LONG-TERM VARIABILITY AND TRENDS IN THE CHARACTERISTICS OF HEATING SEASONS IN CENTRAL EUROPE

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Abstract: The study analysed the temporal and spatial variability of the changes in the start and end dates and the length of heating seasons (HS), as well as the values of heating degree-days (HDD) in Central Europe from 1961/62 to 2020/21. For this purpose, the average daily air temperature values from 12 meteorological stations located in cities with a population ranging from 180 to 17,500 were used. It was found that the start of the seasons was later at most of the studied stations, and the end of the season was hastened across the area, which contributes to the shortening of the HS by an average of 1.46 days per decade and a decrease in HDD by 96.3°C per decade. In warmer regions of Central Europe, with a higher annual average air temperature, the season starts about 4 days earlier, is longer by about 7 days, and is characterised by a decrease of about 300°C in HDD value for every 1°C increase in average annual temperature. However, based on data from selected cities, the number of their inhabitants was not found to have a statistically significant impact on the individual parameters of the studied season.

Keywords: heating seasons, heating degree-days, start and end of heating seasons, duration of heating seasons, trends, climate change, Central Europe

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Introduction

Weather significantly impacts the amount of energy consumption, especially in relation to high and low air temperature values (Atalla et al. 2018, Spinoni et al. 2018, Andrade et al. 2021). The need to use air conditioning during hot days and heating during the cooler half of the year drives energy demand in households and public utility facilities. The increasing demand for energy and the need to care for the environment due to the adverse impact of fossil fuel-based power plants on the Earth's climate necessitate adaptive and mitigative actions (Liu et al. 2010).

The increase in global air temperature is a fact (IPCC 2022). Although the pace of these changes varies across different regions, many scientists point out that the rate of temperature rise has accelerated clearly in the last decade (IPCC 2022). It is indicated that the greater threat from rising temperatures will be in urban areas, especially in large cities where the vast majority

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of the population lives. In 2021, only 21% of the European Union population lived in rural areas (EC 2023). Deviations from thermal comfort conditions in these regions can therefore be harmful to residents, especially to the elderly and children, who are thought to spend even more than 90% of their time indoors (Andargie et al. 2019). However, it is important to remember that the energy used in urban households is more convenient, efficient, and less harmful to the environment than that used in rural areas (Caia, Jiang 2008).

Urban areas, in comparison to rural areas, are characterised by higher air temperature values and reduced natural ventilation (Kohler et al. 2016). The phenomenon known as the Urban Heat Island (UHI) is prominent in these areas (Oke 1982, Oke et al. 1991, 2017). The temperature difference between urbanised areas and those outside the city can reach up to 7°C (Ewing, Rong 2008). Therefore, due to the occurrence of UHI in densely populated city districts, the demand for heating energy is lower, whereas the demand for cooling energy is higher compared to green suburbs. Research conducted by Magli et al. (2015) in Modena (Italy) indicated that the energy demand during the summer in a building located in an urban area is about 10% higher than that of a building in a suburban area. On the other hand, during winter, the energy demand associated with heating in the suburban area is about 15% higher (no UHI effect). Therefore, the total annual energy demand increases by 2% without the UHI effect (Magli et al. 2015).

Trends in changes to heating degree-days (HDD) have been the subject of analysis in various regions of Europe and the world, including Greece (Papakostas, Kyriakis 2005, Moustris et al. 2015), Spain (Ortiz Beviá et al. 2012), Italy (De Rosa et al. 2015), Russia (Belova et al. 2018), Belgium (Ramon et al. 2020), Portugal (Andrade et al. 2021), Turkey (Bilgili et al. 2023), as well as Iran (Sadeqi et al. 2022), Saudi Arabia (Al-Hadhrami 2013, Indraganti, Boussaa 2017), India (Ukey, Rai 2021), Canada (MacDonald et al. 2023), the USA (Petri, Caldeira 2015), and Australia (Livada et al. 2021). On a global scale, such research was conducted by Li et al. (2021). Authors most often presented long-term and seasonal HDD values from various lengths of years using daily or specific period air temperature values. In several of the mentioned publications, not only past trends were provided but also future ones, using climate change scenarios even up to the year 2100 (Ortiz Beviá et al. 2012, Petri, Caldeira 2015, Ramon et al. 2020, Andrade et al. 2021, Ukey, Rai 2021).

Li et al.'s (2021) research indicated that globally, HDD values have generally decreased, more so in areas at higher latitudes. Both HDD values and the pace of their changes were correlated with factors, including latitude and altitude above sea level.

In Central Europe, combined heat and power plants and individual households are usually prepared to start central heating as early as September and to provide heat until around the end of May. Modern central heating systems, not as inert as they were a decade or so ago, allow for quick adjustment of the amount of heat supplied depending on the weather conditions on any given day. In most large cities, heating nodes operate on an automated basis and have weather regulators. Depending on the air temperature, they are automatically turned off or on. Therefore, the length of the heating season (HS) itself and the variability of air temperature during this time will have a significant impact on the amount of energy consumed in a given HS.

It happens that during the ongoing HS, there may be an increase in air temperature above the set threshold value, and according to weather forecasts, this can persist for several days or even longer. In such cases, decisions can be made to significantly reduce or even turn off the heating system. Failing to adjust to the external thermal conditions can lead to overheating of the body, with serious health consequences or large energy losses due to the need to open windows.

The aim of the study is to determine the trends of the HDD values in selected large cities of Central Europe and to identify the trends of the start and end dates and the duration of the HS, often overlooked in such analyses.

Data and methods

In the study, average daily air temperature values, for the seasons 1961/62–2020/21, from 12 meteorological stations representing urban areas in five countries in Central Europe, were used (Fig. 1 and Table 1). The data come from the European Climate Assessment & Dataset (ECA&D database; Klein Tank et al. 2002) and the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB 2023).

Given the aim of the study, an important issue was the method of determining the start and end dates and, consequently, the duration of the HS. The initiation of the HS in various countries is administratively determined (by building managers) or individually by residents in households. In each case, the decision relates to a drop-in air temperature and the need to raise the temperature inside buildings. For example, in Russia, the HS begins in autumn on the day when the average daily air temperature falls below 8°C for five consecutive days, and it ends in spring on the day when, also for five consecutive days, the temperature rises above this value (Belova et al. 2018).

In this study, the start date of the HS is considered to be the first day of at least a 5-day sequence with temperatures equal to or below 15°C, occurring from 1st September or in the last days of August in cases where a sequence of ≥5 days begins before 1st September and continues beyond this date. The end date of the HS is defined as the

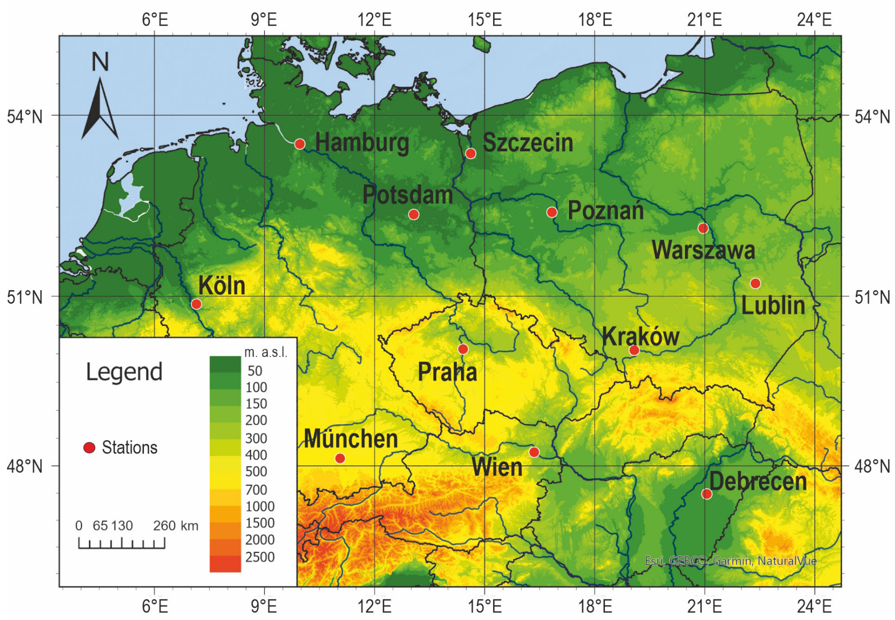

Fig. 1. Location of meteorological stations.

Table 1. Location of meteorological stations, number of populations of selected cities, and average long-term air temperature.

Station	Country	φ [N]	λ [E]	H [m a.s.l.]	Population in 2022* [Thousand]	Mean annual air temperature (1961–2020) [°C]
Debrecen	Hungary	47°29'	21°36'	107	204.1	10.4
Hamburg	Germany	53°32'	09°58'	29	1739.1	9.7
Köln	Germany	50°52'	07°09'	92	1073.1	10.3
Kraków	Poland	50°04'	19°48'	237	755.0	8.4
Lublin	Poland	51°13'	22°23'	239	360.0	7.8
München	Germany	48°08'	11°36'	521	1260.4	9.7
Potsdam	Germany	52°23'	13°04	81	183.4	9.3
Poznań	Poland	52°25'	16°50'	83	570.3	8.8
Praha	Czech Republic	50°05'	14°25'	190	1165.6	10.7
Szczecin	Poland	53°23'	14°37'	1	407.8	9.0
Warszawa	Poland	52°09'	20°57'	106	1702.1	8.4
Wien	Austria	48°15'	16°21	198	1691.5	10.9

* Data from *World Population Review* (www.worldpopulationreview.com).

last day of at least a 5-day sequence with temperatures equal to or below 15°C, occurring up to 31st May or in the first days of June in cases where a sequence of ≥5 days begins before May 31st and continues beyond this date. In the next step, the duration of the HS in each year was calculated. Dates for the start and end of the HS, as well as its duration, were compiled. The standard deviation, coefficient of variation, and trend for each of these parameters were calculated for each station.

Heating Degree-Days (HDD)

According to Buyukalaca et al. (2001), the degree-day method is the simplest climatic indicator used in the heating, air conditioning, and ventilation industry to estimate the demand for heating and cooling energy. It is commonly applied to link outdoor temperature with heating/cooling requirements of spaces, essentially estimating the amount of energy needed to maintain an optimal indoor temperature (Belova et al. 2018, Andrade et al. 2021). Bilgili et al. (2023) suggested that it can be used to update policies and scenarios for energy demand changes in a given region. The value of degree-days, in this case for heating, is an indicator quantifying how low the air temperature was. It assumes that energy consumption is proportional to the difference between the average daily air temperature and the base temperature. Various base temperatures have been used in numerous publications, including 15.5°C (Kodah, El-Shaarawi 1990), 18.0°C (Badescu, Zamfir 1999), or 18.3°C (Environment Canada 1988). A compilation of other values used in publications in this field has been presented in the articles by Atalla et al. (2018) and Harvey (2020). Generally, these values range from 10°C to 20°C (Harvey 2020).

According to Atalla et al. (2018), the HDD method has two main limitations: (1) the absence of an international database that would cover degree days in a functional temporal and spatial aggregation, taking into account different base temperature values and (2) the method considers only the impact of air temperature, while it ignores the influence of other meteorological elements, such as air humidity or solar radiation.

The HDD index is calculated based on a base temperature, defined as the lowest average daily air temperature that does not lead to the heating of a room. The base temperature value essentially depends on several factors related to the building and its surrounding environment. Using a general climatological approach in HDD calculations, the base temperature is set as a constant value of 15°C. For any given day, this number is equal to zero if the average daily temperature exceeds 15°C, and for average daily temperatures below 15°C, it is calculated in this study as:

$$HDD = \Sigma(18°C - T^i m) \text{ for each day when } T^i m \leq 15°C.$$

$$HDD = 0 \text{ for days when } T^i m > 15°C$$

where T^i_m is the mean air temperature of day i.

Degree days over the consecutive days of the HS are summed up, providing information on the heat demand for the entire season.

To determine trends in the characteristics of the considered HS, a linear equation was used, with statistical significance assessed at the 0.05 level using Spearman's rank correlation coefficient and the Mann–Kendall test. Spearman's rank correlation was chosen due to the non-parametric nature of the data, which does not meet the assumptions of Pearson's correlation, such as normality or linearity (Hauke, Kossowski 2011). It is particularly suitable for monotonic relationships between ordinal or non-normally distributed variables and is less sensitive to outliers. Given the similar results, only Spearman's rank correlation coefficients are presented.

Additionally, an analysis of the relationship between various HS parameters and both the population size and the average annual air temperature, taking into account values from all stations included in the study, was conducted. For this purpose, bivariate scatter plots (dependency models) were used. Since many scatter plots showed a gradual increase or decrease in the analysed relationships, similar to linear, a simple linear regression technique was applied in model construction. The degree of model fit to the analysed data was assessed using the coefficient of determination (R^2). This value allows assessing to what extent the estimated model explains the original variance of the dependent variable's values and what percentage of this variance is random or can be explained by the influence of other independent variables not included in the model

(Wątroba 2007). Such regression models enable a better understanding of the variables under study through a quantitative description of the nature and strength of the association between them, and when they are well fitted to the data, they can be used for predicting or simulating the values of the dependent variable at specified values of independent variables (Wątroba 2007).

Study area

The research covered the area of Europe between 47° and 53° North latitude and 7–22° East longitude (Fig. 1 and Table 1). The lowest situated city was Szczecin (1 m a.s.l.), while the highest was München (521 m a.s.l.). Among the selected cities, one-third had a population ranging between 180,000 and 500,000, with Potsdam being the smallest, and 50% were cities with a population of over 1 million. The largest of these were Hamburg and Warszawa (Table 1).

The simplest measure for assessing climatic conditions in the studied area is comparing the average annual air temperature values in selected cities (Table 1). The warmest city over the period studied (1961–2020) was Wien (10.9°C), while the coldest was Lublin (7.8°C).

Results

Between the years 1961/62 and 2020/21, the start of the HS was typically noted in the first decade of September in the eastern part of the discussed area (e.g., Lublin; 6 September), at the beginning of the second decade of September in German cities (e.g., Potsdam; 12 September), in the second half of the second decade of September in Praha and Debrecen (18 September), and the latest in the third decade of September in Wien (24 September; Table 2). The start of the HS was characterised by significant variability from year to year (Fig. 2). This variability was similar across the analysed stations, although the greatest variability was observed in Potsdam, München, and Praha (σ = 11.7 days) and Debrecen (σ = 11.6 days). During the study period, the HS started earliest in Szczecin on 19 August 1981. The latest start of the HS occurred in Praha and Wien on 12 October, in 2011 and 1985, respectively. From these data, it is evident that the range of variability in the start date of the HS was about 2 months. Wien exhibited the least variability in the start date of the HS (V = 3.7%), followed by Kraków and Lublin (V = 3.8%). It was found that in most stations, the start of the HS occurred later than at the beginning of the analysed multi-year period, except for Hamburg, Köln, and Münich. The greatest rate of change was recorded in Warszawa, at 1.97 days per decade, and only there were the changes statistically significant (Table 2).

In the seasons from 1961/62 to 2020/21, the HS ended average in Debrecen (12 May), Wien (15 May), and Praha (16 May) and latest in Köln, Lublin, and Szczecin (26 May). Similar to the

Table 2. Statistical characteristics of the beginning, end, and duration of the heating season at selected stations in Central Europe in 1961/62–2020/21.

Station	Start [date]				End [date]				Duration [days]			
	Mean	σ [days]	V [%]	Trend [per 10 years]	Mean	σ [days]	V [%]	Trend [per 10 years]	Mean	σ [days]	V [%]	Trend [per 10 years]
Debrecen	18.09	11.6	4.4	0.68	12.05	14.2	2.9	−1.75	238.6	18.1	7.6	−2.43*
Hamburg	11.09	10.3	4.0	−0.01	25.05	9.9	1.9	−0.22	258.0	14.1	5.5	−0.21
Köln	11.09	10.6	4.1	−0.07	26.05	9.4	1.8	−1.49*	259.3	13.2	5.1	−1.43
Kraków	09.09	9.6	3.8	1.26	25.05	11.1	2.2	−1.79*	260.1	14.8	5.7	−3.05*
Lublin	06.09	9.6	3.8	1.23	26.05	10.8	2.1	−0.66	263.9	13.5	5.1	−1.89*
München	13.09	11.7	4.5	−0.90	25.05	10.9	2.1	−1.03	256.1	15.0	5.9	−0.13
Potsdam	12.09	11.7	4.6	0.65	25.05	11.1	2.2	−1.35	257.6	16.2	6.3	−2.01
Poznań	09.09	10.1	4.0	1.48	23.05	12.3	2.4	−1.59	258.3	15.8	6.1	−3.07*
Praha	17.09	11.7	4.5	0.69	16.05	14.7	2.9	−2.63*	243.6	19.1	7.9	−3.32*
Szczecin	09.09	10.9	4.3	1.12	26.05	10.4	2.0	−1.31	260.9	15.3	5.8	−2.43*
Warszawa	09.09	11.5	4.5	1.97*	22.05	13.7	2.7	−1.52	256.5	17.3	6.8	−3.50
Wien	24.09	9.9	3.7	0.59	15.05	15.2	3.0	−2.56*	235.4	15.3	6.5	−3.16*

* Statistically significant changes at a level of 0.05; σ – standard deviation; V – variation coefficient.

start dates, significant year-to-year fluctuations were also noted for the end dates. These fluctuations were greater in stations located in the eastern part of the area and smaller in the west compared to the start of the HS. This is confirmed by the standard deviation values ranging from 9.4 in Köln to 15.2 in Wien. The earliest end of the HS was recorded on April 4, 2009, in Wien (Fig. 2). It is noteworthy that for most stations, the earliest ending was characteristic of the 2017/18 season. The latest HS ended on 17 June 1975 in Lublin. The range of variability for the end date of the HS was larger compared to the start of the HS, amounting to about 2.5 months. The variability of the end date of the HS increased from west to east of the discussed area – the coefficient of variation ranged from 1.8% in Köln to 3.0% in Wien. In all stations, there was a tendency for the HS to end earlier; however, the rate of this change varied significantly, ranging from −0.22 days/10 years in Hamburg to −2.63 days/10 years in Praha. Changes were statistically significant only in Köln, Kraków, and Wien.

The average duration of the HS in the seasons from 1961/62 to 2020/21 ranged from 235 days in Wien to 264 days in Lublin (Table 2). Year-to-year fluctuations, similar to the two previous characteristics, varied across Central Europe, as confirmed by standard deviation values ranging from 13.2 days in Köln to 19.1 days in Praha. The shortest season was in 1999/2000 in Debrecen, lasting only 193 days, and in Praha, 195 days. The longest HS occurred in Hamburg at the turn of

Fig. 2. Dates of start and end and duration in the particular heating seasons in Central Europe in the period 1961/62–2020/21.

1986/1987, lasting 292 days. Therefore, the range of fluctuations in duration across all stations was as much as 97 days. The coefficient of variation ranged from 5.1% in Köln and München to 19.1% in Praha. The heating period has shortened across the entire area considered, but these changes do not occur uniformly everywhere. The smallest changes were noted in München and Hamburg (respectively −0.13 and −0.21 days/10 years). The tendency for the greatest changes occurs in Warszawa (−3.50 days per 10 years) and Praha (−3.43 days per 10 years). Statistically significant changes are characteristic of Praha, as well as Debrecen, Lublin, Kraków, Poznań, Szczecin, and Wien. Of course, the varied change in the duration of the HS is a consequence of the uneven shifting of the start and end dates of this period in the area studied.

The demand for heat, as determined by the HDD coefficient in the seasons from 1961/62 to 2020/21 in Central Europe, is lowest in the southern and western parts, ranging from 2749°C in Wien to 3669°C in Lublin (Table 3). The spatial distribution reflects the air temperature distribution and the influence of local conditions. The western part of the study area is characterised by the least variability of the HDD coefficient, as indicated by the standard deviation from 261.9°C in München to 267.5°C in Hamburg. The greatest variability is observed in Warszawa (σ = 350.7°C), Poznań (σ = 341.8°C), and Szczecin (σ = 337.2°C). The maximum HDD values in most stations, i.e., in 9 of the 12, occurred in the 1962/63 season, ranging from 3470°C in Wien and 3471°C in Köln to 4209°C in Warszawa. However, the highest HDD, equal to 4375°C, characterised the 1986/87 season in Lublin. The lowest demand for heat occurred in the 2006/07 season at all stations, with HDD ranging from 1963°C in Praha to 2916°C in Lublin. The variability of heat resources was greatest in Praha (V = 10.7%), Szczecin (V = 10.4%), and Wien (V = 10.3%), while Lublin (V = 8.5%) and München (V = 8.6%) showed the least variability.

Across the entire studied area of Central Europe, the demand for heat during the HS decreased in the years 1961/62–2020/21 (Fig. 3). The analysis of the trend variability showed that the most significant changes occurred in the central and northern parts and smaller changes in the southern and western parts of the study area (Fig. 3). These changes are statistically significant everywhere. The tendency for the greatest changes occurs in Warszawa (−117.4°C per 10 years) and Praha (−113.2°C per 10 years). The decidedly slowest pace of decline in heat demand occurs in Hamburg (−55.9°C per 10 years).

There is noticeable variability in the demand for heat in the successive months of the HS across different regions of Central Europe, reflecting the frequency of days characteristic of this period (Fig. 4). In months where the season started earlier or ended later (August and June), such days occurred sporadically, especially in the southern part of the discussed area, and most frequently in Lublin. September is characterised by spatial variability resulting from the start dates of the HS at various stations. Days typical of the HS

Table 3. Statistical characteristics of heating degree-days (HDDs) in particular stations in Central Europe in the period 1961/62–2020/21.

Station	Mean	Max	Min	σ	V	Trend
	[°C]	[°C] (year)		[°C]	[%]	[°C per 10 years]
Debrecen	2986	3541 (1963/64)	2296 (2006/07)	279.4	9.4	−87.92*
Hamburg	2964	3526 (1962/63)	2171 (2006/07)	267.5	9.0	−55.86*
Köln	2783	3471 (1962/63)	1971 (2006/07)	261.9	9.4	−92.38*
Kraków	3476	4113 (1995/96)	2752 (2006/07)	314.2	9.0	−95.47*
Lublin	3669	4375 (1986/87)	2916 (2006/07)	312.9	8.5	−83.69*
München	3053	3817 (1962/63)	2286 (2006/07)	263.2	8.6	−85.53*
Potsdam	3162	3850 (1962/63)	2237 (2006/07)	318.9	10.1	−103.89*
Poznań	3336	4118 (1962/63)	2511 (2006/07)	341.8	10.2	−110.25*
Praha	2810	3556 (1962/63)	1963 (2006/07)	301.4	10.7	−113.16*
Szczecin	3228	4044 (1962/63)	2323 (2006/07)	337.2	10.4	−107.35*
Warszawa	3485	4209 (1962/63)	2651 (2006/07)	350.7	10.1	−117.38*
Wien	2749	3470 (1962/63)	2012 (2006/07)	283.5	10.3	−102.35*

* Statistically significant changes at a level of 0.05; σ – standard deviation; V – variation coefficient.

occurred most frequently in Lublin, Warszawa, and Poznań, and least frequently in stations located in the south, e.g., Wien, Praha, and Debrecen. October and March exhibit the most even spatial distribution of days characteristic of the HS. From November to February, especially

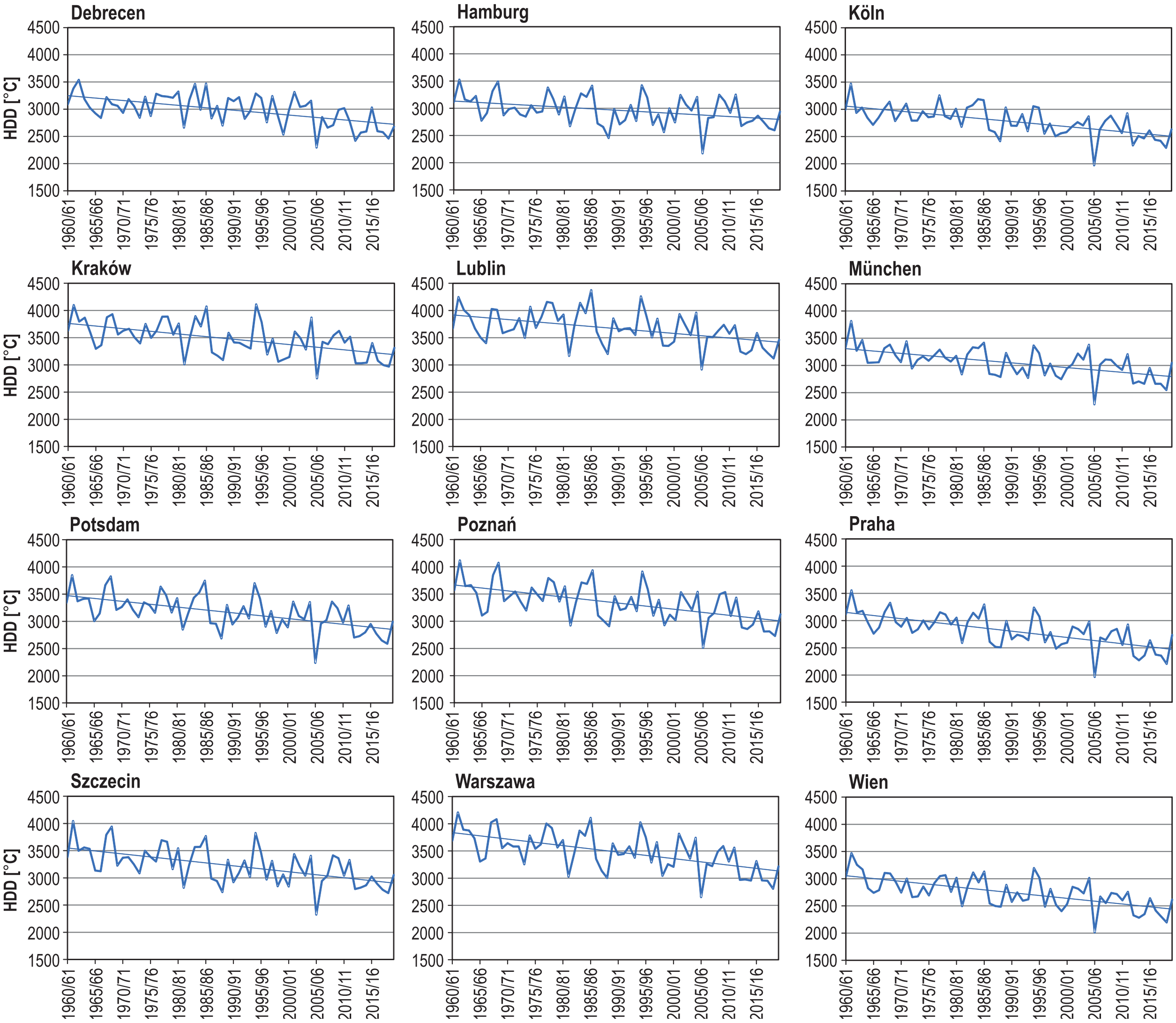

Fig. 3. Sum of heating degree-days (HDDs) in the particular heating season (HSs) in Central Europe in the period 1961/62–2020/21.

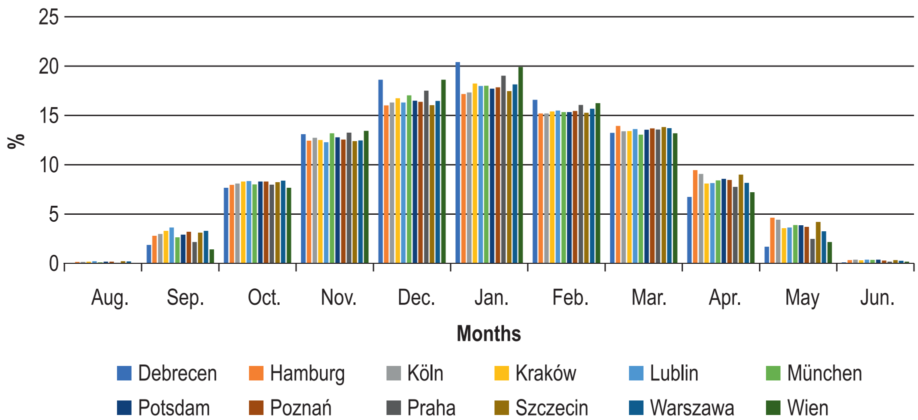

Fig. 4. Monthly frequency of the number of heating degree-days (HDDs) during heating season (HS) in Central Europe in the period 1961/62–2020/21.

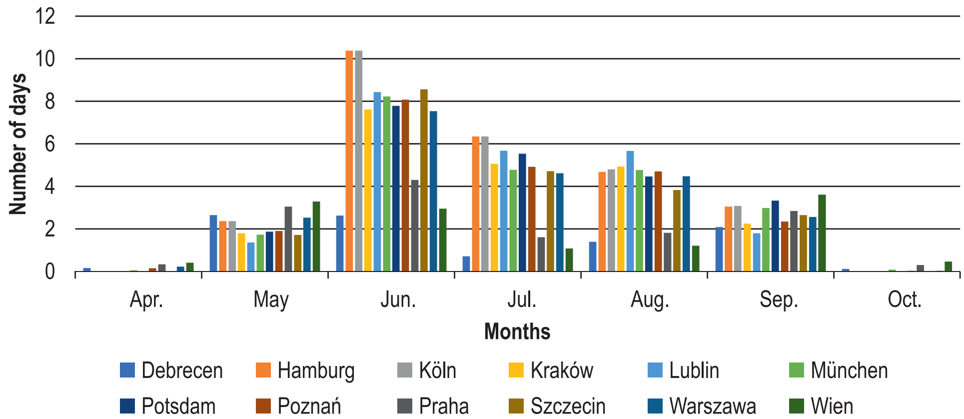

Fig. 5. Monthly number of heating degree-days (HDDs) outside the heating season (HS) in Central Europe in the period 1961/62–2020/21.

in December and January, the highest frequency of days characteristic of the heating period is observed in southern areas, i.e., Debrecen, Wien, Praha, and München. Such days appear least frequently in Köln and Hamburg during this time. The situation reverses at the end of the HS, when the demand for heat significantly drops in stations located in the south, hence the frequency of characteristic days decreases.

On the other hand, individual days characteristic of the heating period also occur outside the designated season (Fig. 5). They most commonly appear in June at all stations of the discussed region, but their number is also significant in July

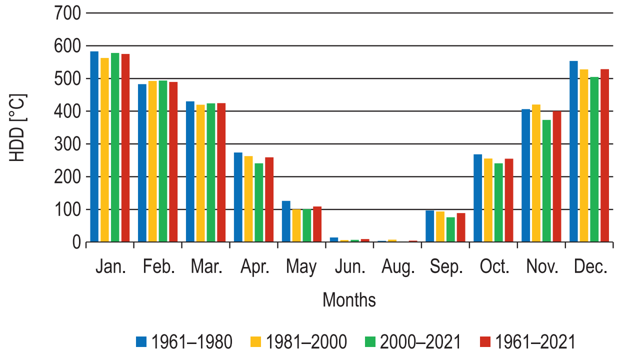

Fig. 6. Heating degree-days (HDD) in degree days. The mean monthly values in heating seasons (HS) in three 20-year periods and years 1961/62–2020/21.

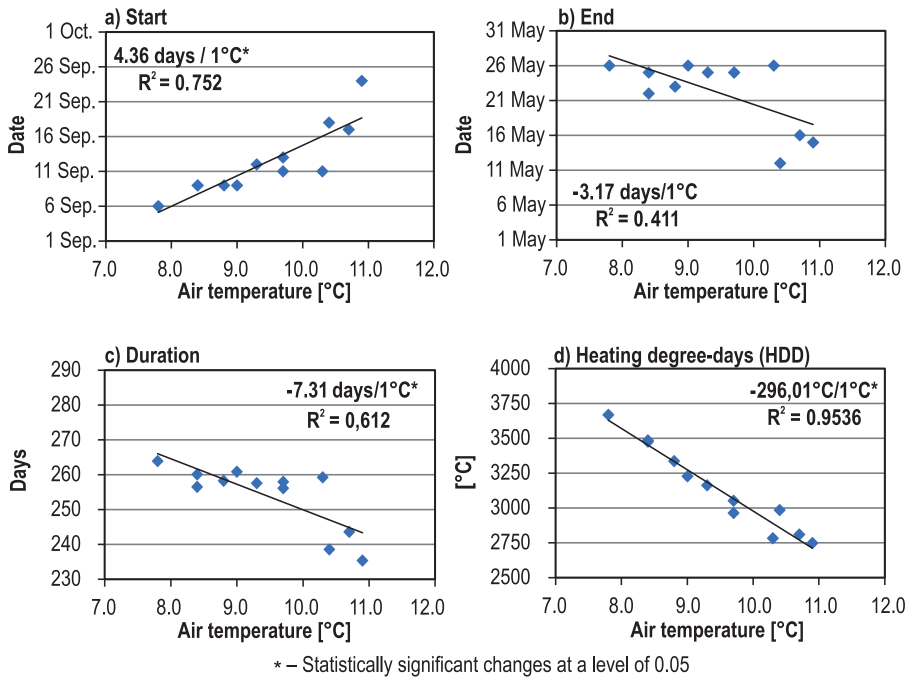

Fig. 7. The relationship between the average annual air temperature and the parameters of the heating season (HS): (A) start date, (B) end date, (C) length, and (D) heating degree-days (HDD).

and August. During the summer months, such days occur least frequently in stations from the southern part of the region. However, in months outside the HS, it is precisely in these southern stations that there are more days with increased demand for heat than in the others.

The HDD index exhibits a very clear annual pattern with a peak in January exceeding an average of 575-degree days. In all months of the HS, including the summer months, the average HDD value is greater than zero (Fig. 6). Average values for subsequent 20-year periods were compared with the long-term average. A clear decline in HDD over the subsequent decades is noted in April, September, October, and December. In February, the demand for heat increased in subsequent decades. A less significant decrease in HDD occurred in May.

The final stage of the conducted research was the analysis of the relationship between various Heating Season (HS) parameters and the population size and average annual air temperature. It was found that, based on data from selected cities in Central Europe, the population size did not have a statistically significant impact on the individual parameters of the studied season. However, in the case of the average annual air temperature, the relationships turned out to be statistically significant in most cases. It was observed that with an increase in the average annual air temperature in Central Europe by 1°C (Fig. 7):

- the start of the season occurs approximately 4 days later ($r < 0.05$),
- the end date proved to be not statistically significantly correlated,
- the season duration is shorter by around 7 days,
- the total HDD is lower by around 300°C.

Discussion

Research by Deroubaix et al. (2021) indicated that across all continents, climate-induced trends in energy demand for heating and cooling were weak. They changed by <10% between 1950 and 1990, although they became stronger between 1990 and 2030 (changing by >10%). In the case of upward trends, those in the demand for energy for cooling are more pronounced than the downward trends for heating, which additionally vary greatly depending on the individual climate change simulations, ranging from a few to several 100% in most densely populated areas located at mid-latitudes (Deroubaix et al. 2021).

A greater delay in the start of the HS, averaging 0.97 days per decade, as well as an acceleration of the end of the HS by 1.49 days per decade, was recorded in China for the years 1960 to 2020 (Shen et al. 2017). In the north-eastern part of China, however, these changes were smaller (Shen, Liu 2016). The start of the HS shifted by an average of 0.77 days per decade, but the end was accelerated by 1.19 days per decade, similar to Central Europe. In the distant future, changes in both the start and end of the growing season will occur much more intensely than in the near future (Szyga-Pluta et al. 2023a). The most intense changes are forecasted in the long-term perspective in the scenario involving a high level of greenhouse gas emissions.

The HS in China is shortening more rapidly, occurring at 2.47 days per decade (Shen, Liu 2016), although in the northeastern part of China, the rate is slower, averaging 1.97 days per decade. Undoubtedly, the shortening of the heating period is linked with the lengthening of the growing season, which is happening in Central Europe at a rate ranging from 2.14 days per decade in Toruń to 3.88 days per decade in Praha (Szyga-Pluta et al. 2022, 2023b).

Central Europe is characterised by significant spatial variability in changes to HS characteristics. This is confirmed by research conducted by Verbai et al. (2014) in Hungary, which indicated differences of up to 10% across the country.

Mourshed (2011) calculated that since the beginning of the 20th century, the sum of HDD has decreased by 11%–18% depending on the threshold temperature (8°C, 10°C, 12°C) and location in Switzerland. Papakostas et al. (2010) demonstrated that between 1983 and 2002, the reduction in demand for heating energy was 11.5% in Athens and 5% in Thessaloniki, while the increase in energy for cooling degree-days (CDD) was 26% and 10%, respectively. According to Andrade et al. (2021), scenarios for changes in Portugal indicate that the decrease in HDD will be higher than the increase in CDD.

A significantly smaller decline in the demand for heat was observed by Wibig (2003) for Łódź in an earlier period, from 1931 to 2001, where it amounted to −30.6 degree days per decade. But in the second half of the 20th century, the trend in Łódź became more evident, statistically significant at the 5% level, reaching −58.5 degree days per decade. In China, a decrease in the demand for heat was also observed, and it was lower than in Central Europe, averaging 63.22°C per decade (Shen et al. 2017), and in Northeast China, 66.28°C per decade (Shen, Liu 2016).

Studies by Santamouris et al. (2001) and Kolokotroni et al. (2012) conducted in Athens (Mediterranean climate) and London (oceanic climate) show that UHIs contribute to annual energy savings in buildings by significantly reducing the demand for heating energy (about −30%) compared to a much smaller increase in energy needed for cooling rooms (+13%). According to Magli et al. (2015), the most significant effects of UHI during the cooler season occur at night, whereas during the day, since solar radiation reaches its highest values, the temperature of the external roof surface does not change significantly in urban and suburban areas. Studies by Ramon et al. (2020) conducted in Belgium indicated that smaller reductions in average HDD were observed in urban areas compared to rural areas, but higher relative reductions were found for seaside and urban areas. Therefore, the relative reduction in urban areas is stronger than in rural areas.

For the entire European continent, Spinoni et al. (2018) conducted an analysis of change trends up to the year 2100. Based on climate change simulations, the authors observed a significant decrease in HDD, most strongly pronounced in Scandinavia and the European part of Russia, and an increase in CDD, especially in the Mediterranean region and the Balkans. Nonetheless, if population-weighted trends in degree days are considered, there are no significant differences. A scenario with a constant population suggests that the decrease in HDD will balance the increase in CDD in the 21st century across most of Europe. However, if demographic forecasts are included in the calculations, the authors believe that despite the increase in air temperature, energy demand will increase over northern Europe, the Baltic countries, Great Britain, Ireland, Benelux, the Alps, Spain, and Cyprus (Spinoni et al. 2018).

Conclusion

Data from 12 Central European stations provided the basis for analysing the spatial and temporal variability of the HS characteristics, namely the start and end dates and their duration, as well as the demand for heat expressed as HDD, calculated for a threshold of 15°C.

In Central Europe, the HS in the years 1961/62–2020/21 lasted, on average, 254 days, starting on average on 12 September and ending on 25 May. The average HDD value for the season was 3142°C. For comparison, the mean value of HDD during the cold season (September–April) in Łódź (Poland) is 3478°C (Wibig 2003). In Hungary, the average value ranges from 3156.4°C to 3262.76°C depending on the database considered (Verbai et al. 2014).

It was found that the start of the HS has been delayed at most of the studied stations by an average of 0.61 days per decade, and its ending has been accelerated across the entire studied area by an average of 1.18 days per decade in the years 1961/62–2020/21.

Accordingly, the duration of the HS in Central Europe has decreased by an average of 1.46 days per decade. Consequently, there was also a decrease in the demand for heat. HDD decreased by an average of 96.3°C per decade.

Generally, fluctuations in HDD values indicate that in spring, the demand for heat is characterised by smaller variations than in autumn, whereas the greatest decline in HDD over the long term is observed in April, September, October, and December. A less significant decrease in HDD occurred in May. This suggests that in autumn, the demand for heat may vary significantly from year to year, especially considering that studies conducted in Poland indicate that this season is characterised by the smallest warming among all seasons (Kożuchowski 2000, Wibig, Głowicki 2002, Wibig 2003, Ustrnul et al. 2021).

The spatial distribution of changes in the length of the HS does not exactly match the change in HDD. The increase in temperature seems to have a greater impact on the duration of the HS in the warmer southern stations, but a more pronounced effect on HDD is observed in the northern regions of Central Europe. It was found that in the warmer regions of Central

Europe, with a higher average annual air temperature, the season starts approximately 4 days earlier, is longer by about 7 days, and is characterised by a decrease of about 300°C in HDD value for every 1°C increase in average annual temperature. However, the end date of the season did not show statistically significant changes depending on the average annual air temperature.

The significant year-to-year variability of HS characteristics also determines the spatial diversity of these changes. Some of these changes are associated with economic losses, while others bring benefits. The shortening of the heating period and the decrease in the HDD index lead to lower heating costs and a reduction in air pollution.

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Author's contribution

K.S.-P.: investigation, methodology, writing – original draft, writing – review & editing, conceptualisation, visualisation, and data curation; K.P.: supervision, writing – review & editing, conceptualisation, methodology, visualisation, and data curation.

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