

2024: The year with too much summer in the eastern part of Europe

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Introduction

The year 2024 was unexpectedly warm, exceeding climate model predictions by a significant margin, with January–December 2024 global mean surface air temperature being $1.60 \pm 0.13^\circ\text{C}$ above the pre-industrial average. Over a span of 16 consecutive months (June 2023 to September 2024), the global mean temperatures consistently surpassed all previous records (Ripple *et al.*, 2024). According to the Copernicus Climate Change Service, in summer 2024 a global mean temperature of 16.8°C was recorded ($+0.03^\circ\text{C}$ warmer than the old record in 2023). At the European level, the 2024 summer mean temperature was the highest on record, with a temperature anomaly of $+1.54^\circ\text{C}$ (relative to the climatological mean over the period 1991–2020) and exceeding the previous record from 2022 ($+1.34^\circ\text{C}$). The extreme temperature anomalies in 2024 came after 2023 has been considered one of the most difficult years to understand from a climatic point of view. In a recent paper, Schmidt (2024) argued that the observed temperature spike in 2023 could not be fully explained either by natural climate variability or anthropogenic factors (e.g. the influence of El Niño, reduced sulphur emissions from cleaner shipping fuels, the aftermath of the Hunga Tonga–Hunga Ha’apai volcanic eruption and/or a spike in solar activity). This lack of knowledge and understanding of the 2023 and 2024 warming levels highlights a knowledge gap in our understanding of the climate system and raises concerns about the potential for more rapid climate change than previously anticipated.

Eastern Europe, which is usually characterised by a temperate climate, is now facing an escalating crisis of increasingly frequent and intense heatwaves (Nagavciuc *et al.*, 2022; Luo *et al.*, 2023; Ionita *et al.*, 2024). These

extreme weather events threaten human health, ecosystems, and vital infrastructure (Feng *et al.*, 2020; Benz and Burney, 2021; Malik *et al.*, 2022). The primary driver behind this concerning trend is climate change, fuelled by human activities such as greenhouse gas emissions, and compounded by natural variability (Miralles *et al.*, 2019; Vautard *et al.*, 2019; IPCC, 2021). The resulting rise in global temperatures creates conditions conducive to the formation and persistence of high-pressure systems, leading to stagnant air masses that intensify heat and drought (Bakke *et al.*, 2023; Faranda *et al.*, 2023). Additionally, regional factors such as shifts in atmospheric and oceanic circulation, coupled with land-use practices, further contribute to this growing problem (Horton *et al.*, 2015; Dima *et al.*, 2021; Ionita *et al.*, 2021; Bakke *et al.*, 2023; Ma *et al.*, 2024). The consequences of prolonged heatwaves are extensive and intricate, necessitating immediate action and mitigation strategies. The most direct impact is on human health, with elevated risks of heatstroke, dehydration and cardiovascular issues, particularly for vulnerable populations like the elderly and young children (Bosch, 2003; Antonescu *et al.*, 2021; Vicedo-Cabrera *et al.*, 2021). Furthermore, heatwaves disrupt agricultural activities, jeopardise food security, worsen drought conditions, strain water resources and heighten the risk of wildfires (EEA and Fussler, 2017; Zscheischler and Seneviratne, 2017; Zscheischler *et al.*, 2018; Bakke *et al.*, 2020; Ionita and Nagavciuc, 2020).

The 2024 heatwave surpassed previous events in its severity and duration, impacting especially the eastern part of Europe, with a focus on Romania, Bulgaria, Hungary and Ukraine (Copernicus Climate Change Service, 2024a). This paper aims to provide a comprehensive analysis of the 2024 Eastern European heatwave, focusing on a long-term dataset (1885–2024) at Bucuresti Filaret station in Romania). The utilisation of long-term meteorological records, spanning more than 100 years, is of paramount importance in the analysis of extreme events and their variability and trends (Hawkins *et al.*, 2022; Yule *et al.*, 2023; Ionita *et al.*, 2024). The Earth’s climate system is characterised by complex, long-term cycles and fluctuations that can only be adequately captured and understood through extensive historical

data. Shorter datasets may not encompass the full range of natural climate variability, potentially leading to misinterpretations of trends and an underestimation of the true frequency and intensity of extreme events (Hegerl *et al.*, 2019; Hawkins *et al.*, 2022). Through a synthesis of this long-term observational data, this study seeks to enhance our understanding of the long-term evolution of extreme temperatures, which in turn can contribute to the development of effective strategies for mitigating and adapting to the growing threat of heatwaves in a warming world. Moreover, by employing a tool for attribution of extreme events to climate change (Rantanen *et al.*, 2024), we aim to analyse if such temperature anomalies like the ones recorded throughout the summer of 2024, could have been possible without the contribution of climate change.

Data and methods

In this study, we focused on one of the longest meteorological records in the eastern part of Europe, namely at Bucuresti Filaret meteorological station. In addition to some publicly available data, for this study we have also digitised daily meteorological records from the yearly meteorological books of the Romanian Meteorological Institute, data which have never been published until now (Hepites, 1899). We have extended the daily meteorological records for the maximum daily temperature by 31 years and 3 months (1 January 1885–31 March 1916). Moreover, we also digitised extreme events (daily maximum temperature $\geq 30^\circ\text{C}$, TX30) recorded at Bucuresti Filaret station from 1885 until 1929 (Constantin, 1933), which allowed us to have a complete record for TX30 from 1885 until 2024. Additional to the daily maximum temperatures, we also make use of monthly mean temperature and precipitation at Bucuresti Filaret covering an even longer period, namely 1857–2024. For the large-scale daily maximum temperature, we made use of the ERA5 dataset (Hersbach *et al.*, 2020).

Heatwaves are commonly defined in two ways: either by using a threshold relative to local temperatures, or by looking for days exceeding a specific temperature, often 30°C (Robinson, 2001; Perkins, 2015). In our research, we utilised both of these methods. For the threshold-based method, we used

the 90th percentile of daily maximum temperatures within a 15-day window around each calendar day (Perkins and Alexander, 2013). We also used the fixed absolute method to count the number of days with the daily maximum temperature $\geq 30^{\circ}\text{C}$, $\geq 35^{\circ}\text{C}$ (TX35) and $\geq 40^{\circ}\text{C}$ (TX40), respectively. We considered different heatwave durations (3–6 consecutive days) for the threshold-based method and ultimately selected a 5-day period for our analysis. Our thresholds are consistent with the guidelines provided by the Expert Team on Climate Change Detection and Indices (ETCCDI) and they enable us to concentrate on analysing heatwaves that are particularly severe and have the potential to cause substantial harm. All the anomalies in this study were calculated against the 1970–2000 period.

Results

Summer 2024 heatwaves at Bucuresti Filaret

The summer of 2024 was characterised by an unrelenting sequence of extreme heatwave events that induced significant thermal stress across extensive regions of Europe, with particularly pronounced impacts observed in the eastern part of the continent (Copernicus Climate Change Service, 2024b). Temperatures exhibited substantial positive anomalies, frequently exceeding 35°C , and these conditions endured for multiple weeks, amplifying the strain on both natural and anthropogenic systems. This unprecedented thermal event extended its influence across a substantial swathe of Eastern Europe, encompassing not only Romania and Ukraine but also Bulgaria and portions of Russia (Copernicus Climate Change Service, 2024b).

Between the end of May and the end of August 2024, Romania experienced prolonged and intense heatwave conditions, with 63 days meeting the established heatwave criteria (see the 'Data and methods' section for the HW definition). Daily meteorological records from the Bucuresti Filaret meteorological station indicate four distinct heatwaves during this period. The initial heatwave spanned from 31 May 2024 until 13 June 2024, lasting 14 days with a cumulative intensity (i.e. the sum of the daily temperature anomalies over the duration of the heatwave, CI) of 114.04°C . The second heatwave occurred between 17 June 2024 and 2 July 2024, and exhibited a cumulative intensity of 115.34°C over 16 days. The third heatwave, lasting from 6 July 2024 until 21 July 2024, was the most intense, with a cumulative intensity of 152.02°C over 16 days. This cumulative intensity for the third heatwave is unprecedented in the observational record of the past 130 years, highlighting the exceptional nature of this heatwave

event. Lastly, the fourth event lasted from 11 August 2024 until 27 August 2024, with a cumulative intensity of 143.62°C and a duration of 17 days.

The first HW event was mainly focused on the southeastern part of Europe (Figure 1b), where the maximum daily temperature anomalies, especially over Greece, Bulgaria, the south-eastern part of Romania and large parts of Ukraine, reached values up to 10°C . The next three HW events had a similar spatial structure (Figures 1c–e), the most affected regions being the ones in the eastern part of Europe, where daily maximum temperature anomalies up to 10°C were recorded throughout the duration of the HW. The HW event between 6 July 2024 and 21 July 2024 had the highest magnitude over Romania, Moldova and the western part

of Ukraine. This was also the most intense event recorded at Bucuresti Filaret, where between 8 July 2024 and 19 July 2024, the daily maximum temperature broke all previous records (Figure 1a). On 16 July 2024, daily maximum temperatures above 40°C were recorded at 24 meteorological stations in the Romanian meteorological network, and on 17 July daily maximum temperatures above 40°C were recorded at 17 meteorological stations. Between 1 July 2024 and 18 July 2024, the monthly absolute maximum temperature was equaled or exceeded at 26 meteorological stations (e.g. Botoşani: $+39.4^{\circ}\text{C}$, Holod: $+40.0^{\circ}\text{C}$, Târgu Mureş: $+39.0^{\circ}\text{C}$). Excessive heat also reached mountain areas, where extremely high temperatures were recorded, e.g. Brasov (534.3m) at $+36.6^{\circ}\text{C}$ and Predeal (1090m) at $+31.4^{\circ}\text{C}$.

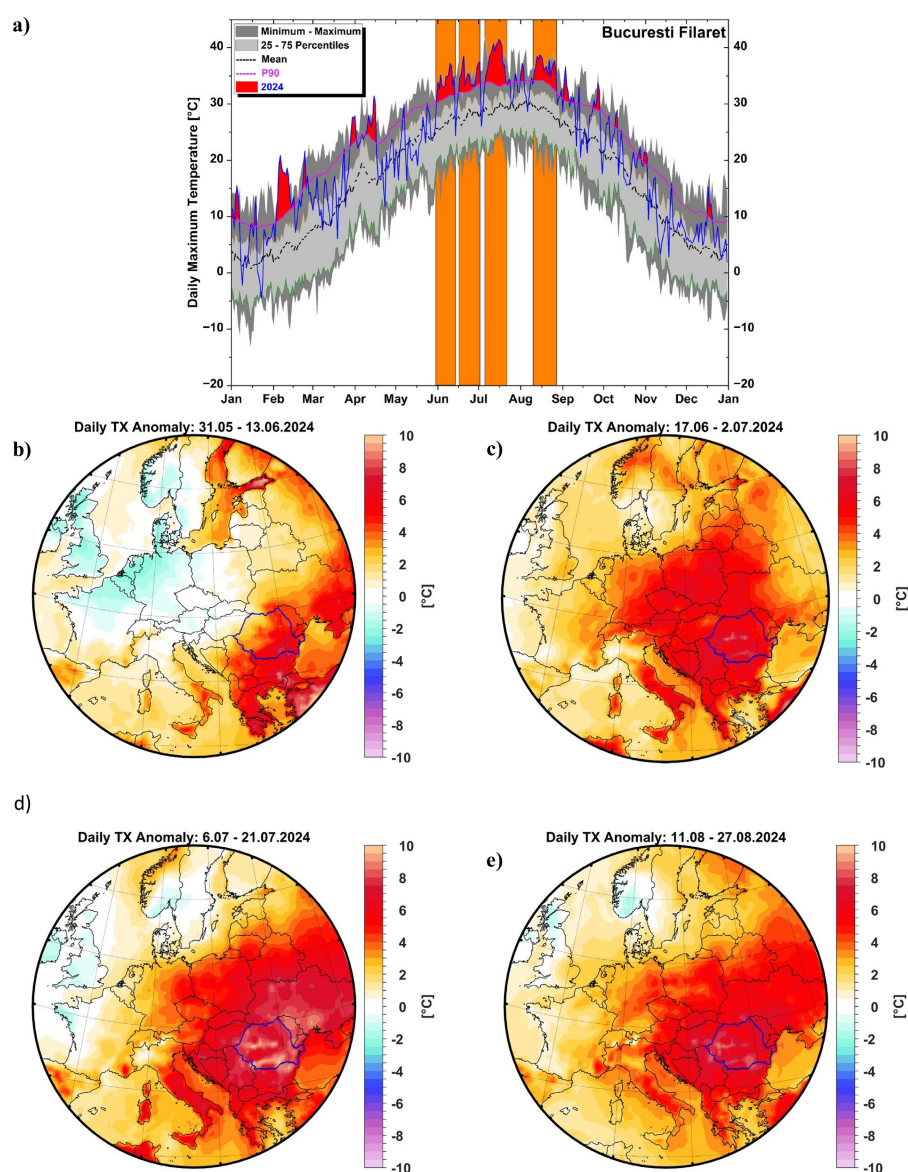


Figure 1. (a) Daily maximum temperature at Bucuresti Filaret meteorological station for the year 2024; (b) daily maximum temperature anomaly, at European level, for the period 31 May–13 June 2024 (HW1); (c) daily maximum temperature anomaly, at European level, for the period 17 June–2 July 2024 (HW2); (d) daily maximum temperature anomaly, at European level, for the period 6–21 July 2024 (HW3) and (e) daily maximum temperature anomaly, at European level, for the period 11–27 August 2024 (HW4). The period 1971–2000 was used to compute the daily maximum temperature climatology.

Long-term perspective of the 2024 HWs

In order to put the 2024 HWs into a long-term perspective, in this sub-section we examine the temporal evolution of the extreme summer temperatures at Bucuresti Filaret (Figures 2 and 3). Figure 2 shows the cumulative intensity of the summer HWs for each year, defined as the sum of the daily maximum temperature anomalies throughout the duration of a HW event and summed also for all the HWs recorded during a year (Figure 2a), the temporal evolution of the number of days per year that meet the heatwave condition (for the definition of heatwaves, see ‘Data and methods’ section, Figure 2b) and the actual number of heatwaves per year (Figure 2c). When looking at the entire analysed period of 1885–2024, a statistically significant trend has been observed for both CI (+88.8°C) and the duration (+11.4 days). In addition to the significant increasing trend in both the CI and the duration, the long-term view of the temporal evolution reveals multi-decadal fluctuations. Two periods stand out: 1930–1960 and 1980 onwards are both marked by an increase in summer day frequency. Nevertheless, when considering only the period 1980–2024, the magnitude of the increase is more than double compared to the period 1930–1960 for both CI (+210.8°C) as well as for the duration of the HW (+27.3 days). Overall, summer 2024 stands out as the most extreme one, with a cumulative intensity of +522°C and an overall duration of 63 days. Throughout the summer of 2024, 63 days out of 92 (i.e. 68% of the time), were HW days. The second most intense summer in terms of HWs was the summer of 1946, with a CI of 251.9°C (i.e. ~half of the CI of summer 2024) and a duration of 37 days. In terms of frequency, over the period 1930–1960 there were 30 HWs, the highest number being recorded in 1946 (5 HW events throughout the summer of 1946). Over the period 1980–2024, the number of summer HWs has also increased compared to the period 1930–1960 (59 events, ~1.3 events/year vs. 30 events, ~1 event/year). In 2012 and 2022 there were five HW events, while in summer 2024 four HW events have been recorded. It is worth mentioning that although in the summer of 2024 we had only four events, their characteristics (i.e. duration and intensity) are unprecedented over the last 140 years. This highlights the limitations of using the number of heatwaves as a statistic. As temperatures rise, individual heatwave events often merge into prolonged periods of extreme heat, leading to a reduction in the counted number of distinct heatwaves despite overall warming.

To gain a deeper understanding of extreme events, we examined the temporal evolution of the number of days with daily maximum temperatures exceeding 30°C (TX30), 35°C

(TX35) and 40°C (TX40) during the summer season (Figure 3). Our analysis revealed a statistically significant increase in the number of days exceeding each temperature threshold (Figure 3). For TX30 (Figure 3a), we observed a statistically significant increase of approximately 16.2 days over the period 1885–2024. When focusing on the period 1980–2024, the increase is even more pronounced, reaching approximately 44.4 days (a threefold increase compared to the entire observational record). A similar trend was observed for the number of days with daily maximum temperatures exceeding 35°C (Figure 3b). Over the entire available record, we found an increase in the number of TX35 days of approximately 8.7 days. However,

during the period 1980–2024, the increase escalated to 24.4 days. Due to the limited number of days with TX40, a trend analysis was not feasible. However, it is noteworthy that the summer of 2024 marked the first instance in the observational record with 6 days surpassing daily maximum temperatures $\geq 40^{\circ}\text{C}$ (Figure 3c).

Long-term evolution of the summer mean temperature at Bucuresti Filaret

The Bucuresti Filaret station, possessing one of the longest monthly meteorological records in Romania (spanning from

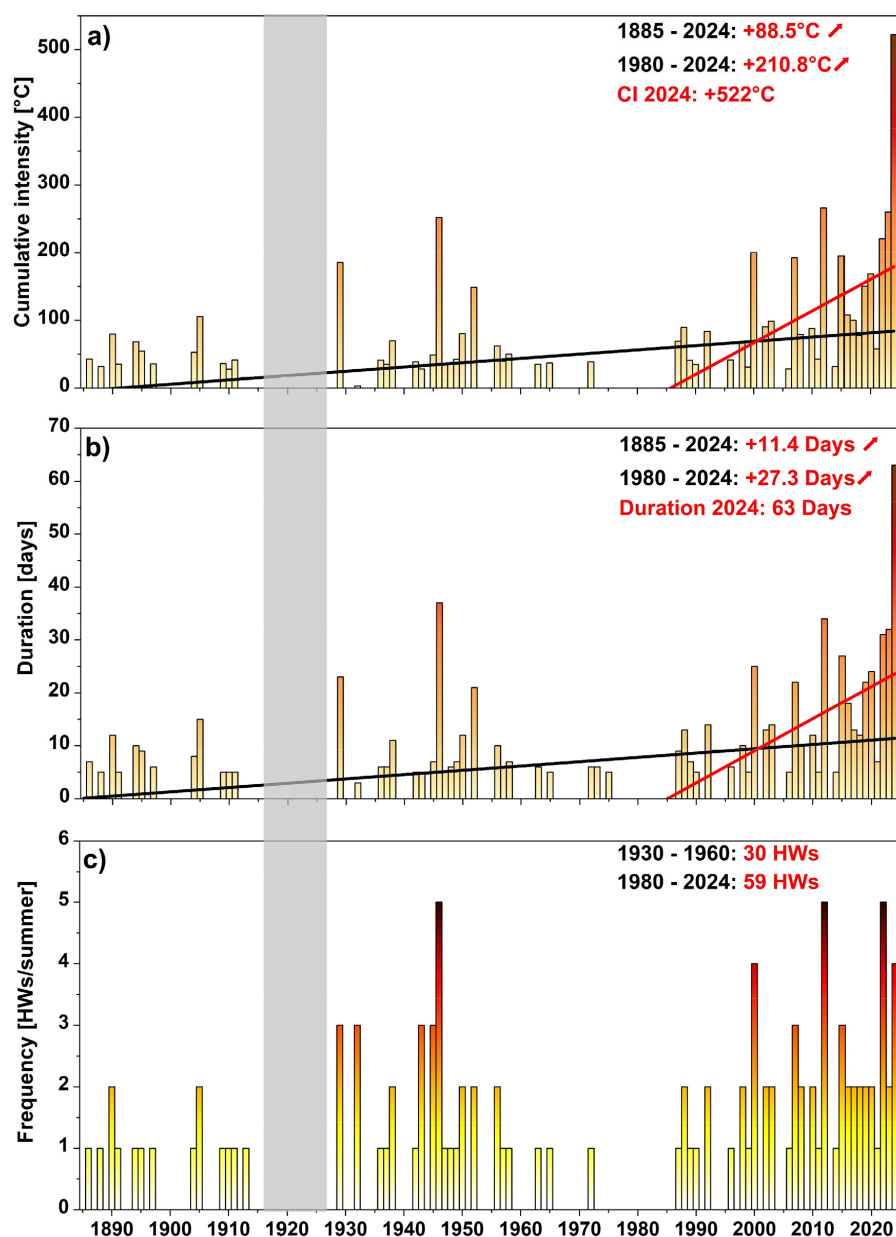


Figure 2. (a) The cumulative intensity (i.e. the sum of the daily maximum temperature anomaly throughout the duration of a HW) for the heatwave events recorded throughout the summer months (June–July–August) and the linear trend over the period 1885–2024 (black line) and over the period 1980–2024 (red line); (b) same as in (a) but for the duration of the HW events and (c) the frequency of HW events for each year over the period 1885–2024. The grey shaded area indicates a period for which no data were available (1916–1928).

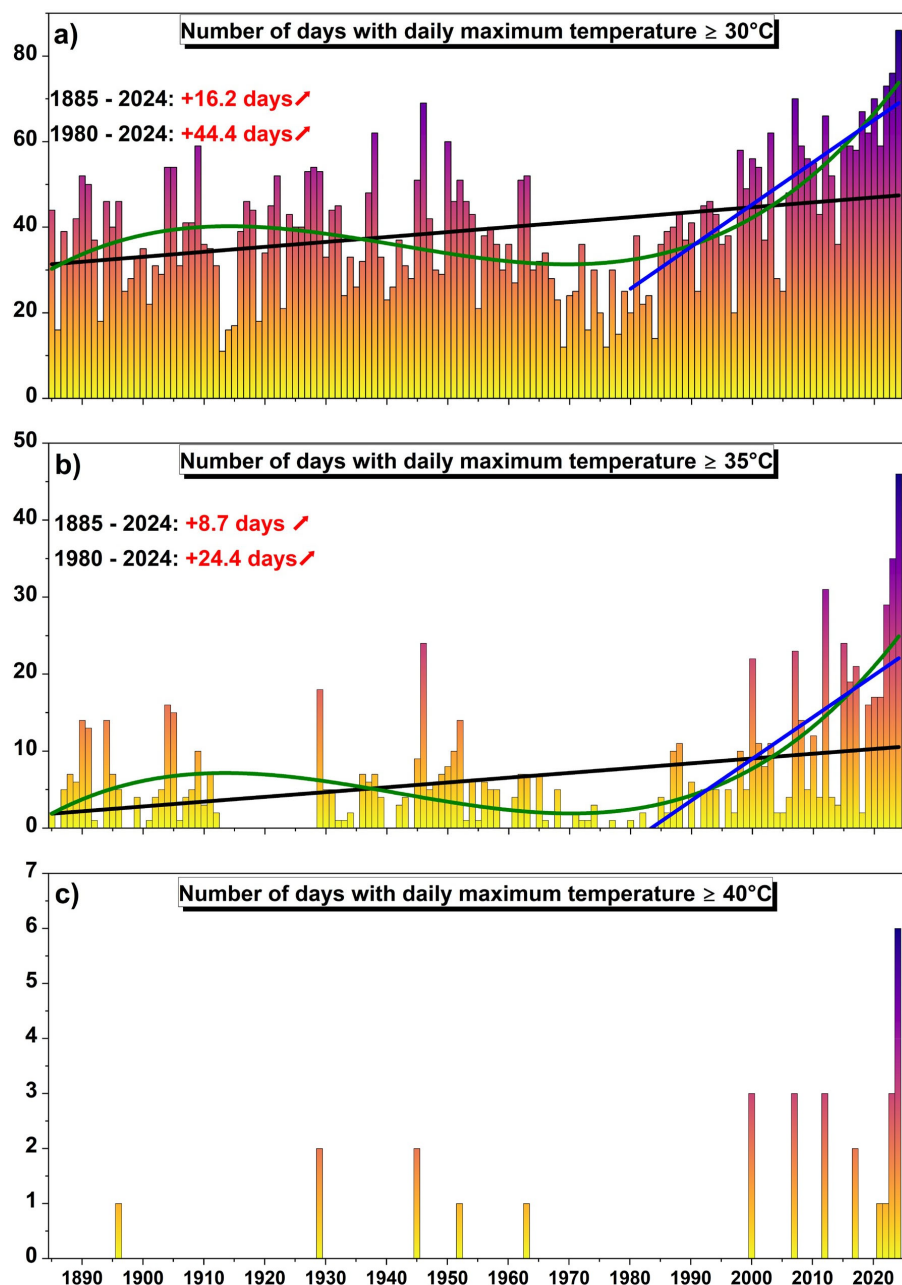


Figure 3. (a) The total number of days with daily maximum temperature above 30°C over the period 1885–2024 and the linear trend over the period 1885–2024 (black line), the polynomial trend over the period 1885–2024 (green line) and the linear trend over the period 1980–2024 (blue line); (b) as in (a) but for days with daily maximum temperature above 35°C and (c) as in (a) but for days with daily maximum temperature above 40°C.

January 1857 to August 2024), offers a valuable perspective on the temporal evolution of summer mean temperatures. Over the 168-year period from 1857 to 2024, the summer mean temperature at this station has increased by approximately +1.22°C (Figure 4a, black line). Notably, a more accelerated warming trend is evident in the recent period from 1980 to 2024, with the summer temperature increase reaching 4.31°C (Figure 4a, magenta line). The summer temperature anomalies in 2024 established a new record in terms of magnitude, with an anomaly of +5.96°C, surpassing the previous record set in the summer of 2023 (+4.33°C) by 1.63°C.

Examining each summer month individually, the most substantial temperature increase over the period 1857–2024 is observed in August (+1.36°C, Figure 4d), followed by June (+1.29°C, Figure 4b) and July (+1.01°C, Figure 4c). Focusing on the period 1980–2024 reveals an even more pronounced warming trend, with the mean August temperature increasing by +5.42°C, followed by July (+4.20°C) and June (+3.32°C). Overall, the summer of 2024 was the warmest on record, with a mean temperature of 27.43°C (+5.96°C above the climatological mean). The years 2023 and 2022 follow, with mean temperatures of 25.80°C (+4.33°C above the climatological

mean) and 25.47°C (+4.00°C above the climatological mean), respectively.

Attribution of the 2024 event

As shown in the previous sub-section, the summer mean temperature at Bucuresti Filaret was record-warm with a value of +27.4°C (+5.96°C above the climatological mean, Figure 3). In order to quantify the contribution of climate change to the 2024 extreme summer temperatures, we employed the method of Rantanen *et al.* (2024). This is designed to assist meteorologists and researchers in quantifying the influence of climate change on mean temperatures at country or station level, across various timescales: monthly, seasonal and annual. The tool leverages observational data of monthly mean temperatures and simulations generated by the Coupled Model Intercomparison Project 6 (CMIP6) climate models, and in this study we focus only on three Shared Socioeconomic Pathways (SSP), namely: SSP1-1.9, SSP2-4.5 and SSP5-8.5. A detailed description of the tool and the CMIP6 models used can be found in Rantanen *et al.* (2024) and in the supplementary file. By using this tool, the analysis suggests that the likelihood of experiencing a summer as warm as the one in 2024 under the climate conditions of 1900 is 0.005%. In the climate of 2024, a summer that is at least as warm will occur on average once every 1895 years, giving an annual probability of 0.1% (0.0%–0.6%, Table 1). Thus, based on the probability ratio, without climate change a summer as warm as the one in 2024 would have been essentially impossible. Projections based on the CMIP6 simulations under the SSP2-4.5 emission scenario indicate that by 2100, a summer as warm as the one experienced in 2024 would be happening approximately once every 6 years (corresponding to an annual probability of 15.6%, Table 1). This underscores the substantial shift in temperature extremes expected by the end of the century, as visualised in Figure 5. For the worst-case scenario (i.e. SSP5-8.5), a summer at least as warm as the one in 2024 would happen every year (corresponding to an annual probability of 94.4%, Table 2). Furthermore, our analysis of the change in intensity (ΔI) suggests that summer 2024 in Bucuresti Filaret was roughly 2.4°C warmer compared to what it would have been in the absence of anthropogenic climate change.

While the method presented here offers valuable insights into the impact of climate change on local temperatures, it is essential to acknowledge its limitations and exercise caution when interpreting its results. One key limitation is the dependence on global mean temperature as a covariate to estimate local temperature changes. This assumes a linear relationship between global and

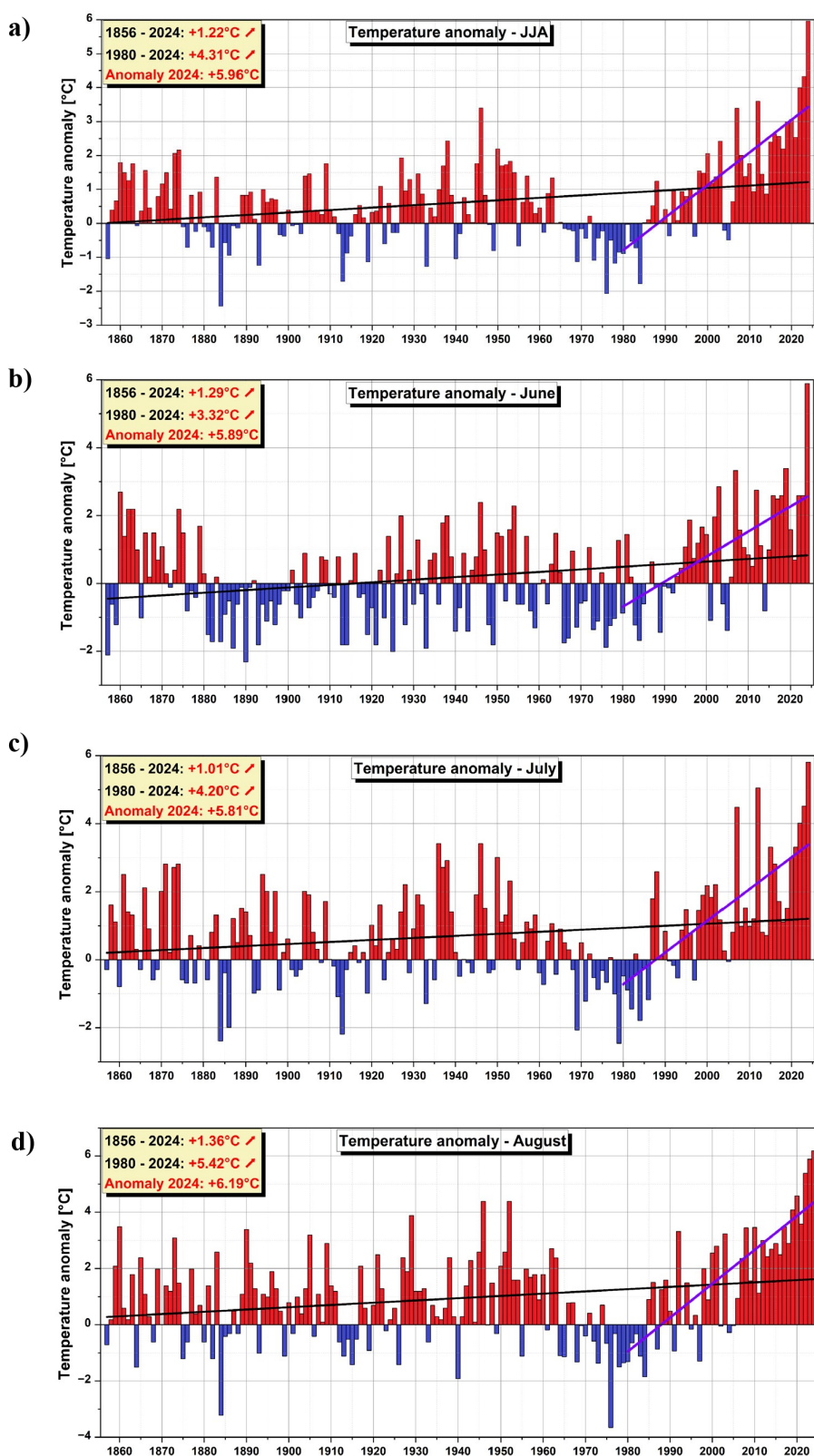


Figure 4. Temporal evolution of the monthly/seasonal mean temperature anomalies at Bucuresti Filaret station over the period 1885–2024. (a) June–July–August (JJA); (b) June; (c) July and (d) August. In (a–d) the black line indicates the linear trend of the mean temperature anomalies over the period 1856–2024 and the magenta line indicates the linear trend of the mean temperature anomalies over the period 1980–2024.

local changes, which may not always hold true. Different regions may exhibit unique responses to global warming due to local feedback mechanisms, atmospheric circulation patterns and regional forcings such as anthropogenic aerosols. Additionally, the

accuracy of the estimated probabilities of extreme events is affected by the availability of long observational records. The method is also sensitive to potential errors in the CMIP6 climate models and uncertainties in the curve fitting method used to estimate

probability distributions. We recognise the need for careful consideration and potential adaptation of the methodology when applying it to any specific region. The limitations associated with the use of global mean temperature, reliance on long observational records, assumption of constant change patterns, sensitivity to model errors and uncertainty in curve fitting should be thoroughly evaluated. In regions with different climate characteristics, local feedback mechanisms or shorter observational records, alternative methods may be more appropriate. Thus, it is crucial to validate the assumptions of the method and assess the potential uncertainties before applying it to new regions or making generalisations about its applicability.

Nevertheless, the method provides a valuable tool for estimating the impact of climate change on local temperatures, but it is essential to apply it judiciously and acknowledge its limitations. Further research into alternative approaches and refinements to address these limitations would strengthen the ability to accurately attribute local temperature extremes to climate change across diverse regions.

Hot and dry at the same time

Summer 2024 was not only the hottest on record over large parts in Romania, but was also extremely dry (Figure 6). The combined effects of high temperatures and reduced precipitation can have cascading impacts on various sectors, including agriculture, water resources and human health. Over the period 1885–2024, there were 62 summers when at least one heatwave event was recorded (Figure 6a). Out of these 62 HW summers, 42 were also accompanied by drought, as defined by the August Standardised Precipitation Evapotranspiration Index for an accumulation period of 3 months (SPEI3 August). This takes into account the deficit of precipitation and the role of temperature throughout the whole summer (see the supplementary file for the computation of SPEI). From 1980 onwards, out of 28 summers with at least one HW event, 22 summers were also dry. As in the case of HW duration (Figure 6a), which shows an increasing trend, especially after 1980s (Figure 2b), SPEI3 August also shows an increasing frequency in the number of dry summers, especially after 1980s (i.e. out of 45 years, 27 have been characterised as dry). The driest summers at Bucuresti Filaret station were recorded in 2000, 2002, 2012, 2020, 2022, 2023 and 2024. In these years, numerous heatwave events were also recorded (Figure 6). Besides the inter-annual variability, the occurrence of combined hot and dry summers also presents a multidecadal component (Figure 6c). A higher frequency of hot and dry summers

Table 1

Estimated annual probabilities, return periods and intensities of a summer mean temperature of 27.4°C at Bucuresti Filaret station for the SSP2-4.5 scenario.

	Probability	Return period (years)	Intensity (°C)
1900	0.0 (0.0–0.005)%	–	25.9 (23.9–26.0)
2024	0.1 (0.0–0.6)%	1895 (161–32 905)	27.4
2100, SSP2-45	15.6 (0.7–62.9)%	6 (2–151)	30.1 (28.7–31.2)

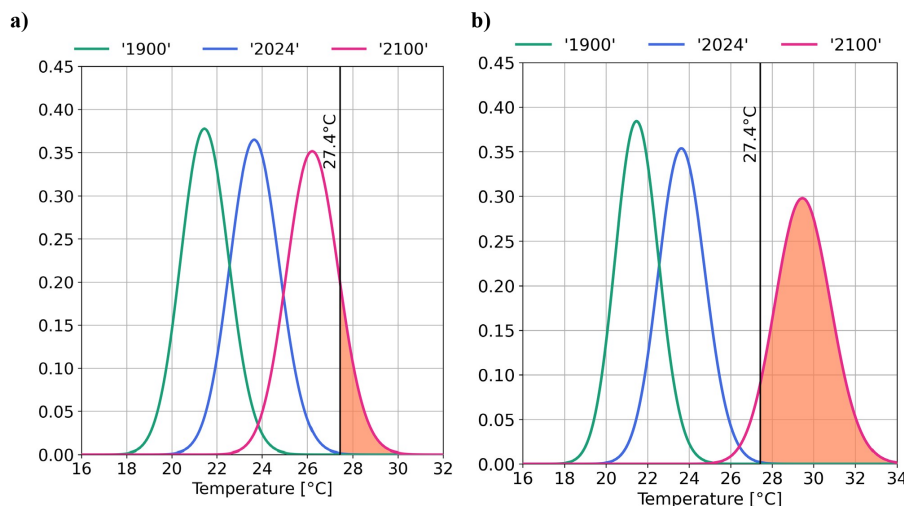


Figure 5. Stochastically generated skewed (SGS) distributions of pseudo-observations for climate in 1900 (green line), 2024 (blue line) and 2100 (magenta line). The black vertical line marks the observed summer (June–July–August) temperature in 2024. (a) SSP2-4.5 and (b) SSP5-8.5.

Table 2

Estimated annual probabilities, return periods and intensities of a summer mean temperature of 27.4°C at Bucuresti Filaret station for the SSP5-8.5 scenario.

	Probability	Return period (years)	Intensity (°C)
1900	0.0 (0.0–0.0)%	–	25.9 (25.2–26.2)
2024	0.1 (0.0–0.3)%	1400 (331–23 263)	27.4
2100, SSP5-85	94.4 (20.6–100.0)%	1 (1–5)	34.0 (31.4–36.0)

has been recorded over the period 1930–1960 and from 1990 onwards, respectively. Nevertheless, the frequency of hot and dry summers has increased especially after the 1990s, when most of the summers that featured at least one HW event were also dry summers (Figure 6).

Conclusions

Over the last decade, Eastern Europe has witnessed a series of intense heatwaves, notably in June/July 2012, June 2019 and August 2023, breaking previous records in terms of intensity and duration, and resulting in severe consequences for human health, ecosystems and infrastructure (Lhotka and Kyselý, 2022; Nagavciuc *et al.*, 2022; Luo *et al.*, 2023; Ionita *et al.*, 2024). The primary cause behind these heatwaves has been linked to persistent large-scale atmospheric patterns, such as the increased occurrence

of atmospheric blocking (Bakke *et al.*, 2023; Vautard *et al.*, 2023). Following the same path, the summer of 2024 was marked by a series of exceptional heatwaves in Eastern Europe, with temperatures frequently surpassing 35°C for prolonged periods. The consequences of such heatwaves were far-reaching, including infrastructure challenges, public health concerns and agricultural losses. As in the previous summer, the HW events throughout the summer of 2024 were driven by a complex interplay of meteorological factors, including a high frequency of atmospheric blocking over the eastern part of Europe, along with a precipitation deficit over large areas throughout the duration of the heatwaves (Figure S1).

In this study, we focused on one of the longest meteorological records in the eastern part of Europe at Bucuresti Filaret meteorological station, extending the daily meteorological records for the maxi-

mum daily temperature by 31 years and 3 months (1 January 1885–31 March 1916). We also digitised extreme temperatures recorded at Bucuresti Filaret station from 1885 until 1929, which allowed us to have a complete record for TX30 from 1885 until 2024. This newly digitised/developed time series, allowed us to put the recent extreme temperatures into a long-term perspective and also to employ attribution tools, which gave us an indication of how extreme the summer of 2024 was.

Our study presents strong evidence of the increasing intensity and frequency of heatwaves in Romania over the past century, particularly since the 1980s: a trend clearly linked to climate change. Additionally, the study investigates whether any past heatwaves rival the intensity of recent events. Analysis of observational data from 1885 to 2024 revealed a rise in both the number of days exceeding the 90th percentile temperature threshold and the overall occurrence of heatwaves at Bucuresti Filaret station. Although our study is limited in terms of spatial extent and we made use of the data at one long-term meteorological station, which cannot be an indicator for the whole country, this study aligns with similar recent findings (Nagavciuc *et al.*, 2022; Antonescu *et al.*, 2023; Ionita *et al.*, 2024) in which it was shown that there is a substantial increase of at least 200% (varying by station) in heatwave metrics for recent events (1980–2023) compared to earlier periods with a high frequency of heatwaves (1920–1965) at country level.

Regardless of the heatwave metric employed in our study (i.e. fixed threshold or percentile threshold), we detected a significant increase both in the duration and magnitude of the HWs, especially when considering the period 1980–2024. Over the period 1980–2024, the number of summer HWs and their duration almost doubled, compared to the period 1930–1960 (another period with a high frequency of HWs). When focusing on the summer of 2024, all parameters analysed in this study indicate that summer 2024 set a new benchmark in terms of duration and magnitude of HWs, which is unprecedented since 1885. The duration of the HWs, summed over the summer of 2024, reached a value of 63 days, which is 26 days more compared to the previous record, which was in 1946 (37 days with HW characteristics) and 29 days more compared to summer 2012, which is ranked the third in terms of HW duration (34 days). In terms of cumulative intensity, the 2024 summer heatwaves (CI=522.1°C) were almost double compared to any previous record (i.e. 1946 had CI=251.0°C and 2012, CI=266.3°C). Nevertheless, it has to be mentioned that the urban heat island (UHI) effect could have acted in amplifying the frequency and intensity of heatwaves at this

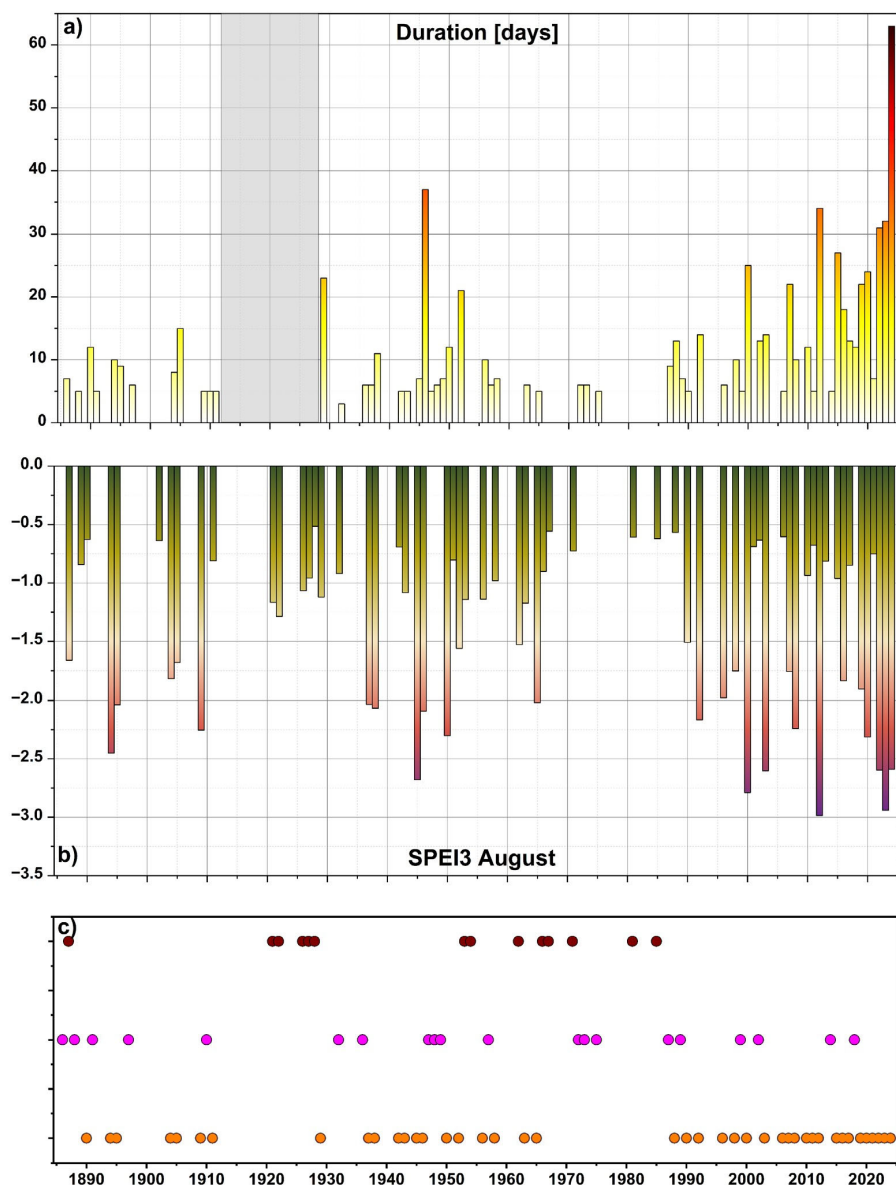


Figure 6. (a) The number of days with heatwave characteristics (see definition in the ‘Data and methods’ section) over the period 1885–2024; (b) August SPEI3 index over the period 1885–2024 and (c) Occurrence of warm (at least 1 HW lasting 5 days) and dry summers (SPEI3 index ≤ -0.5) (orange dots), occurrence of warm summers, but not dry (magenta dots) and occurrence of dry summers, but not warm (brown dots).

particular station, by elevating baseline temperatures through increased heat absorption and retention in urban materials such as asphalt and concrete (Ward *et al.*, 2016). This localised warming exacerbates the occurrence of heatwave conditions by narrowing the margin between typical urban temperatures and heatwave thresholds, leading to more frequent exceedance of these thresholds. Additionally, the reduced nighttime cooling associated with the UHI effect prolongs heatwave episodes, creating extended periods of extreme heat.

Attribution analysis, utilising a method that adjusts local observed temperatures based on the global mean temperature change and the geographical distribution of warming in the CMIP6 simulations (Rantanen *et al.*, 2024), consistently shows that an

extreme summer mean temperature like the one recorded in 2024 would not have been possible without the influence of climate change. Furthermore, depending on the scenario used, such a summer mean temperature might occur in the future either once every ~6 years (SSP2-4.5) or nearly every year (SSP5-8.5). Nevertheless, the results found in this study employing the aforementioned methodology should be treated with care. The limitations associated with the use of global mean temperature, reliance on long observational records, sensitivity to model errors and uncertainty in curve fitting should be thoroughly evaluated.

Apart from being the hottest summer on record since 1857, summer 2024 was also one of the driest. From 1990 onwards, nearly every summer when at least one HW

event was recorded also saw drought conditions, putting additional stress both on society and the economy. In a recent study, Nagavciuc *et al.* (2022) have shown that the eastern part of Romania, where Bucuresti Filaret station is located, is experiencing an increased likelihood of simultaneous hot and dry conditions, especially throughout the summer months. As a concluding remark, we argue that the summer of 2024 served as a stark reminder of the urgent need to adapt to the realities of a changing climate. Investing in resilient infrastructure, promoting sustainable water management practices, and developing strategies to protect vulnerable populations are crucial steps towards mitigating the impacts of future extreme weather events.

Author Contributions

Monica Ionita: Conceptualization; investigation; funding acquisition; writing – original draft; writing – review and editing; visualization; validation; methodology; software; formal analysis; project administration; resources; supervision; data curation.

Viorica Nagavciuc: Data curation; writing – original draft; investigation; writing – review and editing; methodology; formal analysis; visualization.

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Conflict of interest

The authors declare that they have no conflict of interest.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Appendix S1.

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