_{min}, T_{max})$	$T_{mean}(T_{min}, T_{max})$	$T_{mean}(T_{min}, T_{max})$
January	5.3 (-3.5, 13.9)	6.6 (-2.9, 15.4)	6.1 (-3.1, 14.8)
February	5.4 (-3.4, 15.5)	6.9 (-1.5, 16.7)	6.3 (-2.2, 16.3)
March	7.2 (-1.1, 19.8)	8.8 (0.5, 20.1)	8.1 (-0.1, 19.9)
April	11.7 (3.7, 23.8)	12.8 (4.4, 24.4)	12.3 (4,1 24.2)
May	16.0 (7.0, 26.9)	17.9 (9.4, 28.8)	17.1 (8.4, 28.0)
June	20.9 (12.1, 31.9)	22.7 (14.9, 32.4)	22.0 (13.8, 32.2)
July	23.2 (15.4, 33.2)	25.6 (18.2, 33.9)	24.7 (17.1, 33.6)
August	23.1 (15.5, 32.0)	25.8 (18.7, 34.2)	24.7 (17.4, 33.2)
September	20.0 (11.6, 29.9)	21.9 (13.9, 30.8)	21.2 (13.0, 30.4)
October	15.8 (7.4, 26.5)	17.2 (9.1, 26.0)	16.6 (8.3, 26.1)
November	11.1 (2.6, 20.0)	12.8 (3.8, 21.8)	12.1 (3.3, 21.0)
December	7.6 (-0.8, 16.0)	8.9 (0.1, 16.9)	8.3 (-0.3, 16.6)
Season			
Winter	6.1 (-5.2, 16.8)	7.4 (-3.7, 18.0)	6.9 (-4.3, 17.6)
Spring	11.6 (-1.1, 27.1)	13.1 (0.5, 28.9)	12.5 (-0.1, 28.2)
Summer	22.4 (11.9, 34.6)	24.7 (14.8, 35.0)	23.8 (13.6, 34.8)
Autumn	15.7 (2.5, 30.1)	17.2 (3.7, 30.8)	16.6 (3.3, 30.5)
Annual	14.0 (2.0, 27.2)	15,7 (3.8, 28,2)	15.0 (3.1, 27.8)

anticipated patterns for the Mediterranean climate of the region. Notably, the highest mean values occur during summer at 23.8 °C, while winter experiences the lowest mean temperatures at 6.9 °C. Transitional seasons, such as spring (12.5 °C) and autumn (16.6 °C), display intermediate values.

The annual maximum temperature (Tmax) averages 27.8 °C and exhibits seasonal fluctuations from 17.6 °C in winter to 34.8 °C in summer. Spring (28.2 °C) and autumn (30.5 °C) display intermediate values with higher variability. Similarly, the minimum temperature (Tmin) follows a comparable seasonal pattern, ranging from −4.3 °C in winter to 13.6 °C in summer, resulting in an annual average of 3.1 °C (Table 1).

During the 1st climatic period (1973–1993), Tmean was lower in all months and seasons compared to Tmean of 2nd climatic period (1993–2023). This shows that, the 2nd climatic period exhibited warming trends that resulted in an annual average of 15.6 °C which is 1.6 °C higher than the 1st climatic period (14 °C). The annual minimum temperature (Tmin=3.8 °C) and annual maximum temperature (Tmax=28.2 °C) of the 2nd climatic period are also higher than 1st climatic period (2.0 °C and 27.2 °C) (Table 1).

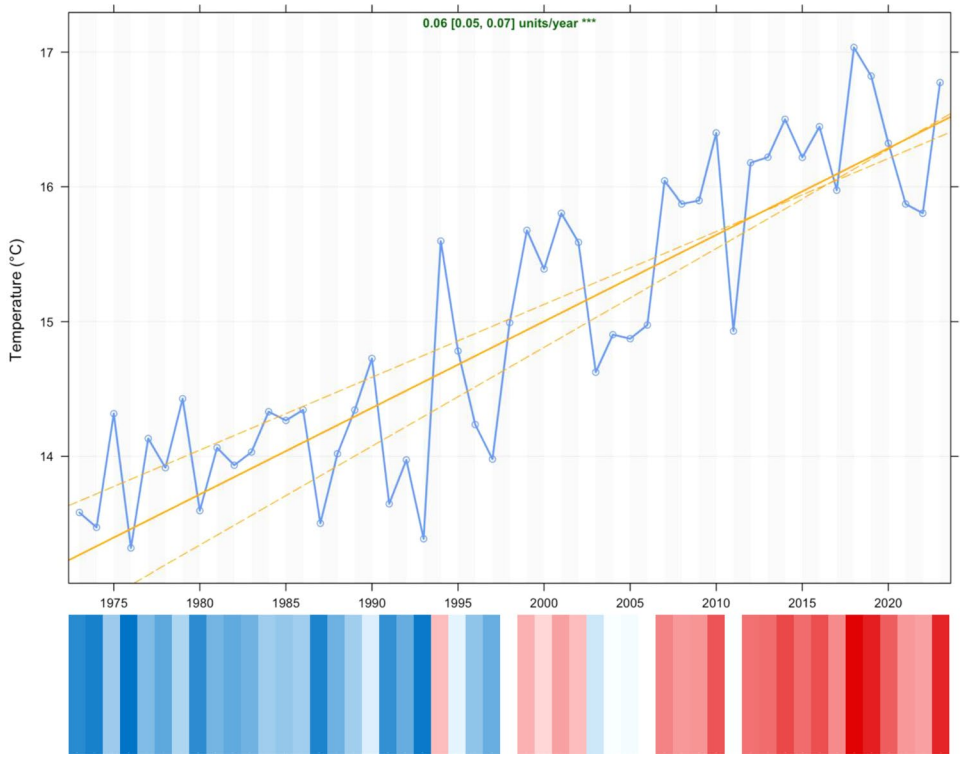

Fig. 2 (**a**) Annual changes and trend of mean temperature for the period of 1973–2023 in İstanbul. The solid orange line shows the trend estimate and the dashed orange lines show the 95% confidence intervals for the trend. The overall trend is shown at the top as 0.06 (°C) per year and the 95% confidence intervals in the slope from 0.05–0.07 °C /year. The symbol (∗ ∗ ∗) shows that the trend is significant to the 0.001 level. (**b**) Climate stripes for yearly mean temperatures. The average temperature (15 °C) in the 1973–2023 period is set as white between blue (cooler) and red (warmer) colors

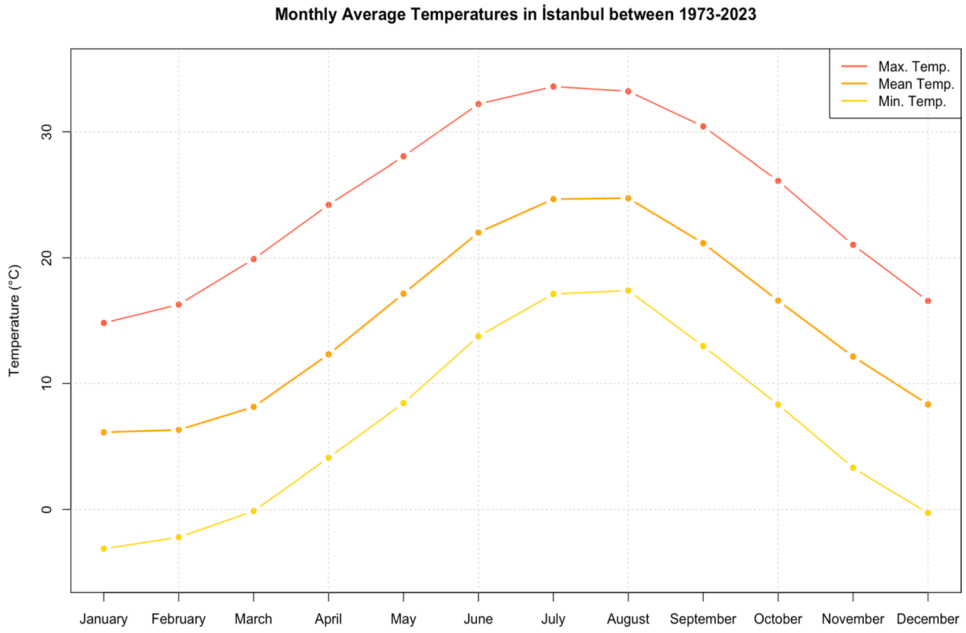

Fig. 3 Monthly averages of temperatures for the period of 1973–2023 in İstanbul

Table 2 Sen's slope Q estimates of the monthly, seasonal and annual mean temperature (Tmean), for the time period 1973–2023 and for the two climatic periods 1973–1993 and 1993–2023 at different levels of significance. Statistically significant values are highlighted in grey and the significance level is indicated with + for a = 0.1, * for a = 0.05, ** for a = 0.01 and *** for a = 0.001

Time period	1973–1993	1993–2023	1973–2023
Trend statistics	**Q (°C/Y)**	**Q (°C/Y)**	**Q (°C/Y)**
January	0.03 (-0.07, 0.16)	0.05 (-0.02, 0.11)	0.05 (0.02, 0.08) ***
February	-0.07 (-0.19, 0.07)	0.08 (0.03, 0.15) *	0.06 (0.03, 0.09) ***
March	0.02 (-0.12, 0.1)	0.09 (-0.01, 0.18) +	0.06 (0.03, 0.09) ***
April	0.03 (-0.06, 0.14)	0.04 (-0.03, 0.12)	0.04 (0.02, 0.08) ***
May	-0.04 (-0.07, 0.02)	0.05 (0, 0.10) +	0.06 (0.04, 0.09) ***
June	0.06 (-0.01, 0.1) +	0.04 (-0.01, 0.1) +	0.06 (0.04, 0.09) ***
July	0.03 (-0.04, 0.1)	0.05 (0.02, 0.09) *	0.08 (0.06, 0.09) ***
August	0.13 (0.07, 0.21) ***	0.07 (0.05, 0.12) ***	0.10 (0.08, 0.12) ***
September	0.03 (-0.02, 0.11)	0.09 (0.03, 0.14) **	0.07 (0.05, 0.10) ***
October	0.03 (-0.1, 0.15)	0.04 (-0.02, 0.11)	0.05 (0.02, 0.09) ***
November	-0.01(-0.13, 0.12)	0.12 (0.07, 0.19) ***	0.07 (0.04, 0.11) ***
December	-0.02 (-0.17, 0.1)	0.08 (0.02, 0.15) *	0.05 (0.02, 0.08) ***
Season			
Winter	-0.03 (-0.10, 0.05)	0.07 (0.04, 0.11) ***	0.05 (0.04, 0.07) ***
Spring	0.01 (-0.09, 0.07)	0.05 (0, 0.11) +	0.06 (0.03, 0.08) ***
Summer	0.07 (0.03, 0.12) ***	0.06 (0.03, 0.09) ***	0.08 (0.07, 0.10) ***
Autumn	0.02 (-0.05, 0.07)	0.09 (0.05, 0.12) ***	0.06 (0.05, 0.08) ***
Annual	0.01 (-0.02, 0.06)	0.07 (0.04, 0,1) ***	0,06 (0.05, 0,07) ***

Mean temperature tmean trends

The yearly trends of mean annual temperatures (Tmean) presented in Table 2 shows an overall increase from 1973 to 2023, with an average rate of 0.06 °C per year. This annual trend is highly significant ($p<0.001$), but its progression was not uniform over the entire study period (1973 – 2023). Notably, there was no noticeable change in the yearly trends of average temperatures until 1993 but then annual temperatures showed a highly significant increasing trend thereafter. A statistically non-significant warming trend was observed for the annual Tmean during the 1st climatic period (1973–1993) with a rate of 0.01 °C per year. The trend changed to a highly significant warming trend during the 2nd climatic period (1993–2023), with an average rate of 0.07 (statistically significant at $p<0.001$).

Similarly, seasonal Tmean values have increased between 1973 and 2023 in all seasons. Positive and highly significant trends were observed during winter, spring, summer and autumn with values of 0.05 °C, 0.06 °C, 0.08 °C, and 0.06 °C per year, respectively (Fig. 4).

The seasonal pattern observed for the entire study period from 1973 to 2023 differs when analyzing the two climatic periods separately. During the 1st climatic period (1973–1993), Tmean became slightly warmer in all seasons except winter. In this period, only statistically significant trend was identified in summer ($p<0.001$) with an average warming rate of 0.07 °C per year. In the 2nd climatic period (1993–2023), all seasons exhibited highly significant warming trends except spring, i.e., 0.09 °C per year ($p<0.001$) in autumn, 0.07 °C per year ($p<0.001$) in winter, and 0.06 °C per year ($p<0.001$) in summer. There was a statistically less significant warming trend in spring with an average rate of 0.05 °C ($p<0.1$) (Table 2).

The monthly analysis revealed significant changes in the mean temperature (Tmean) during the period

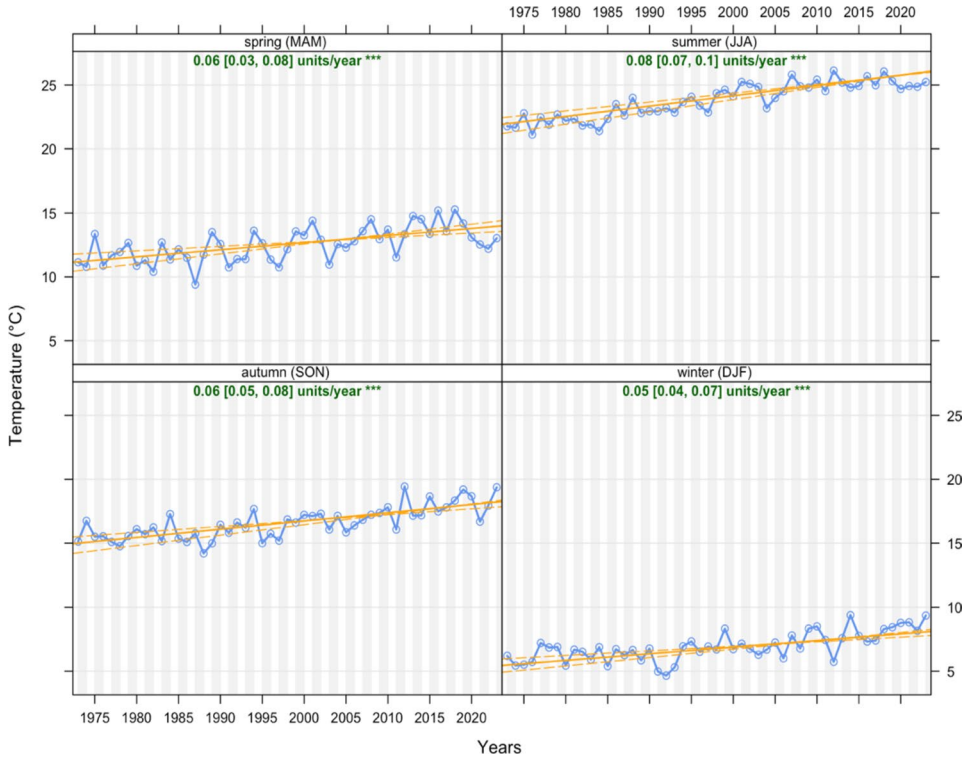

Fig. 4 Seasonal changes and trends of mean temperature for the period of 1973–2023 in İstanbul. The solid orange line shows the trend estimate and the dashed orange lines show the 95% confidence intervals for the trend. The overall trends are shown at the top as units(°C) per year and the 95% confidence intervals in the slope °C /year. The symbols show the significance levels

1973–2023. Highly significant positive Tmean trends were observed for all the months. In July, August, September, and November, there were increasing trends with rates of 0.08, 0.10, 0.07, and 0.07 degrees Celsius per year, respectively (Fig. 5).

During the first climatic period (1973–1993), there were generally non-significant warming and cooling trends. Only significant Tmean trends were observed for June (0.06 °C/year, $p<0.1$), and August (0.13 °C/year, $p<0.001$). The temperature increase in August during the first climatic period is one of the most remarkable increases in this study, because of its rate and significance in that period. In the second climatic period (1993–2023), all of the monthly Tmean trends turned positive. And all months presented significant trends except January, April and October. The highest trends were observed with various significance levels at November (0.12 °C/year, $p<0.001$), September (0.9 °C/year, $p<0.01$), March (0.9 °C/year, $p<0.1$), February (0.8 °C/year, $p<0.05$), and December (0.8 °C/year, $p<0.05$). The increasing trend that occurred in November is remarkable both in terms of its rate and significance (Table 2).

Maximum temperature tmean trends

Between 1973 and 2023, the annual maximum temperature (Tmax) has shown no significant changes (Fig. 6). The seasonal trend is important in spring, with a highly significant increase at 0.06 °C per year ($p<0.001$). In autumn (0.04 °C) and winter (0.03 °C), the rate was also positive, but less significant in both cases ($p<0.1$). No changes were detected for summer (Fig. 7).

Examining monthly Tmax values, highly significant increases were observed in May (0.06 °C, $p<0.001$) and August (0.09 °C, $p<0.001$). Positive but less significant trends were observed in January, February, September, November, and December with values of 0.04 °C ($p<0.05$), 0.05 °C per year ($p<0.05$), 0.04 °C per year ($p<0.05$), 0.07 °C per year ($p<0.05$), and 0.04 °C per year ($p<0.1$), respectively (Fig. 8).

In the first climatic period (1973–1993), the annual maximum temperatures (Tmax) experienced no significant change. Seasonally, only significant changes occurred in winter and autumn. Winter showed a Tmax decrease of -0.14 °C/y ($p<0.05$), while autumn exhibited warming at 0.01°C/y ($p<0.05$). Significant trends in terms of Tmax during this period were identified in August (0.24 °C/y, $p<0.05$) and September (0.09 °C/y, $p<0.05$). The rapid warming trend in August and cooling trend in the winter are remarkable in this period since these trends have the highest magnitudes in this study (Table 3).

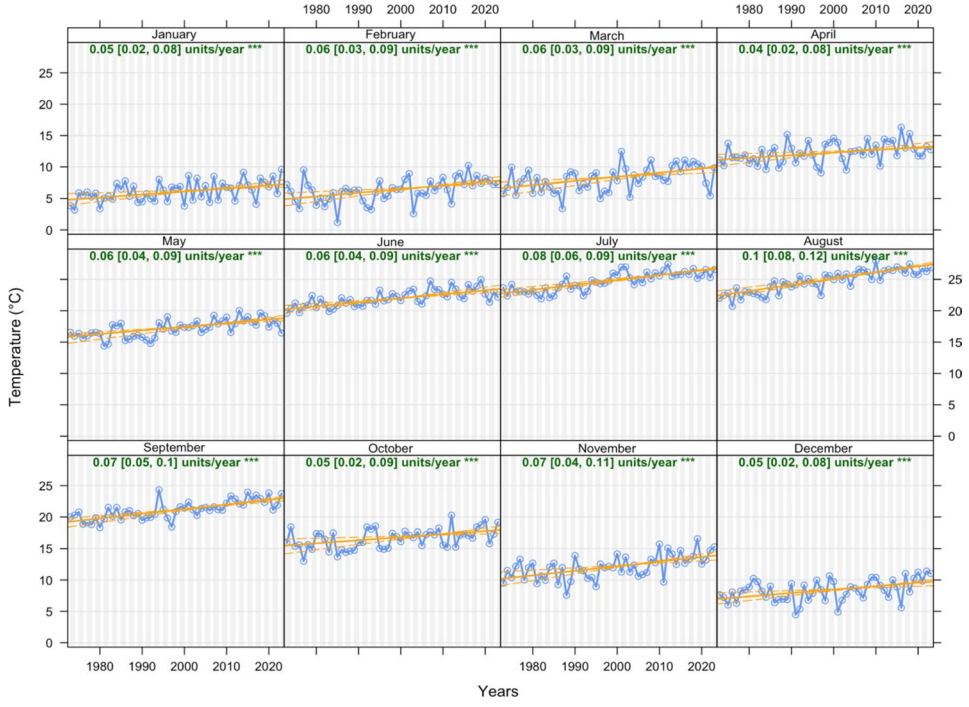

Fig. 5 Monthly changes and trends of mean temperatures for the period of 1973–2023 in İstanbul. The solid orange line shows the trend estimate and the dashed orange lines show the 95% confidence intervals for the trend. The overall trends are shown at the top as units(°C) per year and the 95% confidence intervals in the slope °C /year. The symbols show the significance levels

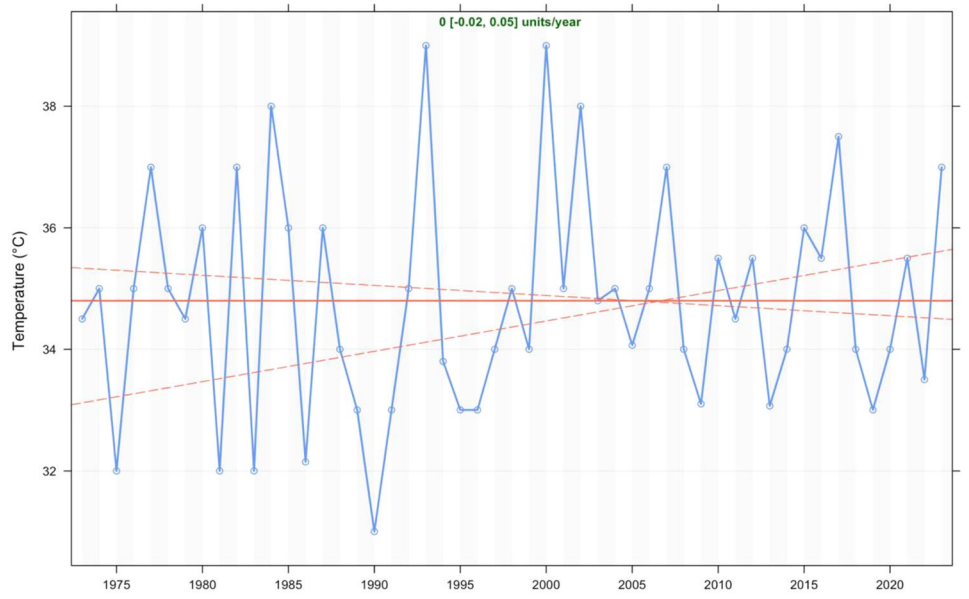

Fig. 6 Annual changes and trend of maximum temperature for the period of 1973–2023 in İstanbul. The solid red line shows the trend estimate and the dashed red lines show the 95% confidence intervals for the trend. The overall trend is shown at the top as 0 (°C) per year and the 95% confidence intervals in the slope from 0.05–0.07 °C /year

Moving to the second climatic period (1993–2023), no significant change was also identified for the annual maximum temperatures (Tmax). Seasonally, only significant trend was observed in winter. The cooling pattern changes radically after the previous climatic period (1973–1993) and a warming trend starts, which is led by a rapid increase of Tmax in winter (0.07 °C/y, $p<0.001$). On a monthly basis, positive but weakly significant ($p<0.1$) trends were observed in February, November, and December. The rapid warming trend during the first

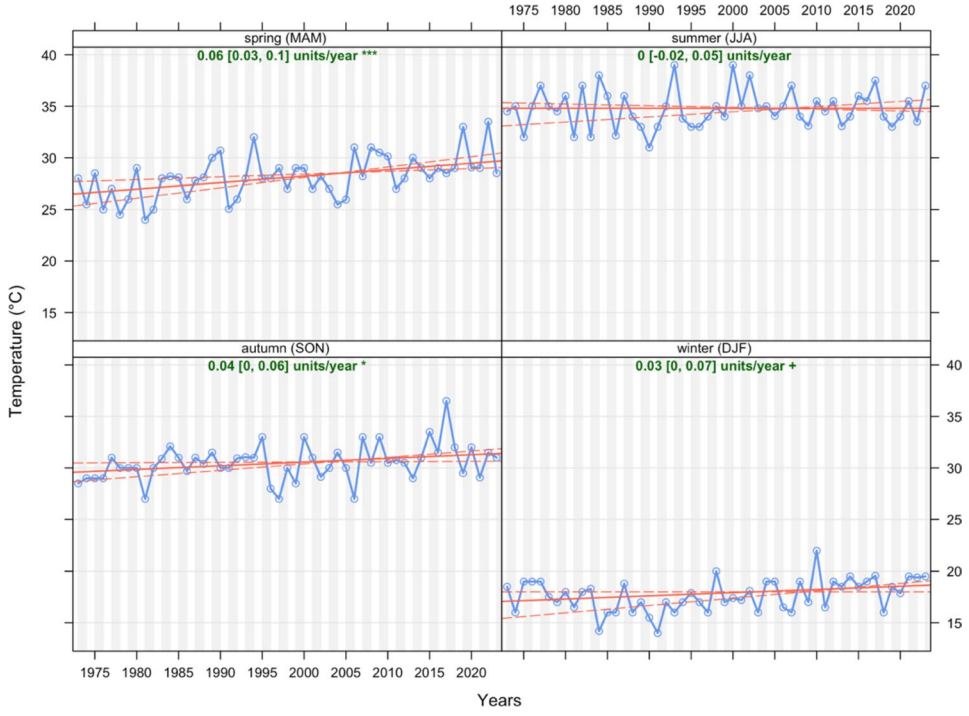

Fig. 7 Seasonal changes and trends of maximum temperature for the period of 1973–2023 in İstanbul. The solid red line shows the trend estimate and the dashed orange lines show the 95% confidence intervals for the trend. The overall trends are shown at the top as units(℃) per year and the 95% confidence intervals in the slope ℃ /year. The symbols show the significance levels

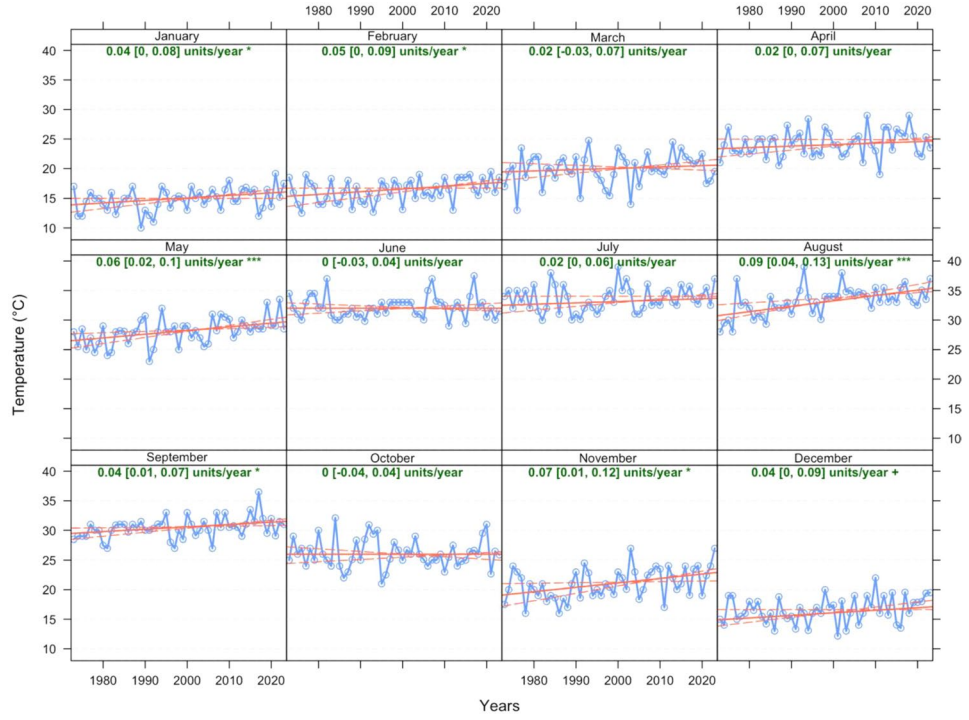

Fig. 8 Monthly changes and trends of maximum temperatures for the period of 1973–2023 in İstanbul. The solid red line shows the trend estimate and the dashed orange lines show the 95% confidence intervals for the trend. The overall trends are shown at the top as units(℃) per year and the 95% confidence intervals in the slope ℃ /year. The symbols show the significance levels

Table 3 Sen's slope Q estimates of the monthly, seasonal and annual maximum temperatures (tmax), for the time period 1973–2023 and for the two climatic periods 1973–1993 and 1993–2023 at different levels of significance. Statistically significant values are highlighted in grey and the significance level is indicated with + for a = 0.1, * for a = 0.05, ** for a = 0.01 and *** for a = 0.001

Time period	1973–1993	1993–2023	1973–2023
Trend statistics	**Q (°C/y)**	**Q (°C/y)**	**Q (°C/y)**
January	-0.11 (-0.27, 0.06)	0.03 (-0.04, 0.11)	0.04 (0, 0.08) *
February	-0.10 (-0.25, 0.05)	0.06 (0, 0.14) +	0.05 (0, 0.09) *
March	0.11 (-0.12, 0.33)	0.05 (-0.07, 0.17)	0.02 (-0.03, 0.07)
April	0.06 (-0.08, 0.22)	0.03 (-0.09, 0.14)	0.02 (0, 0.07)
May	0.05 (-0.11, 0.3)	0.04 (0, 0.17)	0.06 (0.02, 0.1) ***
June	-0.08 (-0.22, 0)	0 (-0.06, 0.03)	0 (-0.03, 0.04)
July	-0.11 (-0.24, 0)	0.05 (-0.02, 0.12)	0.02 (0, 0.06)
August	0.24 (0.02, 0.4) *	0.01 (-0.07, 0.12)	0.09 (0.04, 0.13) ***
September	0.09 (0, 0.17) *	0.05 (-0.02, 0.15)	0.04 (0.01, 0.07) *
October	0.01 (-0.25, 0.25)	0 (-0.12, 0.13)	0 (-0.04, 0.04)
November	0 (-0.4, 0.27)	0.09 (0, 0.2) +	0.07 (0.01, 0.12) *
December	-0.01 (-0.22, 0.08)	0.08 (0, 0.17) +	0.04 (0, 0.09) +
Season			
Winter	-0.14 (-0.25, -0.02) *	0.07 (0.02, 0.11) *	0.03 (0, 0.07) +
Spring	0.09 (-0.03, 0.28)	0.04 (0, 0.15)	0.06 (0.03, 0.1) ***
Summer	0 (-0.17, 0.18)	0 (-0.08, 0.08)	0 (-0,02 0.05)
Autumn	0.1 (0, 0.17) *	0.05 (-0.02, 0.15)	0.04 (0, 0.06) *
Annual	0 (-0.17, 0.18)	0 (-0.08, 0,08)	0 (-0.02, 0,05)

period in August ceased to exist in the second period (Table 3).

Minimum temperature tmin trends

The trend analysis shows a statistically non-significant increase in yearly average Tmin over the past 51 years (1973–2023), with a rate of 0.04 °C per year, as indicated in Fig. 9. The seasonal trend is important in summer, with a highly significant ($p<0.001$) increase at 0.11 °C per year. In autumn (0.05 °C) and spring (0.05 °C), the rate was also positive, but less significant in both of them ($p<0.05$ and $p<0.1$). A positive trend was also detected for winter (0.04 °C), but it was statistically non-significant (Fig. 10). Monthly Tmin values, from February to November, exhibit a significant increase, with June (0.11 °C per year), July (0.09 °C per year), and August (0.11 °C per year) showing higher increasing values (Fig. 11).

The changes in Tmin are primarily concentrated in the second climatic period (1993–2023), with no significant trends detected in the earlier period (1973–1993), except for May, which recorded an important decrease of -0.12 °C per year ($p<0.1$). In the second climatic period, there is a non-significant cooling trend in annual Tmin at a rate of -0.01 °C per year. Throughout the 1993–2023 period, significant warming rates range from 0.10 °C per year ($p<0.001$) in summer to 0.11 °C per year ($p<0.05$) in autumn. On a monthly basis, June, August and November exhibit significant warming trends, with changing rates ranging from 0.06 °C per year in August ($p<0.01$) to 0.1 °C in June ($p<0.05$) and 0.11 °C in November

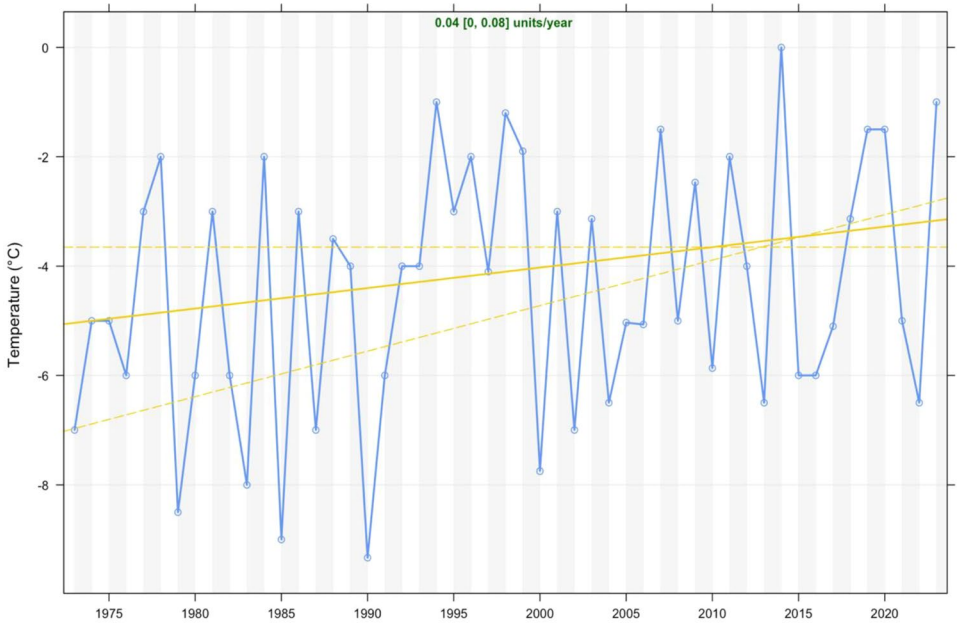

Fig. 9 Annual changes and trend of minimum temperature for the period of 1973–2023 in İstanbul. The solid yellow line shows the trend estimate and the dashed yellow lines show the 95% confidence intervals for the trend. The overall trend is shown at the top as 0.04 (°C) per year and the 95% confidence intervals in the slope from 0–0.08 °C /year. The trend is not statistically significant

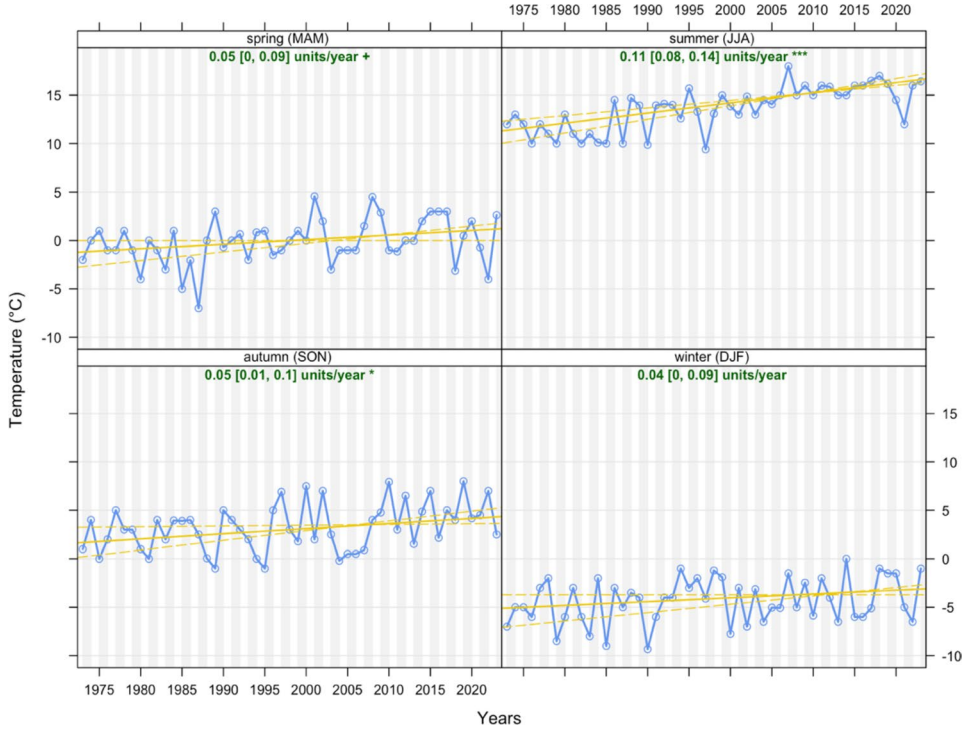

Fig. 10 Seasonal changes and trends of minimum temperature for the period of 1973–2023 in İstanbul. The solid yellow line shows the trend estimate and the dashed orange lines show the 95% confidence intervals for the trend. The overall trends are shown at the top as units(°C) per year and the 95% confidence intervals in the slope °C /year. The symbols show the significance levels

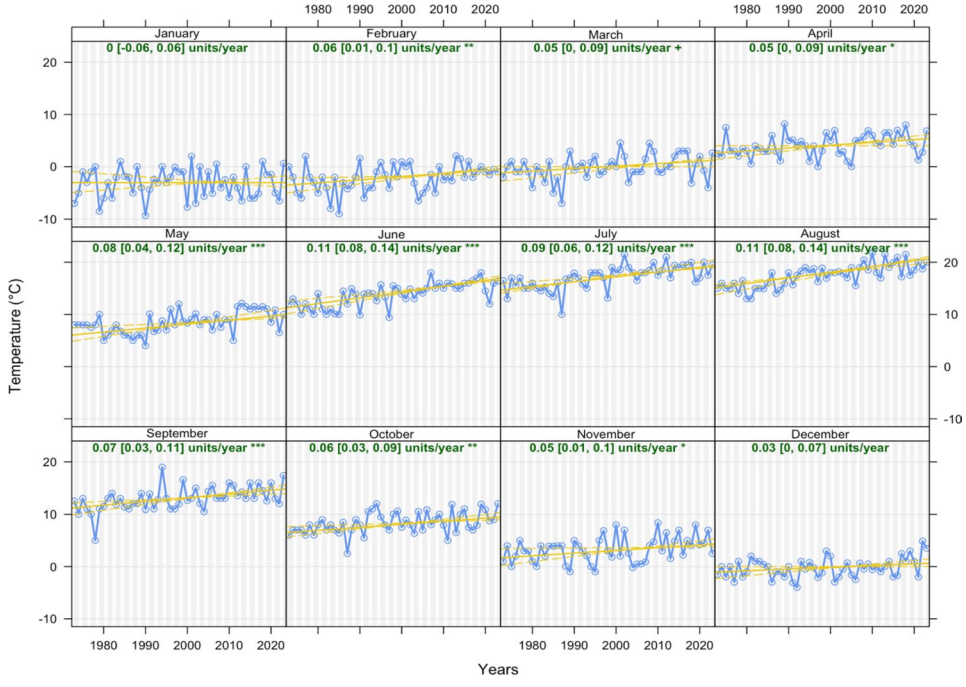

Fig. 11 Monthly changes and trends of minimum temperatures for the period of 1973–2023 in İstanbul. The solid yellow line shows the trend estimate and the dashed orange lines show the 95% confidence intervals for the trend. The overall trends are shown at the top as units(°C) per year and the 95% confidence intervals in the slope °C /year. The symbols show the significance levels

($p<0.05$). The increasing trends in June and November is noteworthy in this period (Table 4).

Another important point is that, minimum temperatures of winter season have never increased significantly in any period. On a monthly basis, only significant increase occurred in February (0.06 °C/y, $p<0.05$) between 1973 and 2023 (Table 4).

Discussion

The findings of this study indicate a significant rise in the mean air temperature (Tmean) of synoptic weather station in İstanbul Atatürk Airport over the past 51 years (1973–2023), with an annual warming trend of 0.06 °C. Tmean values have increased significantly in all seasons and all months between 1973 and 2023. The most pronounced increase in seasonal mean air temperatures has been recorded during the summer season, showing a rise of 0.08 °C per year over the past 51 years. Minimum and maximum temperatures did not change at the same rate. There was a statistically non-significant increase in annual minimum temperature (Tmin) over the past 51 years (1973–2023), with a rate of 0.04 °C per year. And the annual maximum temperature (Tmax) trend has shown no changes between 1973 and 2023. Seasonally, the highest and most significant Tmax increase occurred in spring season (0.06 °C/y) and the highest and most significant Tmin increase occurred in summer season (0.11 °C/y).

The temperature trends did not follow a uniform pattern throughout the entire 51-year period. In the initial climatic period (1973–1993), there was a statistically non-significant increase in the average air temperature (0.01 °C/y), but after 1993, the trend shifted to a highly significant trend, leading to rapid warming conditions (0.07 °C/y) that persist to the present time. Therefore, it can be said that İstanbul's climate has become significantly hotter after 1993. The temperature increase that occurred after the 1990s is a situation observed worldwide. According to World Meteorological Organization (WMO), every decade since the 1990s has been hotter than all the decades preceding it globally (WMO 2022).

Other studies also showed the warming temperature trends in İstanbul and Türkiye and revealed the significant increase of air temperature after 1993. In a study conducted in İstanbul, the examination of temperature time series data from the Kandilli Meteorological Station spanning 1912 to 2016 reveals a noticeable rise in the temperature values post the 1940s. Over the course of the last century, there has been an elevation of approximately 0.94 °C in the daily average temperature series. There was a cool period from 1969 to 1993, followed by a notable upward trend in average annual temperature at a 95% confidence level. The most substantial increase in seasonal daily average temperatures between 1912 and 2016 occurred during the summer months (Toros et al. 2017). For the same meteorological station, there was a notable decreasing trend in the number of cold days and cold nights, with decreases of -0.96 and −1.04 days per decade between 1912 and 2021. Conversely, warm days and warm nights showed a significant increasing trend, with increments of +0.44 and +0.58 days per decade, respectively. (Yurtseven 2023). Ciftci and Sahin (2023) found that summer is the season with the highest temperature increase in Türkiye between 1990 and 2019 according to extreme temperature indices (Ciftci and Sahin 2023).

Hadi and Tombul analyzed the annual and seasonal trends of air temperature over Türkiye between 1901 and 2014 by using 81 grids, with each grid representing a province. All provinces have an increasing temperature trend except for one grid, Bingöl, located in eastern Türkiye. The Theil−Sen slope estimator value was 0.88 °C/century, which was statistically significant. Using the Pettit−Mann−Whitney test, the most probable change year for temperature is identified as 1993 which is repeated in 46 grids including İstanbul (Hadi and Tombul 2018). According to the temperature analysis made by the Ministry of Environment and Urbanization of Türkiye, there have been positive temperature anomalies in Türkiye since 1994 (except 1997 and 2011) (MEUC 2021).

Table 4 Sen's slope Q estimates of the monthly, seasonal and annual minimum temperature (tmin), for the time period 1973–2023 and for the two climatic periods 1973–1993 and 1993–2023 at different levels of significance. Statistically significant values are highlighted in grey and the significance level is indicated with + for a = 0.1, * for a = 0.05, ** for a = 0.01 and *** for a = 0.001

Time period	1973–1993	1993–2023	1973–2023
Trend statistics	**Q (°C/y)**	**Q (°C/y)**	**Q (°C/y)**
January	0 (-0.17, 0.24)	-0.04 (-0.18, 0.07)	0 (-0.06, 0.06)
February	-0.09 (-0.25, 0.14)	0.04 (-0.03, 0.12)	0.06 (0.01, 0.1) **
March	0 (-0.17, 0.13)	0.03 (-0.07, 0.11)	0.05 (0, 0.09) +
April	0.11 (-0.01, 0.18)	0.07 (-0.03, 0.17)	0.05 (0, 0.09) *
May	-0.12 (-0.2, 0) +	0.08 (-0.02, 0.14)	0.08 (0.04, 0.12) ***
June	0.06 (-0.07, 0.24)	0.10 (0.03, 0.16) **	0.11 (0.08, 0.14) ***
July	0 (-0.19, 0.19)	0.06 (0, 0.12)	0.09 (0.06, 0.12) ***
August	0.1 (0, 0.25)	0.06 (0, 0.11) *	0.11 (0.08, 0.14) ***
September	0.07 (-0.03, 0.19)	0.05 (-0.03, 0.16)	0.07 (0.01, 0.11) ***
October	0.11 (-0.03, 0.22)	0 (-0.09, 0.09)	0.06 (0.03, 0.09) **
November	0 (-0.12, 0.18)	0.11 (0, 0.22) *	0.05 (0.01, 0.1) *
December	-0.03 (-0.25, 0.07)	0.06 (-0.03, 0.18)	0.03 (0, 0.07)
Season			
Winter	0 (-0.14, 0.14)	0 (-0.12, 0.1)	0.04 (0, 0.09)
Spring	0 (-0.17, 0.13)	0.04 (-0.07, 0.12)	0.05 (0, 0.09) +
Summer	0 (-0.11, 0.20)	0.10 (0.04, 0.15) ***	0.11 (0.08, 0.14) ***
Autumn	0 (-0.13, 0.17)	0.11 (0.01, 0.21) *	0.05 (0.01, 0.1) *
Annual	0 (-0.15, 0.14)	-0.01 (-0.12, 0.09)	0.04 (0, 0.08)

Güler and Erlat (2023) analyzed the changes and trends observed in the mean air temperatures in Türkiye during the period of 1950–2022 using ERA5-Land data. The highest annual average air temperatures measured in Türkiye in the last 73 years observed after 2005, except for the year of 2011. They also found that annual average temperatures in Türkiye have shown a significant increase since 1994 (Güler and Erlat 2023).

There is an interesting study which utilized one of the oldest meteorological measurements made in İstanbul and Türkiye. This study recovered and used the daily weather observations measured at Halkalı Agricultural School (a school opened in 1892 on agriculture and animal husbandry during the Ottoman period) from 1897 to 1917 in İstanbul. The school was located very close (12 km) to the meteorological station whose data used in this study. The average temperature was 14.2 °C in Halkalı from 1897 to 1917. As it can be seen, the average temperature during the Ottoman period is almost the same to the average temperature of the first period (1973–1993) in this study (14 °C). When seasonal temperatures are compared, it has been revealed that the seasonal temperatures of these two periods are also very similar. In the Ottoman Period (1897–1917), the seasonal mean (T_{mean}, T_{max}, and T_{min}) temperatures were: 6.1 (-5.9, 17.1) in winter, 12.2 (-1.8, 29.6) in spring, 22.5 (10.2, 36.1) in summer, and 15.9 (1.5, 31.8) in autumn, respectively. During the first climatic period (1973–1993) in this study, all seasons exhibited similarity, i.e., 6.1 (-5.2, 16.8) in winter, 11.6 (-1.1, 27.1) in spring, 22.4 (11.9, 34.6) in summer, and 15.7 (2.5, 30.1) in autumn, respectively (Yilmaz et al. 2023). The annual average temperature value of İstanbul Atatürk meteorological station in 2018 (17.0 °C) was 2.8 °C hotter than the average temperature of İstanbul's pre-industrial period (14.2 °C).

Europe is experiencing a more rapid warming trend compared to the global average. In the last decade, the mean annual temperature over European land areas were 2.04 to 2.10 °C warmer than during the pre-industrial era. In 2020, Europe recorded its warmest year since instrumental records began, with anomalies ranging between 2.53 °C and 2.71 °C above pre-industrial levels, according to all datasets utilized. (European Environment Agency 2023). For an example, despite being a mountainous and landlocked country in Central Europe, Switzerland's mean temperature of last ten years (2014–2023) was 2.7 °C above the pre-industrial average. 2022 and 2023 were the warmest years with a deviation of 3.5 and 3.4 °C from the pre-industrial mean of 1871–1900 (MeteoSwiss 2024). Increasing temperature trends have been also reported in Mediterranean countries. Bey et al. (2024) found a significant increase (0.38 °C decade^{-1}) in the mean temperature trend in Norther Cyprus between 1975 and 2021. Sakalis (2024) identified increase of mean annual warming trend by 0.047 °C, for Greece and Lebanon between 1990 and 2021 (Sakalis 2024). Faquseh and Grossi (2024) noted an increasing and significant trend of yearly average temperature in Lombardy - Northern Italy, around 0.04 °C per year from 1990 to 2020 (Faquseh and Grossi, 2020). In a study conducted in the Paris region of France, there was an increase of 1.6 °C for Tmean (0.4 °C per decade), 1.9 °C for Tmax (0.47 °C per decade) and 1.5 °C for Tmin (0.37 °C per decade) from 1979 to 2017 (Ringard et al. 2019). Statistically significant warming trends in the mean annual temperature was found at the Ričice (0.0387 °C) and Imotski (0.0437 °C) stations between 1993 and 2021 in Croatia (Vrsalović et al. 2023). Di Bernardino et al. (2022) found statistically significant positive trend for average air temperature (0.07 °C per year in urban areas), while maximum and minimum temperatures increase more (0.10 °C per year) in Rome between 2000 and 2020 (Di Bernardino et al. 2022). Yilmaz (2023) used ground station-based observations between 1951 and 2020 which included datasets obtained over 540 stations over the entire Türkiye. The trends over all stations identified were 0.3 °C/decade and 0.82 °C/decade over the entire country for the years 1951–2020 and 2001–2020, respectively (Yilmaz 2023). The decadal trend value of İstanbul Atatürk weather station in this study between 2001 and 2020 was 0.8 °C which is similar to Türkiye's overall trend for the same period (0.82 °C).

Conclusion

In summary, the analyses of temperature trend evolution of synoptic weather station in İstanbul Atatürk Airport between 1973 and 2023 identified the rapid warming trend in İstanbul which is consistent with other studies conducted in Türkiye. These findings enabled the identification of a warming period, beginning in the 1990s and the influence of climate change is evident in seasonal and monthly trends. To understand why the warming in Turkey differs from the global average, investigations into various factors such as changes in rainfall, sea surface temperature, and socioeconomics are needed. Further analyses are required to determine the contribution of these different factors and fully comprehend the observed temperature patterns.

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Author contributions
Ö.Ç. made the conceptualization and formal analysis, wrote the main manuscript text and prepared the figures and the tables.

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

Declarations

Competing interests
The authors declare no competing interests.

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