Review paper

Climatic changes in the Kielce region (1966–2023): implications for environmental dynamics and human health risks

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Abstract

Introduction: Climate change significantly affects environmental dynamics and public health. In Poland, rising temperatures intensify local thermal conditions. This study analyzes temperature and precipitation trends in the Kielce region (1966–2023) based on data from the Kielce-Suków station. The aim is to assess these climatic shifts and their impact on ecosystems and health risks, including cardiovascular diseases, providing a basis for regional adaptation strategies.
Aim: The analysis focused on the course of air temperature and monthly precipitation totals for the period 1966–2023, as recorded by the hydrological and meteorological station of the Institute of Meteorology and Water Management (IMWM) in Kielce-Suków.
Results: Based on the collected data, a thermal and precipitation classification was performed, along with an extended analysis of these elements in the vicinity of Kielce. The results confirm a clear warming trend in the Kielce region, with an increasing number of months being warmer than average over the study period. A decline in the number of colder months was observed, which is a typical symptom of climate change. The average annual temperature has been increasing by approximately 0.03°C per year, which translates to about 0.33°C per decade and around 1°C over a 30-year period. A total increase of 1.62°C was recorded from 1966 to 2023, indicating a marked warming of the climate. According to the conducted projection, a further increase of about 1°C is expected by the year 2028.
Conclusions: Such warming not only affects natural and agricultural systems but also raises concerns for public health, as higher average and extreme temperatures increase the risk of heat stress, and cardiovascular and respiratory diseases, and exacerbate conditions such as asthma and allergies.

Introduction

In urban areas, rising temperatures are intensified by the urban heat island effect, driven by the predominance of paved and asphalted surfaces combined with limited dense vegetation. Such materials strongly absorb and retain heat, leading to elevated air temperatures in cities [1]. Higher urban temperatures are associated with increased heat stress, respiratory problems, and cardiovascular risks, highlighting a direct link between climate-driven urban warming and human health [2]. Moreover, impermeable surfaces drastically reduce the natural infiltration of rainfall into the soil, increasing the likelihood of flash floods during intense precipitation events [3]. The lack of greenery and permeable ground accelerates runoff into drainage systems, which are often unable to cope with sudden surges of water, thereby aggravating flood hazards, impacting urban infrastructure, and posing additional risks to human safety and health [4–6].

Contemporary climate research increasingly focuses on identifying trends and extremes in air temperature and precipitation, which are key factors shaping environmental conditions, functioning of the ecosystem, and human well-being. These changes are observed at both global and regional scales, with impacts becoming increasingly evident in landscapes, hydrology, agriculture, and both natural and urban ecosystems [7, 8]. Rising temperatures and shifting precipitation patterns can exacerbate heatwaves, increase the frequency of vector-borne diseases, and strain healthcare systems, particularly in urban settings [9].

In Poland, as in other Central European countries, a systematic increase in average annual temperatures and greater variability in precipitation have been documented, as reflected in numerous meteorological and climatological studies [10, 11]. The Świętokrzyskie region, located in southeastern Poland, is particularly interesting due to its varied terrain, mosaic of land use, and local climatic factors [12]. The Institute of Meteorology and Water Management (IMWM) meteorological station in Kielce-Suków, which has been operating for decades, provides valuable data enabling the analysis of long-term climatic changes in this region.

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Analysis of air temperature and precipitation data from this station fits into the broader context of research on the regionalisation of Poland's climate [13, 14], the assessment of extreme events [15], and the identification of climate change impacts on water management, ecosystems, and human health [16, 17]. Climate change affects not only water balance and agroclimatic conditions but also the dynamics of plant communities – both natural [18, 19] and cultivated – altering the length of the growing season and increasing drought risk, which can indirectly affect nutrition, livelihoods, and population health [20, 21].

Aim of the research

The aim of this article is to characterise changes in air temperature and precipitation in the Świętokrzyskie region, based on data from the IMWM Kielce-Suków station for the years 1966–2023. The analysis uses long-term time series, considering seasonal and annual variability of meteorological parameters and attempting to identify trends and potential phenological shifts. Attention is paid to the potential regional, environmental, and human health implications of the observed changes.

Material and methods

Research area

The IMWM meteorological station Kielce-Suków is located southeast of the city centre of Kielce, in the village of Suków. It is situated at an altitude of approximately 260 metres above sea level, on the edge of a loess upland, in an open area, which facilitates meteorological measurements in accordance with the standards of the World Meteorological Organisation (WMO). This location ensures good representativeness for the climatic conditions of the Świętokrzyskie region, particularly concerning suburban and agricultural areas (Figure 1).

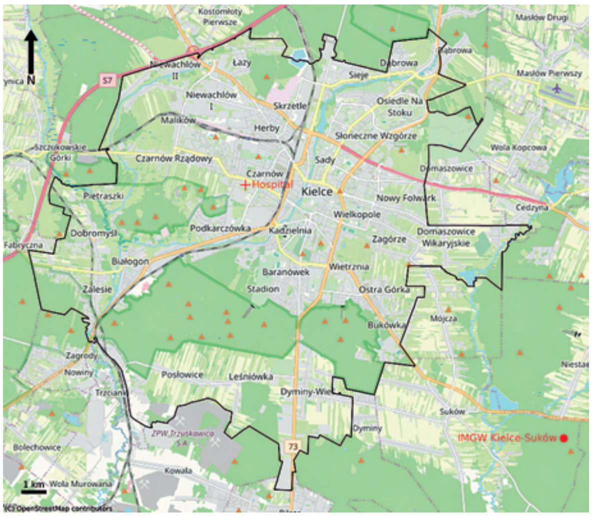


Figure 1. Location of the IMWM Kielce-Suków station and Regional Combined Provincial Hospital in Kielce (based on OpenStreetMap)

According to the physical-geographical regionalisation of Poland by Jerzy Kondracki [22], the Kielce-Suków station is located in the Polish Uplands province, within the Małopolska Upland subprovince, the Kielce Upland macroregion, and specifically in the Świętokrzyskie Mountains mesoregion.

The climate of the Świętokrzyskie region, including the area around Kielce, is shaped by its geographic location and morphological conditions. It exhibits characteristics of a temperate transitional climate, with clear influences from both oceanic and continental air masses. Annual precipitation typically ranges from 600 to 750 mm, and the average annual temperature is about 7–8°C, although an increase has been observed in recent decades [23, 24]. The Kielce Upland experiences a slightly cooler climate than the neighbouring lowlands, which is related to its absolute altitude, the presence of forested areas, and differences in exposure [25].

Methods

The climatic analysis for the Kielce region was based on data from the IMWM Kielce-Suków station for 1966–2023. Three meteorological elements were examined: air temperature, total precipitation, and snow cover. Thermal conditions were classified using the Lorenc and Bogucka method [26], assigning each month to one of 11 classes based on temperature deviations from the average calculated for reference period. Borderline values were rounded to one decimal place. This classification enabled the identification of thermal anomalies and extreme months.

Precipitation totals were classified using percentiles of multi-year values (1966–2023), adopting 5 humidity classes commonly used in Polish climate studies [24–27], allowing identification of dry or wet periods.

Heat waves were determined following Niedźwiedź [28], defined as at least 3 consecutive days (or months in aggregated data) with temperatures exceeding a climatological threshold.

Long-term trends were analysed using linear regression, with significance assessed by Student's *t*-test and Kendall's tau ($p < 0.05$). Calculations and visualisations were performed in R 4.3.1 [29] using the trend and ggplot2 packages.

Bioclimatic conditions were evaluated using the Temperature–Humidity Index (THI) [30], calculated from daily temperature (T, °C) and relative humidity (RH, %): $THI = T - (0.55 - 0.0055 \times RH) \times (T - 14.5)$.

Higher THI values indicate stronger heat stress, while lower ones represent thermal comfort.

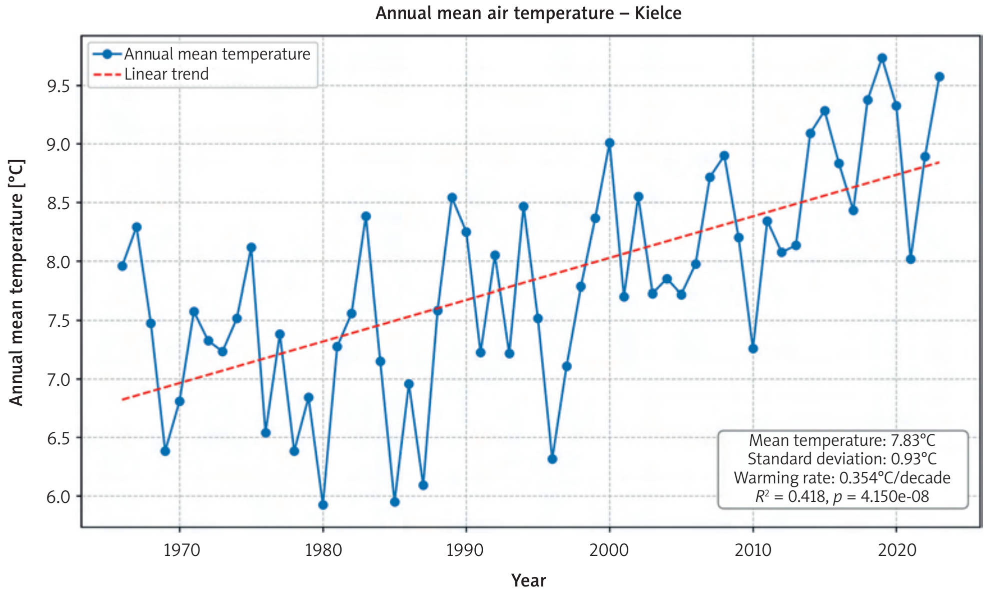


Figure 2. Changes in the average annual air temperature values

Predictive modelling employed the Auto ARIMA algorithm, which automatically selected optimal seasonal parameters (m = 12). Medical data from the Regional Combined Provincial Hospital in Kielce cover the period 2015–2023.

Results

Based on meteorological data from 1966–2023, a clear upward trend in average annual air temperature was observed (Figure 2). In the 1960s, mean values ranged from 6 to 8°C, while in the last two decades they regularly exceeded 8°C, reaching 9.7°C in 2019. This confirms progressive warming in the Kielce region, consistent with global trends.

Thermal classification by Lorenc and Bogucka [26] (Figure 3) showed that 39.5% of months were thermally normal, 15.8% slightly warm, and 13.8% slightly cold. Extremely warm or cold months were rare (below 3%). Over time, the share of warm anomalies increased, particularly after the 1990s. On average, there were 3.52 cold, 4.74 normal, and 3.74 warm months per year. The number of cold months declined (–0.076 months yr^{-1}, R^2 = 0.41), while warm months increased (+0.099 months yr^{-1}, R^2 = 0.51) (Figure 4).

Annual precipitation totals varied greatly (439–1000 mm) without a significant trend (Figure 5). Average annual precipitation (500–750 mm) remained typical for a temperate climate. The greatest temperature rises occurred in January (+5.3°C), August (+2.6°C), and March (+2.1°C). Winters shifted from negative to positive values, while precipitation showed no systematic change and high interdecadal variability (Figure 6).

The obtained results indicate that, despite the observed global warming trend, precipitation in the Kielce region does not show a similar tendency in quantitative changes over the studied period. The limited predictability of annual precipitation totals highlights the need for further detailed studies considering seasonal and long-term fluctuations and their impact on local ecosystems and water management.

Heat waves became more frequent and longer after 1990 (Figure 7). The most intense occurred in 1994, 2006, 2010, 2015, and 2022, lasting up to 15 days. Tropical nights (Tmin ≥ 20°C) appeared only after 2012.

The mean annual air temperature (1966–2023) was 7.88°C (min 5.93, max 9.76). The mean THI was 8.36, increasing by +0.032 units yr^{-1} (R^2 = 0.43, $p < 0.001$), consistent with rising temperature (+0.036°C yr^{-1}, R^2 = 0.42, $p < 0.001$). This indicates intensifying heat stress and declining thermal comfort, with the highest THI in 2019 (10.10).

The linear trend shows a statistically significant increase of 0.032 units per year, which over the studied period corresponds to an increase in mean THI of nearly 1.9 units. The 5-year smoothing highlights a gradual, steady rise in perceived heat and identifies years with particularly elevated heat stress. These results suggest increasing thermal load throughout the year and a growing risk of conditions conducive to heat stress in the region (Figure 8).

Forecasting with the Auto ARIMA model (m = 12) confirmed the model's adequacy, and it projected continued warming for 2025–2030 (Figure 9). Winter temperatures are expected to remain above historical averages, and summer peaks may intensify. The forecast suggests an additional rise of 0.3–0.5°C compared with

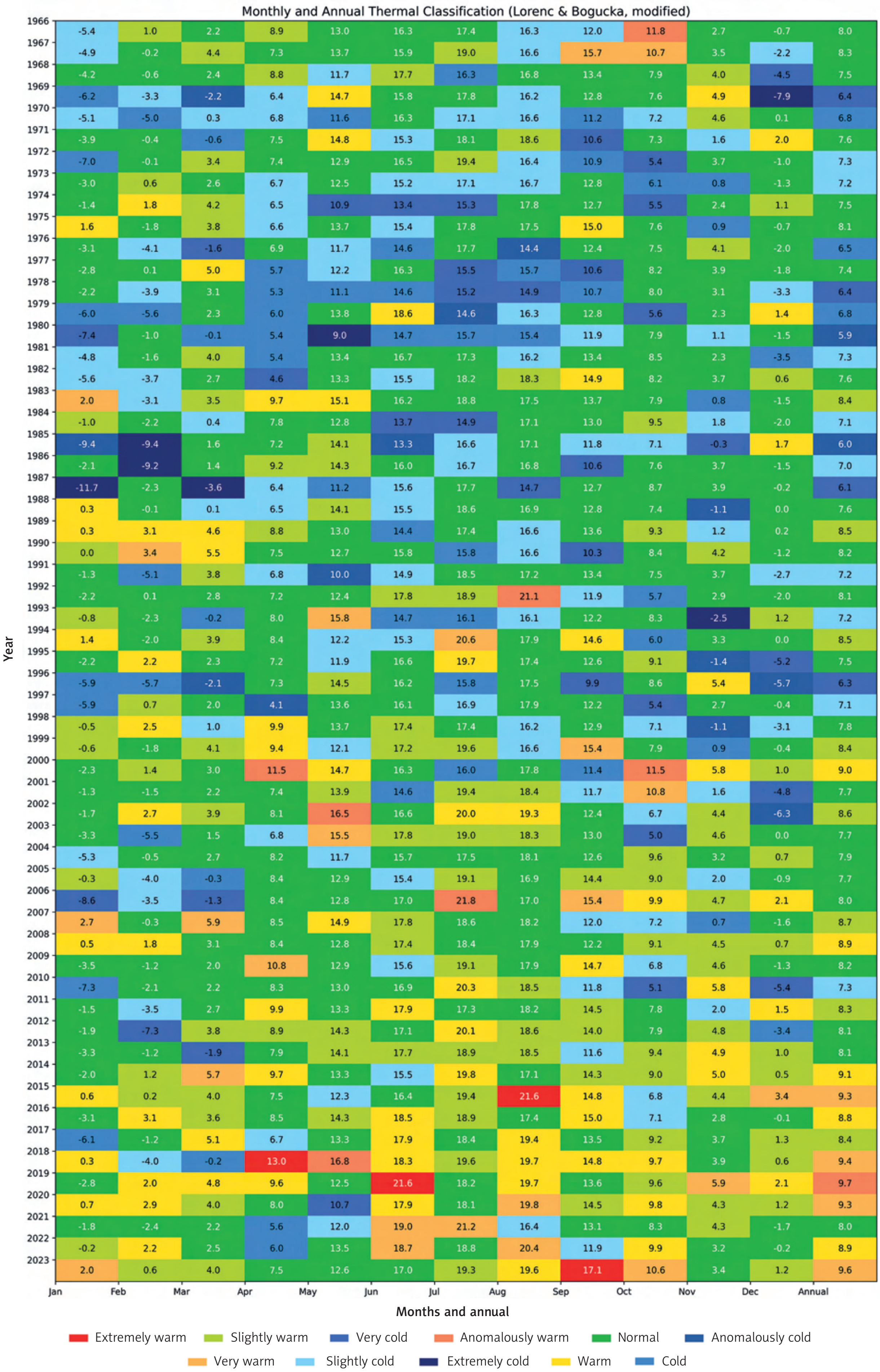


Figure 3. Thermal classification according to Lorenc and Bogucka [26]

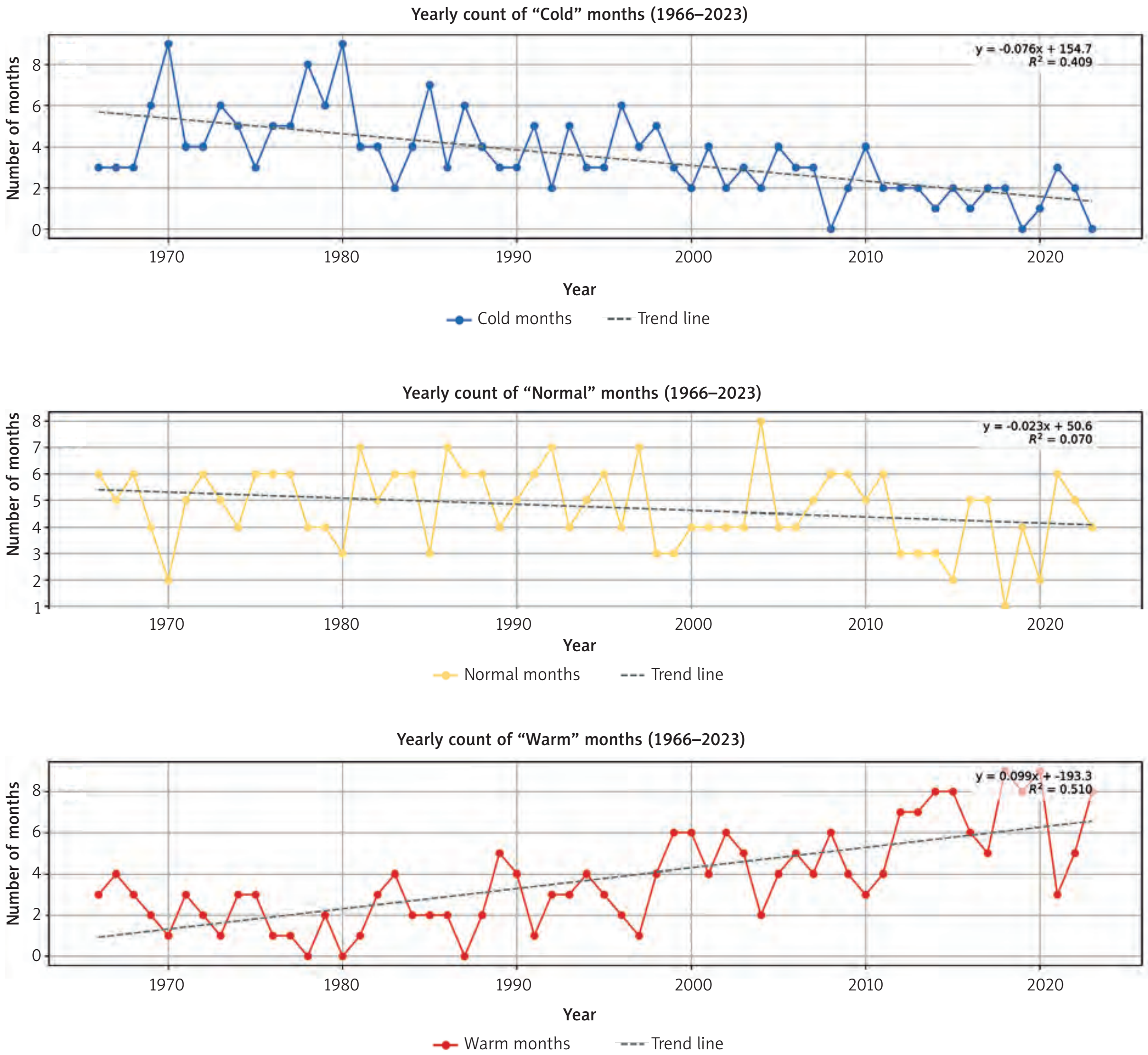


Figure 4. Changes in the occurrence of individual thermal classes over the studied multi-year period (1966–2023)

the previous decade, indicating a persistent warming trend and a growing risk of extreme heat events.

Confidence intervals around the forecast illustrate a certain degree of uncertainty related to short-term climate fluctuations, but the overall direction of change is unambiguous. The lower bounds of the forecast still exceed the historical averages for many months, while the upper bounds point to the possibility of record-breaking temperatures in the coming years. Aggregated annual means derived from the monthly projections confirm this tendency, indicating that the period 2025–2030 is expected to be markedly warmer than previous reference periods.

Taken together, these results provide quantitative evidence supporting the ongoing warming trend in the Kielce region. They not only reflect past observations but also reinforce the broader findings of climate change research in Central Europe, underscoring the likelihood of continued thermal stress in the coming decades.

The above observations are also confirmed by data on hospital admissions. We present data from admissions to the region's largest provincial hospital in Kielce. Based on this data, it can be concluded that hospital admissions of patients with cardiovascular conditions correlate with weather conditions in the region at that time (Figure 10). The medical data from the hospital in Kielce also cover the period of the COVID-19 pandemic, which, as is well known, significantly disrupted the functioning of the pre-pandemic healthcare system. In particular, in the years 2020–2022, the number of admissions and cases of the discussed diseases was heavily affected.

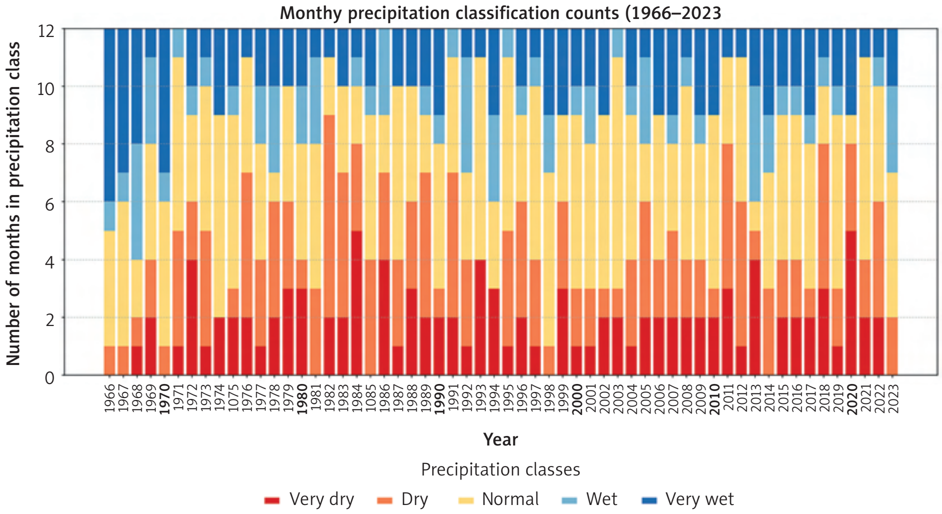


Figure 5. Precipitation classification during the studied period (1966–2023)

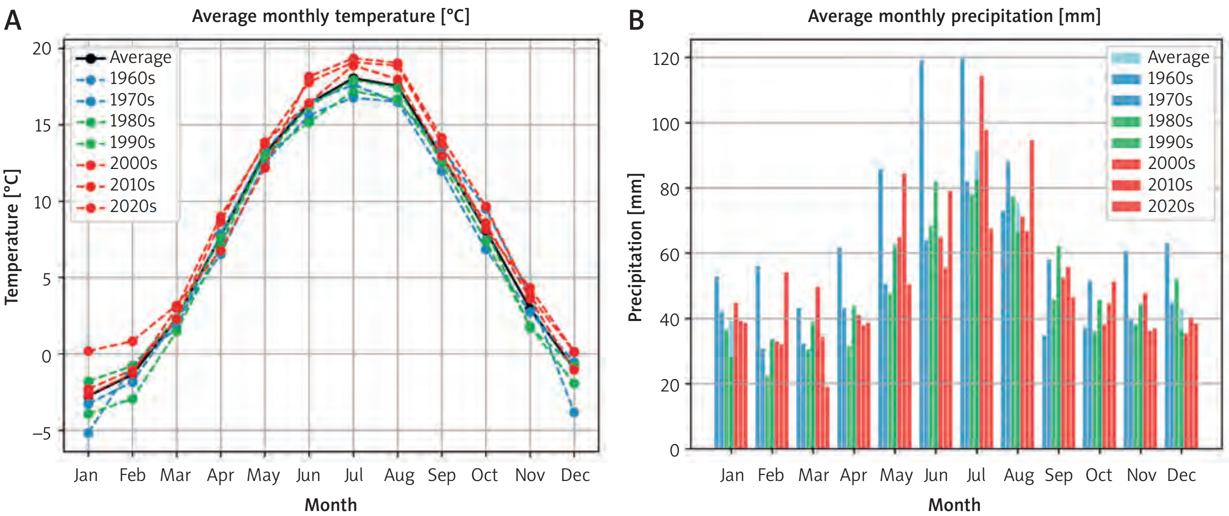


Figure 6. Trends of temperature (**A**) and precipitation (**B**) totals in individual decades of the multi-year period

The correlation analysis between monthly mean air temperature and hospital admissions shows generally weak associations. Admissions for acute myocardial infarction (I21) display a slight negative correlation with temperature, while heart failure admissions (I50) and total admissions show minimal linear relationship. Deaths exhibit a modest tendency to increase during colder months, although this trend is only borderline significant. Overall, these results suggest that month-to-month temperature variations alone explain a limited portion of variability in hospital admissions and mortality, with seasonal and other factors probably playing a stronger role. In the following section, we present a Generalised Additive Model (GAM) analysis with a corresponding figure (Figure 11) to further investigate the non-linear effects of temperature on cardiovascular admissions.

The figure illustrates monthly hospital admissions for acute myocardial infarction (I21) and heart failure (I50) from 2015 to 2023, and their relationship with mean monthly air temperature. Analyses were conducted using Generalised Additive Models (GAM) with a Poisson distribution, incorporating a cubic B-spline ($df = 6$) for temperature to capture non-linear effects, while accounting for seasonal variation by including the month as a categorical variable. Results indicate that admissions for acute myocardial infarction (I21) decrease slightly with increasing temperature, with a predicted change of –2.18% per +1°C, whereas heart failure admissions (I50) are largely insensitive to

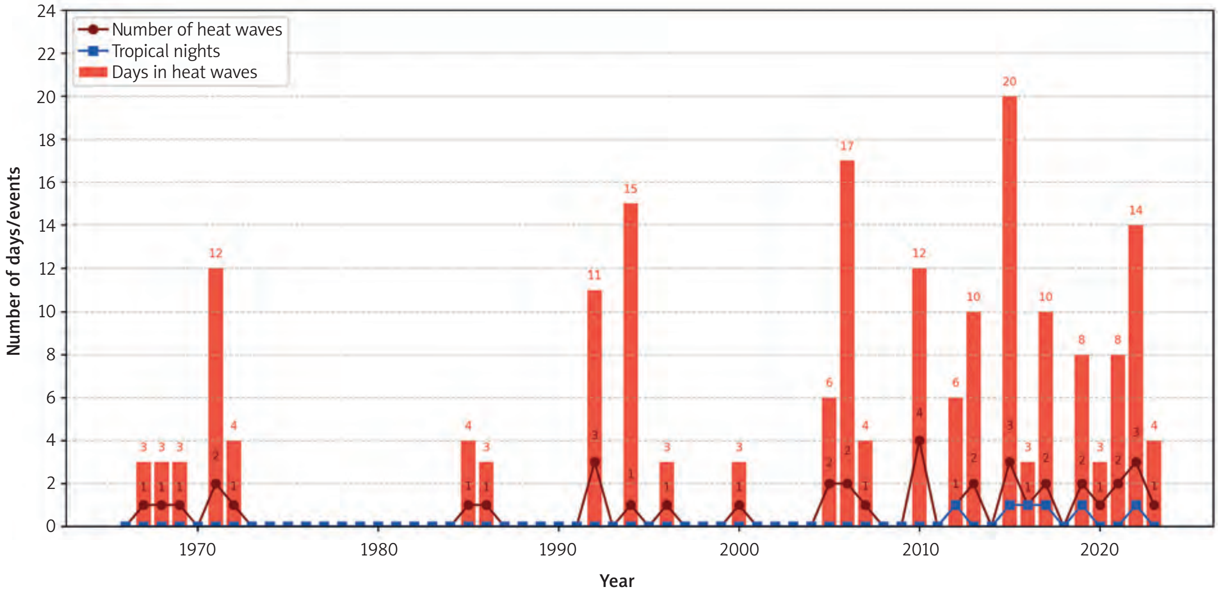


Figure 7. Heat waves and tropical nights in Kielce (1966–2023)

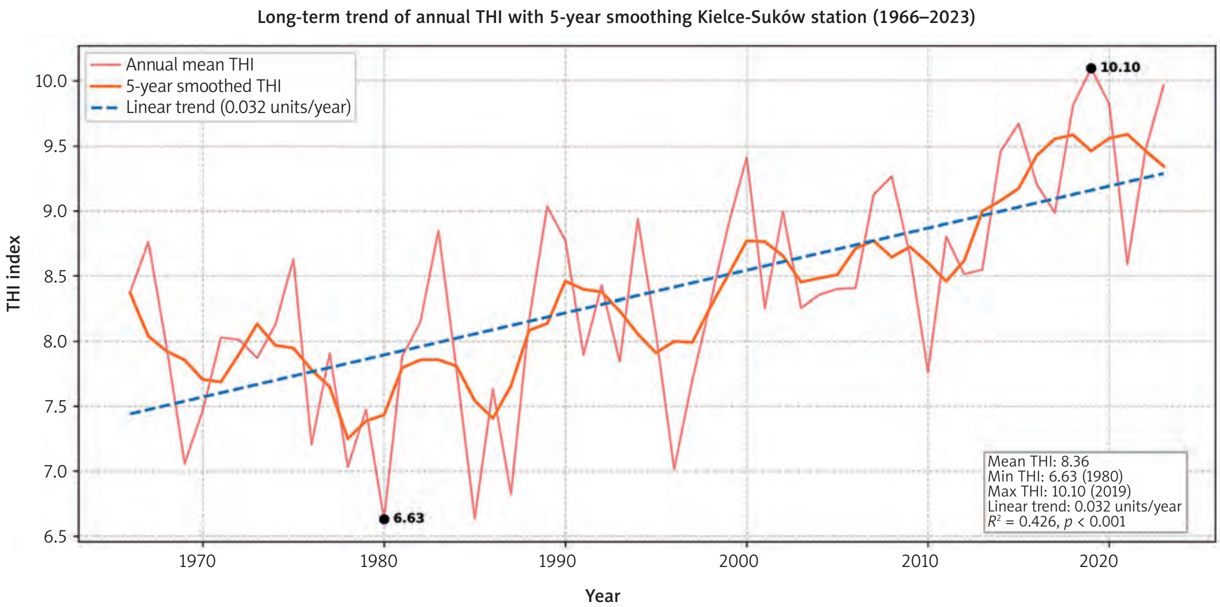


Figure 8. Temporal variability of the THI index in the years 1966–2023

short-term temperature variations (–0.32% per +1°C). Seasonal peaks, particularly during winter months, are clearly visible in both observed data and model predictions. Overall, these findings suggest that hospital admissions for cardiovascular conditions are influenced more by seasonal factors than by modest month-to-month temperature changes, highlighting the importance of accounting for both temperature and seasonality in healthcare planning.

Discussion

The increasing moisture deficit trend in Central and Southern Europe, resulting from rising air temperatures and evapotranspiration, was confirmed by Urban [31]. Climate change disrupts the hydrological regime, and since 1988, it has unevenly affected low flows in Polish rivers. Summer low flows have deepened due to high temperatures and evaporation, while warmer winters with mid-winter thaws have caused

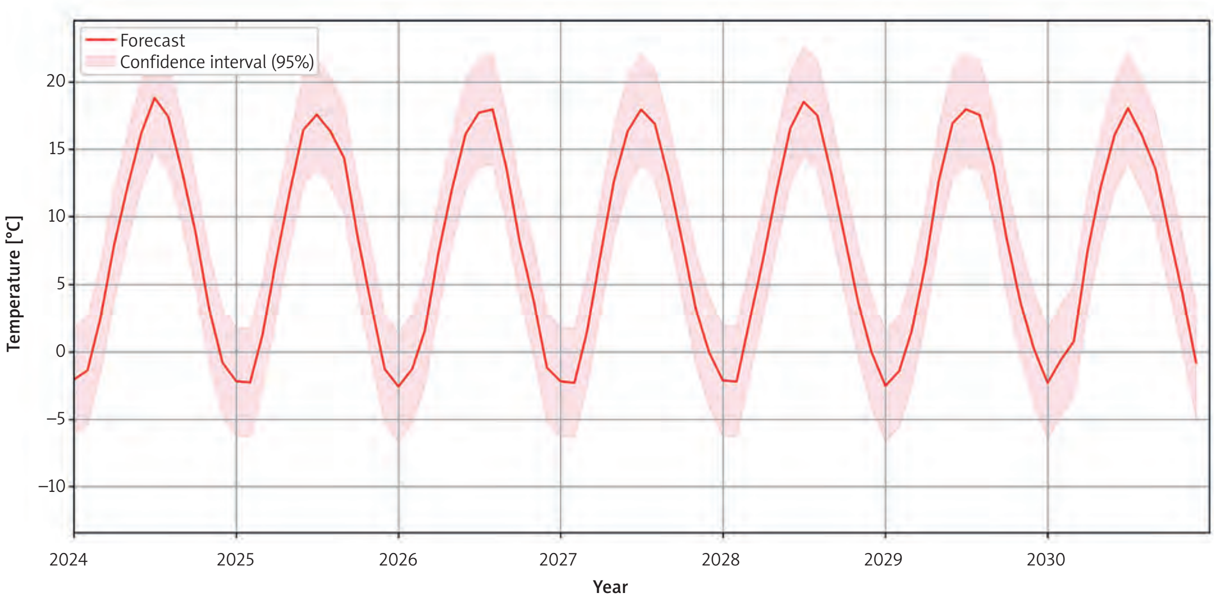
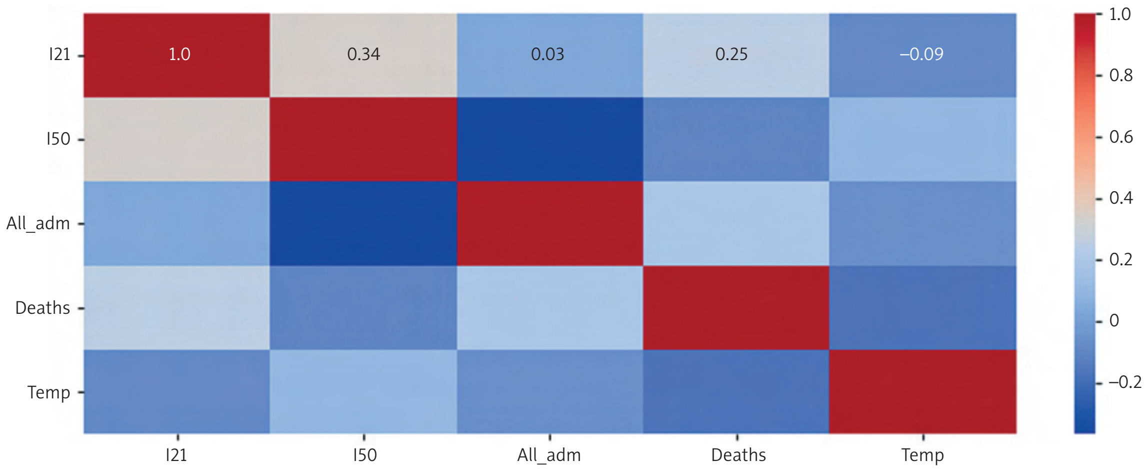


Figure 9. Forecast of monthly average air temperature in Kielce for the years 2024–2030, generated using the Auto ARIMA model



Variable	Pearson *R*	*P*-value
I21	–0.092	0.343
I50	0.1	0.305
All_adm	–0.07	0.474
Deaths	–0.173	0.073

Figure 10. Correlation analysis between monthly mean air temperature and hospital admissions. The heatmap (top) shows Pearson correlation coefficients among temperature and medical variables, while the table (bottom) presents Pearson r and corresponding p-values for temperature versus each medical variable. Data source: Voivodeship Integrated Hospital in Kielce, 2015–2023

increased runoff and the disappearance of winter low flows [32].

In Poland, particularly in the Świętokrzyskie region, the frequency and intensity of heatwaves and droughts have risen, heightening risks to water resources, ecosystems, and public health [33, 34]. As emphasised by Ciupa and Suligowski [35], developing small retention infrastructure and water management systems is vital for enhancing hydrological and ecological stability.

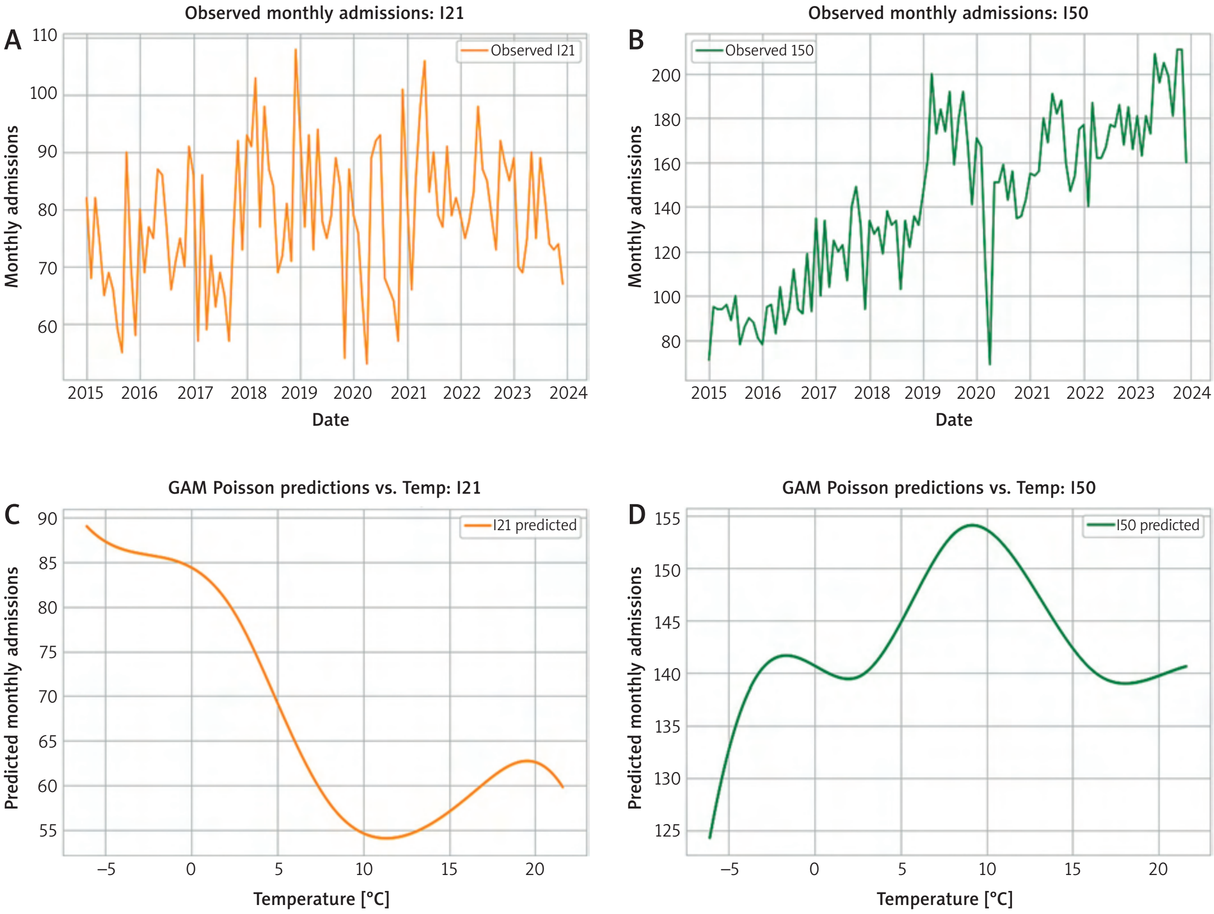


Figure 11. Observed monthly hospital admissions (top row) and GAM Poisson predicted admissions vs. mean monthly temperature (bottom row) for acute myocardial infarction (I21, orange) and heart failure (I50, green) between 2015 and 2023. Predictions account for seasonality (month) using categorical variables and a cubic B-spline ($df = 6$) for temperature. Shaded areas represent approximately ±1 standard error (SE). Data source: Voivodeship Integrated Hospital in Kielce

In Kielce, the water supply system is highly vulnerable to droughts, especially due to the extensive depression cone around the Białogon groundwater intake, which supplies about 64% of the city's population [36]. Water demand increases during heatwaves, while agricultural droughts cause yield losses of 30–50%, affecting most crops in the region [37]. In 2024, 68 of 102 municipalities in the Świętokrzyskie Voivodeship experienced drought.

According to IMWM data [40], the number of days with temperatures above 30°C is steadily rising. Combined with lower precipitation and longer dry periods, this exacerbates meteorological and hydrological droughts [39]. Increased evaporation limits water availability, especially in low-retention regions such as Świętokrzyskie [66].

Phenological studies show accelerated seasonal changes and an extended growing period in Poland, reflecting global temperature rise [41, 42]. IMWM data from 2007–2018 indicate that early spring and spring onset advanced by 9–11 days, while autumn was delayed by 3 days, extending the growing season by 12 days [43].

Heatwaves significantly increase hospitalisations and deaths due to cardiovascular and respiratory diseases, particularly among vulnerable groups [44, 45]. Temperature trends at the Kielce-Suków station align with national data based on WMO guidelines for the 1991–2020 climate normal period [46]. Studies from the Integrated Environmental Monitoring Network confirm these patterns, representing Poland's key landscape zones [47].

Data indicate a growing frequency of heatwaves, with 60–70% of years in the 2010s and 2020s affected. Although droughts were most frequent in the 1980s, they have moderately resurged. The increasing concurrence of heatwaves and droughts heightens risks to water, ecosystems, and health, underscoring the need for adaptation and improved water management.

Rising temperatures and more frequent heatwaves contribute to higher morbidity and mortality, especially among the elderly and chronically ill [44, 45]. Epidemiological studies and the IPCC report [7, 39] confirm that heatwaves elevate mortality in Central Europe, and health risks from hyperthermia and dehydration are expected to intensify in the coming decades.

Higher air temperatures also indirectly affect human health by altering the dynamics of air pollutants. Elevated temperatures promote the formation of tropospheric ozone, which negatively affects the respiratory system, exacerbating symptoms of asthma and chronic obstructive pulmonary disease [8]. Moreover, climate warming extends the pollen season of many plant species, increasing the prevalence of allergies and atopic diseases [21].

The psychological effects of prolonged exposure to heat stress should also be considered. Research shows that high temperatures and associated extreme weather events increase the risk of mood disorders, anxiety, and sleep problems, which can negatively impact overall population well-being [44].

According to the confirmed and significant trend of warming observed both in Central Europe and in Poland, numerous data demonstrate the impact of this phenomenon on cardiovascular, respiratory, metabolic, and other diseases. Contemporary healthcare still primarily focuses on classical risk factors such as elevated arterial blood pressure, high LDL cholesterol levels, overweight, diabetes, and smoking. However, studies have confirmed the substantial contribution of environmental factors to the pathogenesis of these conditions. The most important among them include air pollution, extreme heat and cold, noise, exposure to toxic chemicals, and, in particular, lead. These factors are currently recognised as classical environmental risk factors 48, 49].

The impact of high temperatures on cardiovascular disease is particularly evident in conditions such as coronary heart disease, hypertension, cardiac arrhythmias, and stroke. These data are supported by numerous studies conducted by, among others, Bunker, Chen, and the Eurowinter Groups [50–52]. Similar conclusions were obtained based on the analysis of large groups of patients Alahmad, Chen, Sun, Yang, and Silveira [53–58]. Recent studies have shown a significant synergistic effect between global temperature rise, air pollution, and cardiovascular morbidity and mortality [59–62]. In addition to these factors, large-scale wildfires also play an important role in climate warming [63, 64]. Another major concern related to climate warming is the impact on respiratory diseases, particularly in relation to the onset and course of asthma and allergic rhinitis [65–67]. Therefore, as numerous studies show, daily hospital admissions are significantly dependent on weather conditions [68–73]. Our own research confirms the dependence of admissions to the largest hospital in the region on weather conditions and ambient temperature.

In recent years, the concept of the exposome has gained increasing attention in risk assessment. This concept was first introduced by Christopher Paul Wild [74]. In his work, the author demonstrated that the risk of disease is determined not only by the well-known risk factors – such as smoking, hypertension, diabetes, dyslipidaemia, age, sex, and family history – but also by the cumulative impact of environmental exposures throughout life. The exposome encompasses the totality of environmental exposures from the moment of conception and is essential for a modern, holistic approach to population-level exposure assessment [74].

The exposome integrates all environmental factors encountered by an individual during their lifetime, including chemical pollutants, social determinants of lifestyle, and psychosocial conditions. It examines these exposures in the context of an individual's genetic susceptibility and biological responses, providing a comprehensive framework for understanding the complex interactions between environment and health [74].

In summary, the observed increase in temperatures and the growing frequency of heatwaves in the Świętokrzyskie region pose a significant threat to public health. It is therefore necessary to implement adaptation measures, including early warning systems, the development of urban green infrastructure, and educational campaigns targeting the most vulnerable groups.

Conclusions

The results show that thermally normal months dominate the temperature distribution in Kielce; however, recent decades have seen a marked increase in warm and very warm months, reflecting the ongoing climate warming trend. Extremely cold months are rare (only 18 out of 708), indicating a decline in the severity and frequency of cold winters.

Long-term meteorological data from the IMWM Kielce–Suków station confirm a significant rise in average annual air temperature, pointing to evident local manifestations of climate change. The absence of clear precipitation trends highlights the need for continued observation and modelling to better understand Kielce's evolving climate conditions.

The increasing co-occurrence of heatwaves and droughts poses growing challenges for Kielce's water management, spatial planning, and public health protection, emphasising the importance of cooperation between scientists, local authorities, and the community in adapting to changing climatic conditions.

The analysis of heatwaves and tropical nights by decade reveals a pronounced warming trend. Their frequency rose from 16 and 7 days in the 1970s–1980s to 69 in the 2010s, along with the first recorded tropical nights (5 in total). These results confirm a significant intensification of extreme heat events in Kielce in recent decades.

Based on the detailed analysis, it can be concluded that seasonality and other temporal factors have a greater impact on monthly hospital admissions than air temperature alone. Temperature did not show a statistically significant effect on acute myocardial infarction admissions during the period 2015–2023 in monthly analyses. The non-linear effects observed suggest a slight decrease in admissions at higher temperatures, consistent with epidemiological observations, but the effect did not reach statistical significance and would require a larger dataset or daily-level analysis to confirm. For future studies, it is recommended that more detailed daily data, additional risk factors, and potential interactions with other variables be incorporated, such as air pollution, patient age, or comorbidities, to better understand the determinants of cardiovascular hospitalisations.

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Ethical approval

Not applicable.

Conflict of interest

The authors declare no conflict of interest.

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