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Analysis of heating and cooling periods in Budapest using station data

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Abstract— The built environment has a very complex role in cities. On the one hand, various urban climatological phenomena are caused and influenced by buildings (e.g., urban heat island effect, local wind conditions, air pollution). On the other hand, buildings are important contributors to energy use via heating and cooling, e.g. they account for about 40% of total energy consumption on average in Europe. Daily average outdoor temperature is taken into account to design the heating and cooling systems of residential, commercial, or office buildings. That is why we analyzed the available temperature time series of the capital of Hungary, Budapest for the period between 1901 and 2019. The aims of this study are (i) to investigate the changes in temperature data series that influence building energy design parameters, (ii) to analyze the heating and cooling periods in the last 119 years based on different definitions, and (iii) to define a third (transitional) period between the heating and cooling periods. Based on the results, it can be concluded that the variability of warm days is smaller than that of cold days, consequently, the optimal design of heating systems is a greater challenge compared to cooling systems. Furthermore, the length of the temperature-based heating period decreased substantially, while the length of the cooling period increased as a consequence of overall regional warming.

Key-words: air temperature, heating system design parameter, heating and cooling period definitions, frequency distribution, regional warming, warm and cold extremes

1. Introduction

Nowadays, one of the most important global environmental problems is climate change. In addition to warming trends, other substantial changes can also be observed in the past few decades, for example, the increase of the frequency of extreme temperatures (*IPCC*, 2013, *Meehl* and *Tebaldi*, 2004). The changes draw a spatial pattern with different trends in different regions (*Seneviratne et al.,* 2006). Several studies have also been conducted for the Carpathian Basin. For instance, *Bartholy* and *Pongrácz* (2007) and *Pongrácz et al.* (2009) examined the effect of climate change on temperature and precipitation extremes using station data and regional climate model simulations. Furthermore, *Spinoni et al.* (2015) analyzed the increasing trends of heat waves and the decreasing trends of cold waves on the basis of gridded data. Climate change has an impact on the urban climate as well (*Masson et al.*, 2014, *Bokwa et al.*, 2018) in addition to several special effects due to artificial surfaces and built-up areas (e.g., the urban heat island effect, see *Oke*, 1973).

More than half of the world total population lives in cities, and the ratio is even greater in Europe (*United Nations*, 2015); therefore, it is necessary to analyze the climatological conditions affecting the urban areas. Buildings have fundamental roles in cities, because on the one hand, buildings are key factors in determining the urban climate, on the other hand, they substantially contribute to the energy use, e.g., they account for 40% of total energy consumption in the European Union (*Directive 2010/31/EU*, 2010). The energy consumption of buildings and the design parameters of energy systems depend on the outdoor air temperature. *Cho et al.* (2004) examined the relationship between energy consumption and temperature, and a regression model was built for a commercial building located in a South Korean city. Furthermore, *Roberts* (2008) investigated the impacts of climate change on buildings, and highlighted the effects of warming among the possible impacts. Further studies were carried out on the effects of urban heat island intensity and heat load on buildings and built-up areas, *Short et al.* (2004) focused on Great Britain, whereas *Bokwa et al.* (2019) studied five Central European cities (i.e., Bratislava, Brno, Krakow, Szeged, Vienna) taking into account the possible regional climatic changes. Since a specific temperature interval ideal for personal preferences has to be maintained inside buildings, neither too cold, nor too warm outdoor conditions are acceptable indoors, consequently, the energy demand of buildings highly depends on the outdoor temperature, from which the ideal conditions should be set. Too cold (warm) conditions can be specified by heating (cooling) demands, heating (cooling) degree-days, etc. Some studies aimed to analyze the heating and cooling degree-days, i.e., for Lithuania (*Martinaitis*, 1998) and Serbia (*Janković et al.*, 2019). *Kaynakli* (2008) determined the heating period for 14 years to optimize the insulation of buildings in Bursa, Turkey. According to the conclusions, the length of the heating periods was between 206 and 239 days in the fourth most populated city located in northwestern Turkey, moreover, the maximum energy demand did not occur in the case of the longest heating period.

As it is mentioned above, the heating and cooling periods have an important role in building energy calculations, but their definitions are not uniform in different regions, they are based partly on actual temperature measurements and partly on calendar days. For example, Italy can be divided into the following six climatological zones, where heating systems start and end on different dates (*Bottio et al.*, 2014):

- Zone 1: from December1 to March 15,
- Zone 2: from December 1 to March 31,
- Zone 3: from November 15 to March 31,
- Zone 4: from November 1 to April 15,
- Zone 5: from October 15 to April 15,
- Zone 6: no heating is necessary throughout the year.

These zones represent the substantial extension of Italy from south to north. As we move towards the north, the overall climate becomes colder and the heating period becomes longer. Another example illustrates this climatic feature from Central Europe, namely, the official heating period lasts from September 1 to May 31 in Slovakia. More precisely, the heating must be started during this period, when the average daily temperature remains below 13 °C for two consecutive days (*Ministry of Economy*, 2005). Unlike these two countries, there is no official definition in Germany, however in practice, the heating period is between October 1 and April 30 (heating period definition in Germany).

The target area of our study is Budapest, the most populated city and capital of Hungary. Several studies have already evaluated the urban climatological conditions in Budapest, e.g., the extreme temperature values (*Göndöcs et al.*, 2018) or the urban heat island intensity using satellite data (*Pongrácz et al.*, 2010). In addition, the relationship between energy parameters and air temperature has also been analyzed for Hungary (*Talamon et al.*, 2016). The main aim of the present paper is to investigate the heating and cooling periods in Budapest, however, there are several definitions for the beginning and end of these periods, which will be compared. According to the current official regulations (*Government Decree* 157/2005. (VIII.15.)), the heating period is between September 15 of the actual year and May 15 of the following year. It is divided into three parts by the *FŐTÁV Zrt.* (2020): pre-heating period (between September 15 to October 14), heating period (between October 15 to April 15) and post-heating period (April 16 to May 15). In addition, there are unofficial definitions for the heating period, which fix the beginning and end of the period using different temperature threshold values. The part of the year outside the heating period is called the cooling period (*Talamon*, 2014).

We aim to address the following objectives: (1) to examine the extreme cold and extreme warm days, (2) to compare temperature-based and calendar-based cooling and heating periods, (3) to define a third, transitional period, and to determine the average temperature and average length of the three periods, (4) to investigate the relationship between the climate change and the heating/cooling periods using the different definitions.

2. Data

In general, daily average temperature values are used for the building energy planning (e.g., *Matzarakis* and *Balafoutis*, 2004, *Christensen et al*., 2006, *Mourshed,* 2016, *Cheng and Li*, 2018), including the heating system design parameters. Because of its common use, we also used daily temperature data for Budapest. The station data series of five Hungarian cities are publicly available on the website of the Hungarian Meteorological Service for the period 1901–2019. The daily datasets include the following variables: mean temperature, maximum and minimum temperature, precipitation amount, precipitation type, sunshine duration. In this study we focus on Budapest, because this is the largest and most populated city of Hungary. The official measuring station of Budapest was relocated twice during the whole measuring period. The temperature measurements were performed near the Chain Bridge in the Buda side of the city, in Fő Street (47°30’3”N, 19°2’15”E) between January 1, 1901 and February 2, 1910. Then, the station was relocated to the instrumental garden near the Meteorological Institute in Kitaibel Pál Street (47°30’46”N, 19°1’34”E) and continued the measurements between March 1, 1910 and March 31, 1985. Since April 1, 1985, measurements have continued at Kitaibel Pál Street 1. On January 1, 1998, traditional thermometers were replaced with electric thermometers (https://www.met.hu/).

In order to evaluate the effect of instrument relocations and replacements, the mean temperature time series are compared to other databases. The entire study period can be covered using the Climate Research Unit Time-series (CRU TS) dataset. The CRU TS 4.03 version contains monthly average temperature values between 1901 and 2018 in high-resolution (0.5 degree) grids (*Harris et al.,* 2020, CRU dataset: http://www.cru.uea.ac.uk/). Moreover, the E-OBS v20.0e dataset (*Cornes et al*., 2018, E-OBS dataset: https://www.ecad.eu/) is available from January 1, 1950 to July 31, 2019, and CarpatClim is available between 1961 and 2010 (*Szalai et al*., 2013).

As a first step in the data evaluation, we selected the nearest grid points for the different geographical coordinates of the instrument from each database. As a second step, the root mean square error (RMSE) and the mean absolute error (MAE) were calculated for 3 years before and 3 years after each relocation and instrument replacement. *Table 1* shows the comparison with CRU TS dataset based on monthly data for the three above-mentioned dates occurring over the entire period. The largest difference in RMSE and MAE were observed at the first relocation in 1910, the differences are about -0.65 °C and -0.75 °C, respectively. For the second instrument relocation (1985), the RMSE and MAE differences are also around 0.1 °C, while RMSE is less than 0.05 °C and MAE is around 0.07 in the case of the transition to a digital instrument (in 1998).

Table 1. Time series comparison with CRU TS dataset, RMSE and MAE values 3 years before and 3 years after the relocation and instrument change based on monthly data

		3 years before March 1, 1907 – February 28, 1910	**3 years after March 1, 1910 – February 28, 1913**	**difference between after and before values**
compared with CRU TS dataset	RMSE (°C)	2.230	1.580	-0.649
	MAE (°C)	2.208	1.456	-0.752

		3 years before April 1, 1982 – March 31,1985	**3 years after April 1, 1985 – March 31,1988**	**difference between after and before values**
compared with CRU TS dataset	RMSE (°C)	2.112	2.008	-0.104
	MAE (°C)	2.069	1.969	-0.100

		3 years before January 1, 1995 – December 31, 1997	**3 years after January 1, 1998 – December 31, 2000**	**difference between after and before values**
compared with CRU TS dataset	RMSE (°C)	1.978	1.932	-0.047
	MAE (°C)	1.943	1.876	-0.068

The comparison between E-OBS and CarpatClim daily mean temperatures is shown in *Table 2* for the second relocation in 1985 and the instrument change in 1998. In both cases, MAE values are lower than RMSE values. RMSE and MAE values with CarpatClim dataset are very similar to RMSE and MAE values with CRU TS dataset. In contrast, the comparison with E-OBS shows much lower values than when the comparison is done with CRU TS, thus the similarity between station data and E-OBS gridded data is greater.

In addition, the distributions of the values 3 years before and 3 years after the two relocations and replacement were compared using a $\square^2$ homogeneity test. In the case of the two relocations, the before and after distributions can be considered homogeneous at the significance level of 0.95, while distributions before and after the replacement are homogeneous at the significance level of 0.90.

On the basis of the comparison and the $\square^2$ homogeneity test we conclude that the suspected breakpoints of the temperature time series can be eliminated.

Thus, for building energy planning we can use the mean temperature time series of the Hungarian Meteorological Service.

Table 2. Time series comparison with E-OBS and CarpatClim datasets, RMSE and MAE values 3 years before and 3 years after the relocation and instrument change based on daily data

		3 years before April 1, 1982 – March 31, 1985	**3 years after April 1, 1985 – March 31, 1988**	**difference between after and before values**
compared with E-OBS dataset	RMSE (°C)	0.201	0.216	0.016
	MAE (°C)	0.151	0.168	0.017
compared with CarpatClim dataset	RMSE (°C)	1.903	1.899	-0.003
	MAE (°C)	1.719	1.670	-0.049

		3 years before January 1, 1995 – December 31, 1997	**3 years after January 1, 1998 – December 31, 2000**	**difference between after and before values**
compared with E-OBS dataset	RMSE (°C)	0.235	0.377	0.142
	MAE (°C)	0.177	0.285	0.109
compared with CarpatClim dataset	RMSE (°C)	1.787	1.810	0.023
	MAE (°C)	1.548	1.556	0.008

3. Methodology

3.1. Analyzing the extreme low and high temperatures

It is important to take into account the extremes of daily average temperature in building energy planning, because the extremes determine the entire range of temperature from where the optimal indoor temperature interval should be maintained. Buildings must be prepared for the cold extremes during the heating season and for the warm extremes during the cooling season. For the purpose of this analysis, the coldest and warmest days were selected from each year, namely, altogether 10% of the whole year, i.e., 18 days for cold extremes and 18 days for warm extremes.

First, the cold extremes are shown in *Fig. 1.* These selected yearly extremes are represented by decadal box-whiskers diagrams. Furthermore, a linear trend is fitted to the 119-year-long time series of the average temperature of the 18 coldest days of each year. These cold days form a quite wide interval within the earlier decades of the entire period. The greatest difference between the minimum and maximum values is around 20 °C (in the 1920s and 1940s). Then, the whole range of the selected extremes decreased, the smallest range is only 10 °C in the 1990s, and it remained under 13 °C during the last two decades of the current analysis. This detected change stems from the lack of very extreme cold days with a mean temperature below -12 °C, whereas the higher cold extremes (i.e., the 5th percentiles) within the decades remained within the interval of freezing temperature, i.e., (-1 °C; 1 °C). Moreover, an overall warming trend of 1.9 °C/100 years can be clearly detected in Budapest based on the fitted linear trend to the yearly average temperature of the 18 cold days. This warming of the coldest days should certainly be taken into account when designing heating systems. It is clearly shown that lower values (even lower than -20 °C) occurred more frequently in the first half of the entire analyzed time period. In contrast, the median value of decades became higher since 1970, namely, more than half of the coldest 5% of the days of individual years were over -5 °C.

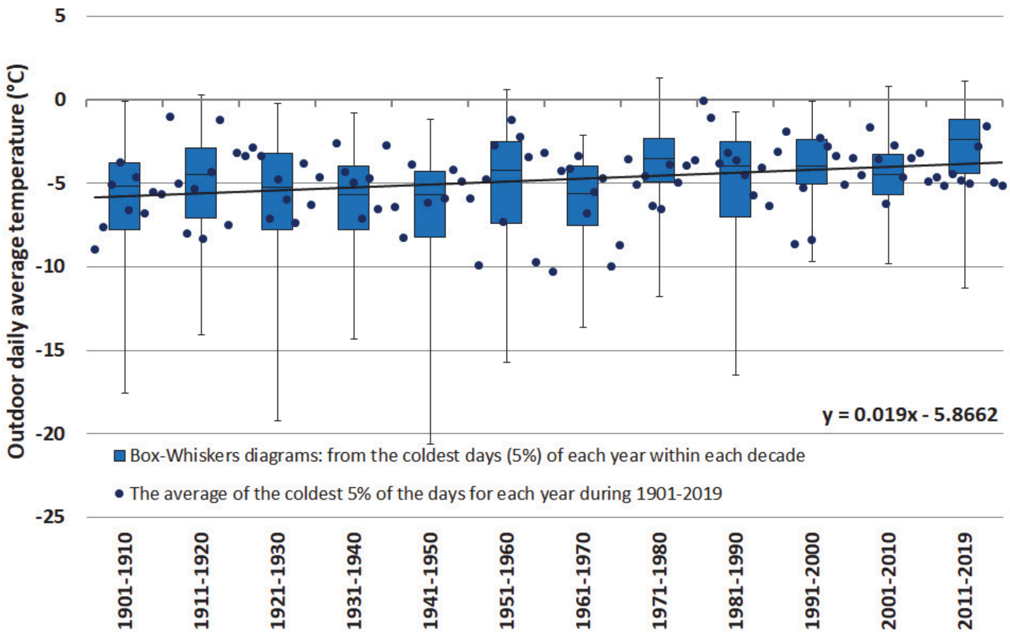


Fig. 1. The coldest 18 days of each year (5%) per decade on a box-whiskers diagram (with minimum, lower quartile, median, upper quartile, maximum) and the time series of the average of these 18 days per year (blue dots) with the fitted linear trend (the regression equation is also shown)

The same methodology was applied for the warmest 5% of days (*Fig. 2*). Temperature values of warm days form much narrower intervals than that of cold days. The greatest difference between maximum and minimum values is only 10 °C, which is the lowest difference in case of cold days. Moreover, the observed warming trend is slightly greater in warm days (2.2 °C/100 years) than in cold days. The decadal temperature intervals of warm extremes do not exhibit the decreasing width that can be detected in the cold days. This coincides with the increase of the intensity and frequency of heat extremes and heat waves due to climate change (*Lakatos* and *Bihari*, 2011; *Göndöcs et al.*, 2018).

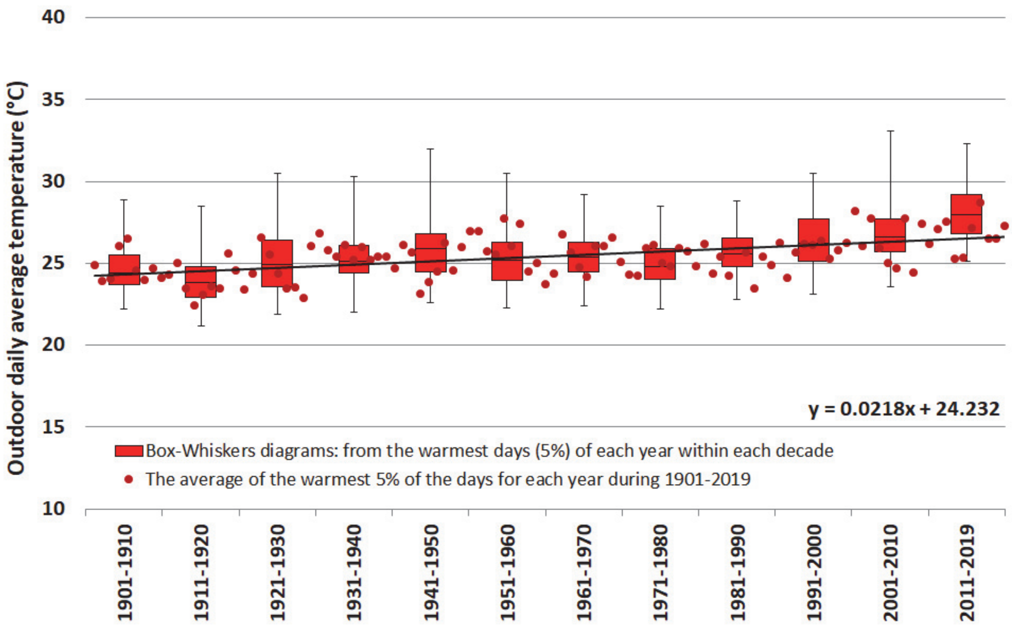


Fig. 2. The warmest 18 days of each year (5%) per decade on a box-whiskers diagram (with minimum, lower quartile, median, upper quartile, maximum) and the time series of the average of these 18 days per year (red dots) with the fitted linear trend (the regression equation is also shown)

3.2. *Analysis of standard deviation and empirical density function of temperature time series*

We evaluate the standard deviation and empirical density function of the 119-year-long time series in each decade as the second part of the analysis. Daily mean temperatures were ranked for each year from the coldest day to the warmest day. Then, the standard deviations for all the 365 ranked members were calculated for each decade. We selected two decades from the beginning (1901–1910, 1911–1920), middle (1951–1960, 1961–1970), and end (2001–2010, 2011–2019) of the study period, for which the results are shown in *Fig. 3* together with the average standard deviation for the whole 119-year period. This average standard deviation of extreme temperatures reaches 3 °C on the coldest days, whereas the standard deviation of the coldest days is 4 °C in the early 20th century. In general, the standard deviations of daily mean temperature during the ranked cold days decrease fast and are close to the 119-year average, except during 2001–2010, when they are much lower (between 1 °C and 1.5 °C). Then, the standard deviations during the rest of the year (i.e., when it is not so cold, more specifically, above the 15th percentiles) are within the interval of 0.5–1.5 °C. An overall slight decrease can be detected in the standard deviation, however, it is not monotonous and contains local maxima during the individual decades. There is a smaller second maximum (exceeding 1 °C) in the standard deviations of the warmest days of most decades as well as in the 119-year average standard deviations. Consequently, on the one hand, it is difficult to design heating systems due to the large variance in the temperatures of cold days. On the other hand, the smaller standard deviation values of the warmest days cause less challenge for the design of cooling systems.

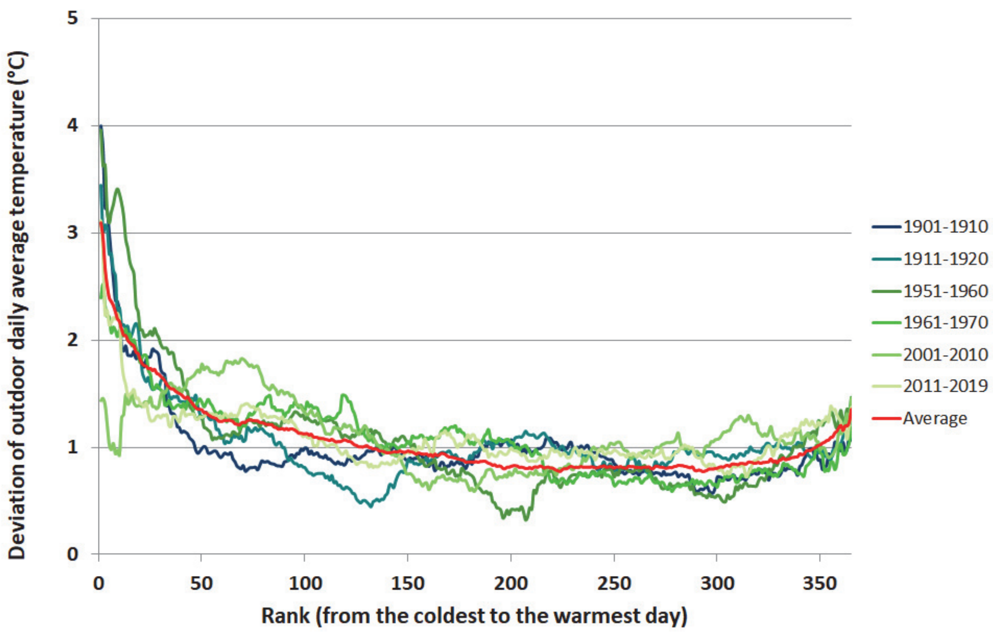


Fig. 3. The standard deviation of the sorted daily average temperatures from the coldest day to the warmest day for the beginning, middle, and end of the study period; in addition, the average of 119 years is also shown.

Finally, the empirical density functions of the selected decades and the total average of the 119 years are compared in *Fig. 4*. This calculation determines the average annual occurrence frequency of daily mean temperature from -10 °C to +35 °C using 1 °C resolution for the entire range. As the diagram shows, there are two peaks in the density functions, around 2–3 °C and around 20 °C. These two maximum locations occur because of considering the daily average temperatures of the entire year. The colder maximum represents the winter half-year, whereas the warmer maximum of the empirical density function refers to the summer half-year. The asymmetry between the left and right tails is because of the fact that cold extremes show much higher variability than warm extremes (as it was already demonstrated in *Figs. 1–3*). The greatest variability between decades can be seen in the range of 0–22 °C. Moreover, in case of high temperatures, the frequency was clearly higher in the last two decades than at the beginning or the middle of the century. The warmest extremes after 2000 are about 2–4 °C higher than before. So, all these imply that temperature-related changes in summer appears to be more obvious and clearer than in winter, therefore, building energy planning is easier on the basis of warm days than cold days.

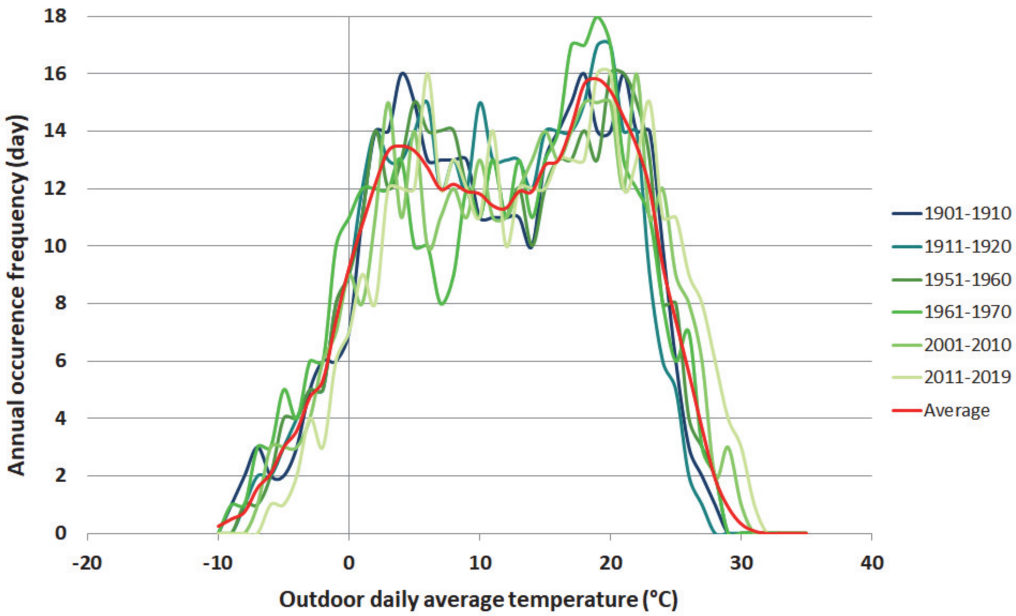


Fig. 4. The average annual occurrence frequency of the daily mean temperatures for the beginning, middle, and end of the study period; in addition, the average for the entire 119-year-long period is also shown.

4. Results and discussion

The previous section shows that cold and warm days changed to different degrees and with different variability over the past 119 years. Therefore, it is worth examining the cold and warm days separately. Our aim is to determine and analyze the heating and cooling periods based on the empirical density function presented in the previous section.

Three definitions were used to determine the heating and cooling periods:

1. TA (*Talamon*, 2014) definition:
   virtual heating and cooling periods are based on outdoor daily average temperature (lengths vary)
2. OA (October-April) definition:
   heating period is between October 15 and April 15 (length: 183 days), cooling period is between April 16 and October 14 (length: 182 days).
3. SM (September-May) definition:
   heating period is between September 15 and May 15 (length: 243 days), cooling period is between May 16 and September 14 (length: 122 days).

TA definition uses the properties of daily average temperature time series to determine the heating and cooling period (*Talamon*, 2014). As it was shown in Section 3 the standard deviation of cold days is much larger than the deviation of warm days. Furthermore, decadal density functions show clearer changes at higher temperatures. Therefore, we first determine the empirical density curve for the cooling season (i.e., summer) from the average density function of the 119 years. For this purpose, a partially symmetric density function is generated in the warm range using the temperature value of the highest frequency and the maximum temperature value. To obtain the empirical density curve of the virtual cooling period, the values of annual density function are reflected below its inflection point. Then, the virtual heating period is determined as the difference between the annual density function and the virtual cooling curve. In the OA and SM definitions heating and cooling periods were simply separated on the basis of calendar days. The density functions of the annual average and the heating and cooling periods for the three definitions are shown in *Fig. 5*. Because of the asymmetry in the annual average density function, the heating period covers a wider range of temperature values than the cooling period. Therefore, the occurrence frequencies of the cooling period are higher except for the SM definition (when the two parts of the year include substantially different number of days). The virtual heating and cooling curves based on the TA definition are very similar to the curves of the OA definition. The intersection of the heating and cooling curves coincides in the case of these two definitions around 11 °C. As a consequence of the SM definition, the heating period according to SM is clearly longer than the cooling period.

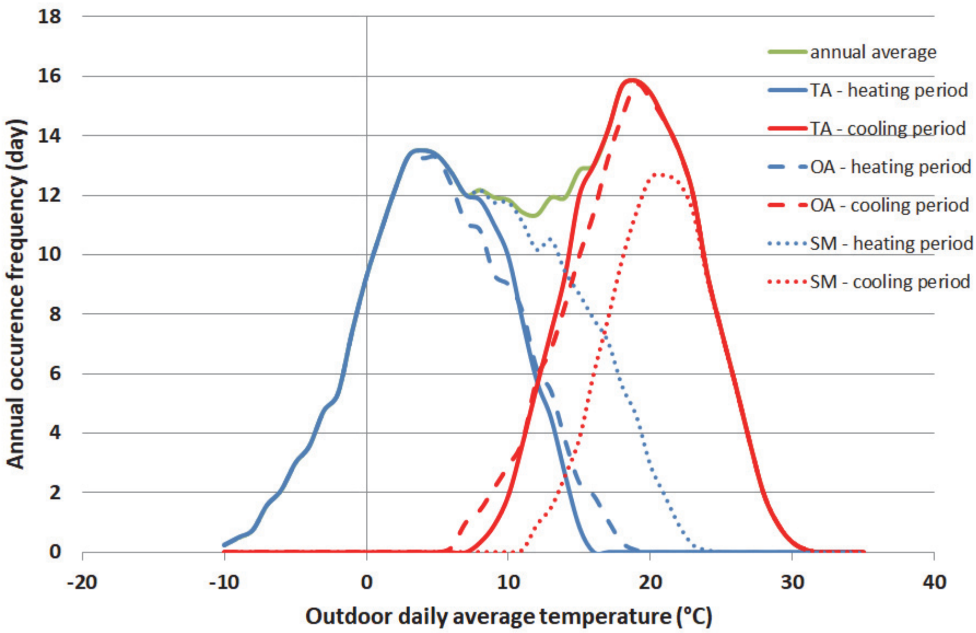


Fig. 5. The annual average empirical density function and the curves of heating and cooling periods for the average 119 years based on the three definitions.

As presented above, the whole year is divided into two parts from the aspects of building energy, namely, the heating and cooling period. However, the SM definition also includes a pre- and post-heating period representing the relatively fast inter-weekly temperature decrease and increase, respectively. Since the temperature of specific periods of the year changes from one year to the other, and also, an overall warming trend is identified due to global climate change (*Lakatos* and *Bihari*, 2011), a third period with higher inter-annual variability should be distinguished between the heating and cooling periods. For example, the autumn is becoming warmer (when cooling may be needed), while the typically winter low temperature values are extended to March or even April (with occasional heating demands). So instead of dividing the annual average density function into two parts, we separated the year into three different periods in the rest of the analysis. The common part of the heating and cooling curves is called the transitional period. Thereafter, the heating and cooling season does not include the transitional period. This procedure is applied to all the three definitions. *Fig. 6* shows the relationship between the average temperature of a period and the number of days within each period for the three definitions. According to the SM definition, more than half of the year belongs to the heating period (~ 200 days), while the cooling and the transitional periods last about the same number of days (~ 80 days each). When using this definition, the average temperatures are higher than in the other definitions, by 5 °C in the transitional period, and by 2 °C both in heating and cooling periods. The average temperatures of the different periods using the TA and OA definitions are similar, around 3-3.5 °C in the heating period, 20 °C in the cooling period, and 12 °C in the transitional period. The transitional period is longer when using the TA definition than the OA definition. The comparison also shows that the TA definition, which is based on temperature, results in similar values overall to the OA definition (which is the most often used definition in Hungary), but it is more flexible and can reflect climate changes better.

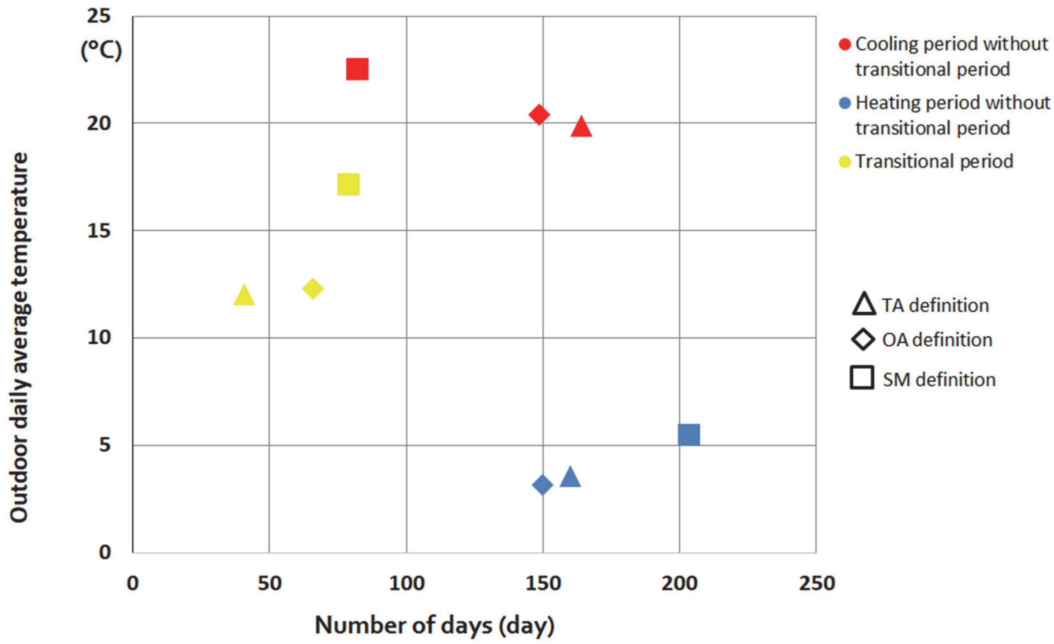
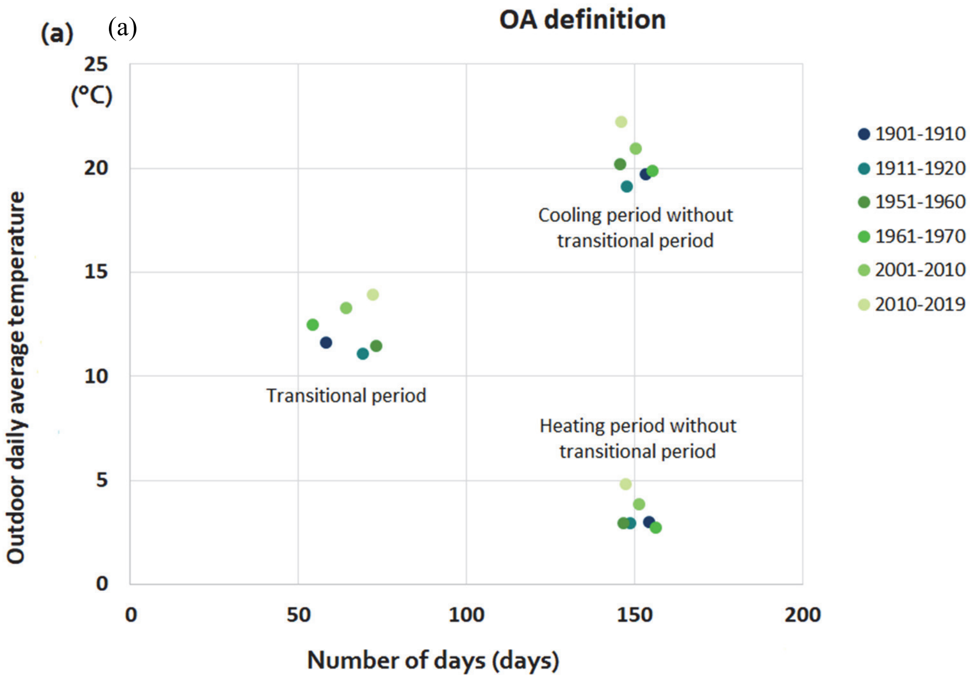


Fig. 6. The average temperature and the number of days in the heating, cooling, and transitional periods based on the TA, OA, and SM definitions.

After comparing the different definitions, *Fig. 7* shows the average temperature and the length of three periods using the OA and TA definitions (*Fig. 7*) for the previously selected six decades. When using the OA definition (*Fig. 7a*), the difference between the early 20th century and the early 21st century is about 2 °C in each period. Moreover, the length of the cooling and heating period decreased in the last two decades, while the yearly average total number of days in the transitional period increased. In contrast, when using the TA definition (*Fig. 7b*), which is based on outdoor daily average temperature, the cooling period was more than 20 days longer in the early 21st century than in the early 20th century, while the length of the heating period decreased by more than 40 days.



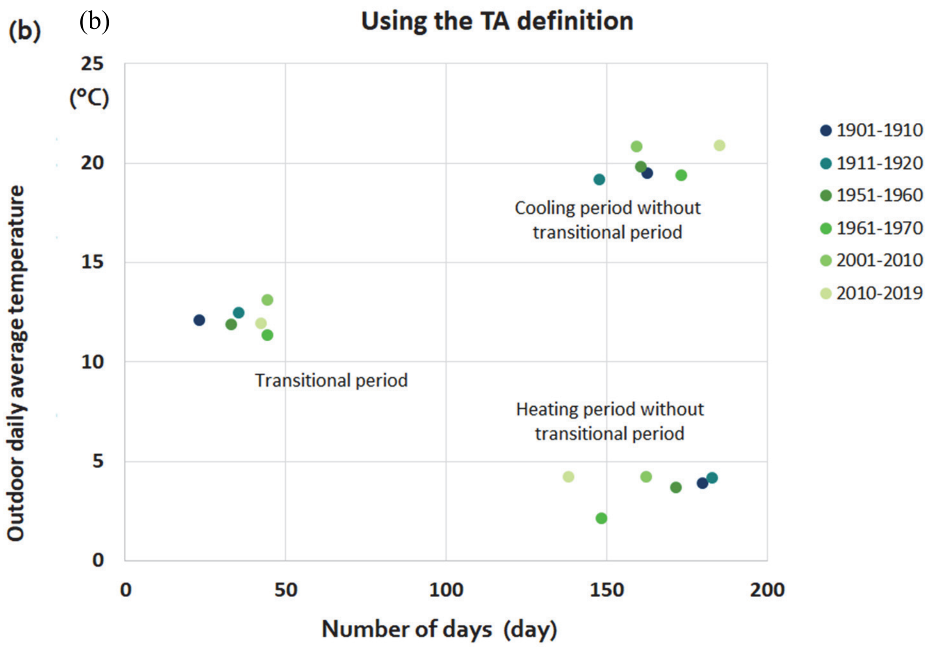


Fig. 7. The average temperature and the number of days in heating, cooling, and transitional periods for the six selected decades using the (a) OA definition and (b) TA definition.

The average temperature difference from the 119-year average was calculated for each decade for heating, cooling, and transitional periods using the OA and TA definitions (*Fig. 8*). *Fig. 8a* shows the results for OA definition. These difference values were below the average until about 1980, but after that large increases can be detected in the differences for all the three periods due to the regional warming trend (e.g., *Lakatos* and *Bihari*, 2011) in the last few decades. When using the definition of TA, no such warming trend is seen in average temperatures for the three periods (*Fig. 8b*). However, the temperature differences simultaneously increase or decrease in the heating, cooling and transitional periods from the middle of the 20th century.

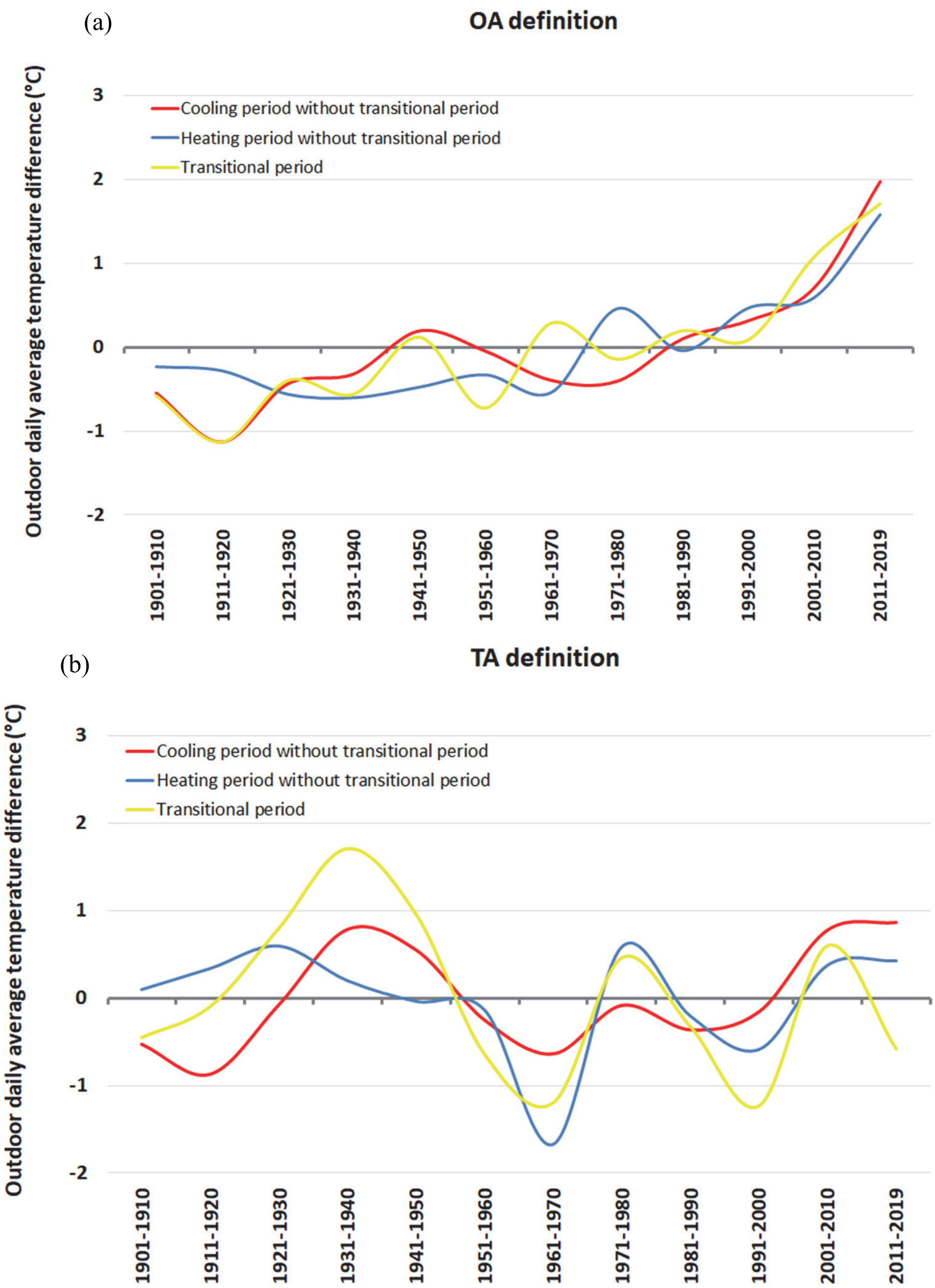


Fig. 8. Difference of the outdoor daily average temperature from the 119-year average for all the decades during 1901-2019 using (a) the OA definition and (b) the TA definition.

Based on these results, it is necessary to revise the parameters of building energy designs, especially when they depend on temperature.

5. Conclusions

In this study, we examined the daily average outdoor temperature of Budapest, the capital of Hungary, because it is an important meteorological parameter for building energy planning. For this purpose, the publicly available daily mean temperature time series of the Hungarian Meteorological Service were analyzed.

Since indoor temperature should be maintained within a stable interval throughout the year, the outdoor temperature of extremely cold and warm days is especially important in energy planning. In the case of cold days, a warming trend of 1.9 °C/100 years can be observed in Budapest, while the detected warming trend was 2.2 °C/100 years in warm days. The average standard deviation of the lower temperatures is about 2 °C greater than the deviation of the warm days. Thus, cold and warm days, with different energy demands, can be well separated if the entire year is divided into heating and cooling periods and analyzed correspondingly. For this purpose, we used three different definitions for heating and cooling periods. Furthermore, a third period (i.e., transitional period between heating and cooling periods) was also determined in the case of each definition.

Based on the analysis presented in this paper, the following main conclusions can be drawn. (1) The curves of heating and cooling periods using OA and TA definitions were quite similar for the average of 119 years. (2) The average temperature was 2 °C higher in the early 20th century than in the early 21st century in each period due to the detected regional warming trend, when using the OA definition. (3) The length of the heating period decreased by around 40 days, while the length of the cooling period increased by more than 20 days using the TA definition. (4) The use of temperature-based definitions in determining the building energy demand is certainly beneficial due to the overall warming trend. This can be especially important when developing adaptation strategies for the coming decades and the entire century.

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