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Short-term variations in air temperature in Krakow (Poland) as an indicator of climate change in Central Europe

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Abstract—The paper discusses the long-term variability of maximum (Tmax) and minimum (Tmin) air temperature variations, both occurring from one day to the next and over several consecutive days (3-4), in Krakow (Poland, Central Europe) from 1826 to 2015 (i.e., over a period of 190 years). The authors analyzed the seasonal variability of short-term variations in air temperature, looking at the most significant changes (±10 °C), as well as at their dynamics and trends over the analyzed multi-annual period. A clear decrease has been observed both in the values of short-term Tmax and Tmin variations and in the number of cases with their significant fluctuations. The decrease has been gradual, without clear abrupt changes to the overall trend. The greatest short-term variations in temperature were most frequent in the cooler half-year, being smaller and less frequent in the summer months. If the observed trend persists, in the upcoming years we can expect a further decrease in the dynamics of variations in thermal conditions, i.e., short-term variations in temperature may more frequently be small, i.e., ±0.1–4.0 °C. However, it is worth noting that Tmax more frequently increased from one day to the next and over several consecutive days, while Tmin more frequently decreased. The reasons for the analyzed changes remain unclear. It seems that natural factors, mainly including the advection of air masses, have a significant impact on short-term variations in air temperature, coupled with local factors, which have been strengthened by the human impact on the environment, including the urban heat island.

Key-words: Air temperature, short-term variations, day-to-day temperature variation, Central Europe, Poland

1. Introduction

Long-term air temperature variability analysis is among the essential research topics in contemporary climatology (*Brunetti et al.*, 2000; *Moberg* and *Jones*, 2005; *Lorenc*, 2007). To analyze relevant data, the authors of this paper have relied on weather data series of various lengths from a single weather station or from several different sites, as well as on grid-point values which enable the analyzed data to be interpolated to large areas. A reliable assessment of the variability and trends in thermal conditions is only possible on the basis of very long and homogenous instrumental record series (*Moberg et al.*, 2000). However, few such datasets are available in Europe, and where they do exist (*Jones et al.*, 2002), they most often represent the climate conditions prevalent in large urban agglomerations. Such data series include records from the historic weather station in Krakow, where weather data was first recorded in 1792, while daily values have been uninterruptedly tracked since 1826. This dataset has been repeatedly used in studies of long-term climate variability and compared against records from elsewhere in Europe and especially from Central European sites (e.g., *Trepińska*; 1990, *Piotrowicz*, 2010).

Most climate change studies point to a very clear rise in global temperatures, especially since the 1970s (*Kożuchowski et al.*, 2000; *Wibig* and *Głowicki*, 2002). Although far from exhibiting a regular spatial or temporal pattern, such variations have been used by many authors to prove that each consecutive decade has become warmer than the preceding one (*Frich et al.*, 2002; *Klein Tank* and *Können*, 2003; *Moberg* and *Jones*, 2005). An increase in temperature can be seen not only in mean annual values, but also in seasonal data. Researchers most often point out a clear increase in temperature in the winter season, which can also be observed, albeit less frequently, in summer (*Rebetez*, 2001; *Gough*, 2008). In the 20th century, it was in winter that the highest increase in temperature was recorded, e.g. in Central and Eastern Europe it reached 0.35 °C/10 years (*Brázdil et al.*, 1996; *Jones et al.*, 2002; *Wibig* and *Głowicki*, 2002). For spring and autumn, different and sometimes contradictory results have been obtained regarding temperature increases, depending on the study area and the length of the analyzed record (*Frich et al.*, 2002; *Klein Tank et al.*, 2002; *IPCC*, 2007, 2014). However, according to *Alexander et al.* (2006), the rise in temperature can be observed in all seasons of the year. The changes are clearer from March to May and less distinct from September to November. It is also worth emphasizing that variations in minimum temperatures are usually greater than those in maximum temperatures (*Rebetez*, 2001).

The dynamics of temperature variations in various regions of the world is yet to be analyzed. Some authors have pointed to an increasing frequency of abrupt temperature shifts in recent decades, while others claim that global warming manifests itself in the "attenuation" of temperature fluctuations, i.e., greater temperature stability over time (*Rebetez*, 2001; *Ciaranek* and *Piotrowicz*, 2014).

Air temperature variability in short time intervals provides insights into climate dynamics, but it is also relevant for practical reasons (*Tam* and *Gough*, 2012). Sudden rises and falls in temperature, both occuring from one day to the next and over several consecutive days (3–4), have a negative impact on human health and wellbeing, and may be detrimental to various sectors of the economy, including agriculture, transport, and construction. Very significant temperature drops in spring can cause winterkill or black ice, while warm spells before snow cover melts pose a risk of flooding (*Fortuniak et al.*, 2004).

In climatology literature, most papers on short-term variations in temperature focus on day-to-day fluctuations (*Kossowska-Cezak*, 1987; *Tam et al.*, 2015). In Poland, in the early 20th century, *Merecki* (1903) claimed that substantial variations in temperature are caused by atmospheric circulation and local factors. Central European climate is dominated by small (2–3 °C) day-to-day variations in temperature throughout the year. In extreme cases, however, such fluctuations may even exceed ±10–15 °C (*Kossowska-Cezak*, 1987). They most frequently occur in winter and are related to the advection of both warm and cold air masses. The authors have not only analyzed the impact of atmospheric circulation (*Kossowska-Cezak*, 2003), but also that of urbanization and the urban heat island (UHI), on day-to-day temperature changes (*Tam et al.*, 2015).

In this paper, the authors decided to look at the nature of variations in temperature occurring from one day to the next and over several (3–4) consecutive days during the last 190 years (1826–2015) in Krakow (Southern Poland). Are short-term variations in temperature increasing or decreasing due to the clear overall increase in temperature values? What dynamics and trends can be identified? Consideration was also given to seasonal variability of short-term changes in temperature, including the most significant fluctuations.

2. Data and methods

The paper is based on data concerning the daily values of maximum (Tmax) and minimum (Tmin) air temperature at the historic weather station in Krakow (φ=50°04'N, λ=19°58'E, h=220 m a.s.l.). It represents one of the longest weather data records in Europe. It is homogenous and very much representative of the area of Central Europe located below 600 m a.s.l. (*Trepińska*, 1997).

Authors of papers on day-to-day temperature changes have used both mean daily temperature values and Tmax and Tmin in their research. In this paper, only extreme temperatures were taken into consideration due to the numerous modifications introduced over time in the methods of calculation of the daily mean values. The authors also agree with *Kossowska-Cezak* (1987), who claimed that Tmax and Tmin describe actual variations, while the mean daily temperature values may only be treated as indicators which, however, fail to reflect the actual day-to-day temperature increases or decreases.

Short-term temperature changes were calculated as the difference (*Δ*) between the values recorded on the next and on the preceding day ($\Delta T=T_2-T_1$; day-to-day) and additionally over three ($\Delta T_{3-1}= T_3-T_1$) and four ($\Delta T_{4-1}= T_4-T_1$) days. These calculations took account of both the absolute values the changes and of the actual values – decreases (–) and increases (+) in temperature in the analyzed cases.

Following the approach adopted by other researches (*Kossowska-Cezak*, 1987; *Tam* and *Gough*, 2012), the authors defined "significant" temperature changes as cases where the values of the calculated differences were above 10 °C or below –10 °C.

Without doubt, the increase in temperature in Krakow since 1826 has been driven not only by natural factors (atmospheric circulation) but also by human impact. Special caution was therefore exercised when analysing the causes of the observed variations. The changes occurring over time were compared to the history of the city's development (its surface area, population size, and industrial development).

A statistical analysis of relevant trends was performed using the nonparametric Mann-Kendall test (*Kendall*, 1975). The variations were deemed statistically significant when they were smaller than 5%.

The analysis also included cases where the day-to-day temperature difference had the same mathematical sign, i.e., it was positive or negative, on consecutive days. The persistence of such phenomena, defined as series of days with day-to-day increases or decreases in temperature, was determined. In terms of length, one-day long, short (2–4 days), medium (5–9 days), and long (≥10 days) sequences of days were identified. Their number in each analyzed year was calculated. The fewer of them occurred, the longer they were in a given year, i.e., the temperature more frequently changed in a single direction, i.e., rose or fell, from one day to the next.

3. Essential characteristics of short-term variations in air temperature

Regarding the short-term variations in Tmax taken into account in the analyzed multi-annual period, increases were slightly more frequent than decreases, while the opposite was true for Tmin. It more frequently decreased than increased, both on a day-to-day basis and over three or four consecutive days (*Table 1*). Cases where no temperature changes were recorded, were accounted for between 1.1% and 2.3%. As the measurement error for the analyzed meteorological element amounts to 0.1 °C, the analysis also took account of cases where ΔT amounted ±0.1 °C (ΔT=±0.1 °C). The frequency of occurrence of such cases is shown in *Table 1*. They were most numerous for day-to-day variations in Tmin (5.6%), and least numerous for Tmax changes over four days (2.6%).

Table 1. Essential characteristics of short–term variations in maximum and minimum air temperature in Krakow in the period 1826–2015

Short–term variations	**Maximum temperature**			**Minimum temperature**		
	Freq. (%)	**mean**	**σ**	**Freq. (%)**	**mean**	**σ**
$\Delta T_{2-1}>0.0°C$	50.8	2.5	2.0	46.1	2.3	2.1
$\Delta T_{2-1}<0.0°C$	47.3	–2.7	2.3	51.6	–2.1	1.7
$\Delta T_{2-1}=0.0°C$	1.9	–	–	2.3	–	–
$\Delta T_{2-1}=\pm0.1°C$	4.5	–	–	5.6	–	–
$\Delta T_{3-1}>0.0°C$	50.4	3.5	2.7	48.4	3.0	2.7
$\Delta T_{3-1}<0.0°C$	48.4	–3.7	3.0	50.0	–2.9	2.4
$\Delta T_{3-1}=0.0°C$	1.2	–	–	1.6	–	–
$\Delta T_{3-1}=\pm0.1°C$	3.0	–	–	3.7	–	–
$\Delta T_{4-1}>0.0°C$	49.9	4.1	3.1	49.2	3.4	3.0
$\Delta T_{4-1}<0.0°C$	49.0	–4.2	3.2	49.4	–3.4	2.8
$\Delta T_{4-1}=0.0°C$	1.1	–	–	1.4	–	–
$\Delta T_{4-1}=\pm0.1°C$	2.6	–	–	3.4	–	–

The mean multi-annual values of differences in temperature and standard deviation (σ) indicate that small changes of ±2–4 °C were the most abundant (*Table 1*). In the case of Tmin, ±4 °C changes were a little more frequent (>70%), while they were the least numerous for Tmax variations over 4 days (>58%).

Clear patterns can be seen in terms of short-term variations in temperature during the year (*Fig. 1*). An analysis of changes to Tmax shows that the greatest mean monthly values of the differences occurred in April and May, while the same was true for Tmin in winter (Dec-Feb). Higher values were recorded for variations over a period of four days ($\Delta T_{4-1}= T_4–T_1$), and the lowest values were recorded for day-to-day changes ($\Delta T_{2-1}= T_2–T_1$). However, in general, the pattern of the mean monthly values of the analyzed differences is more varied than for Tmin, with smaller ones recorded in summer (Jun-Aug). The differences between the mean monthly values of Tmax variations are clearly smaller.

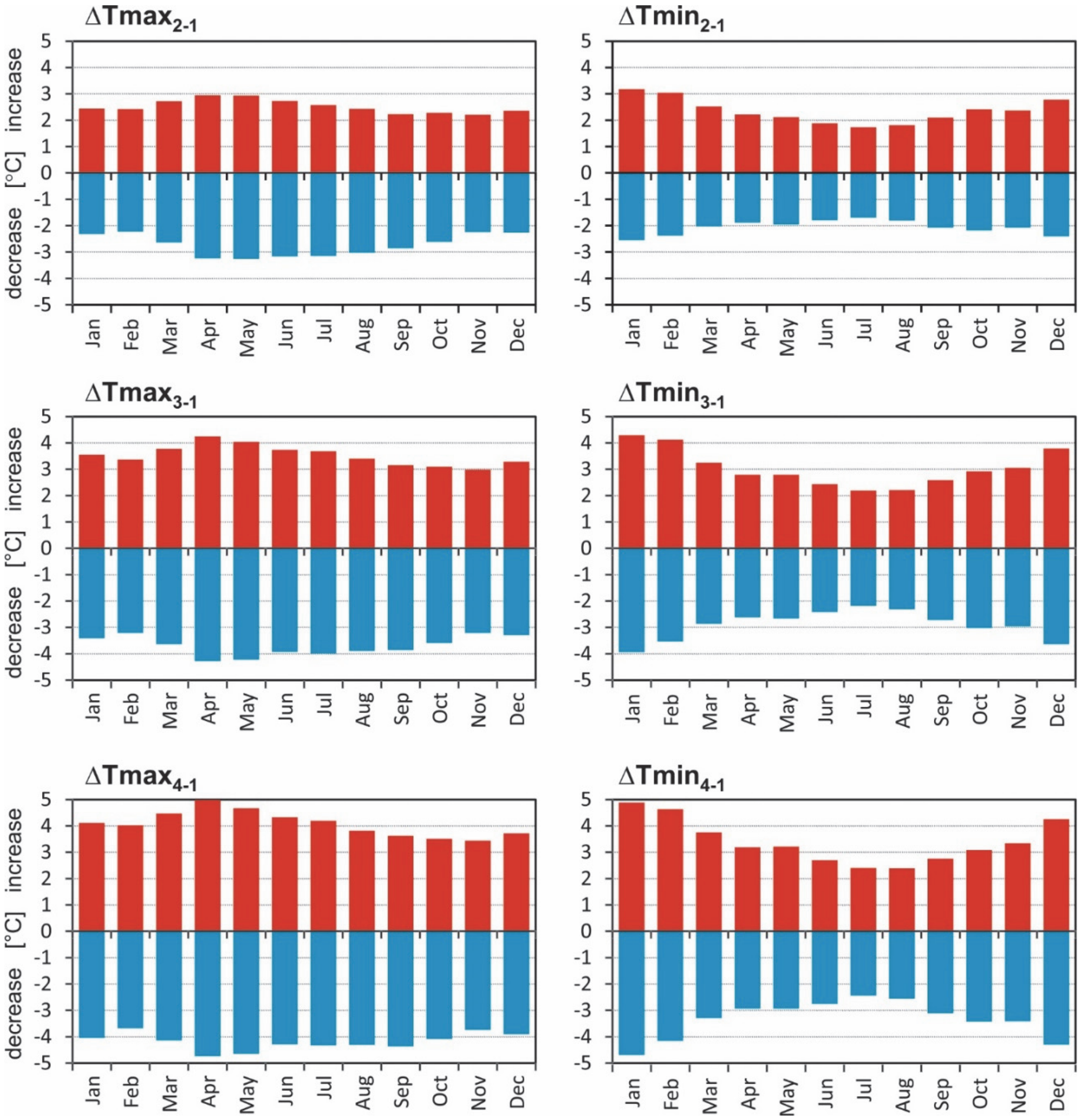

Fig. 1. Mean monthly values, increases and decreases in maximum and minimum air temperature of day-to-day (ΔT_{2-1}), over three (ΔT_{3-1}), and four (ΔT_{4-1}) days in Krakow in the period 1826–2015.

The above-described analysis was complemented by the identification of patterns in the annual variability of cases with no variation, i.e., $\Delta T = \pm 0.1$ °C (*Fig. 2*). An average of ca. 8% of such cases per month was recorded. For Tmax, they mainly occurred in winter and particularly in December (more than 10% of all days). Tmin most frequently remained the same in summer (Jun-Aug). However, it is worth noting that no day-to-day Tmin changes were recorded with equal frequency in spring (Mar-Apr), September November, and December (more than 8% of all cases).

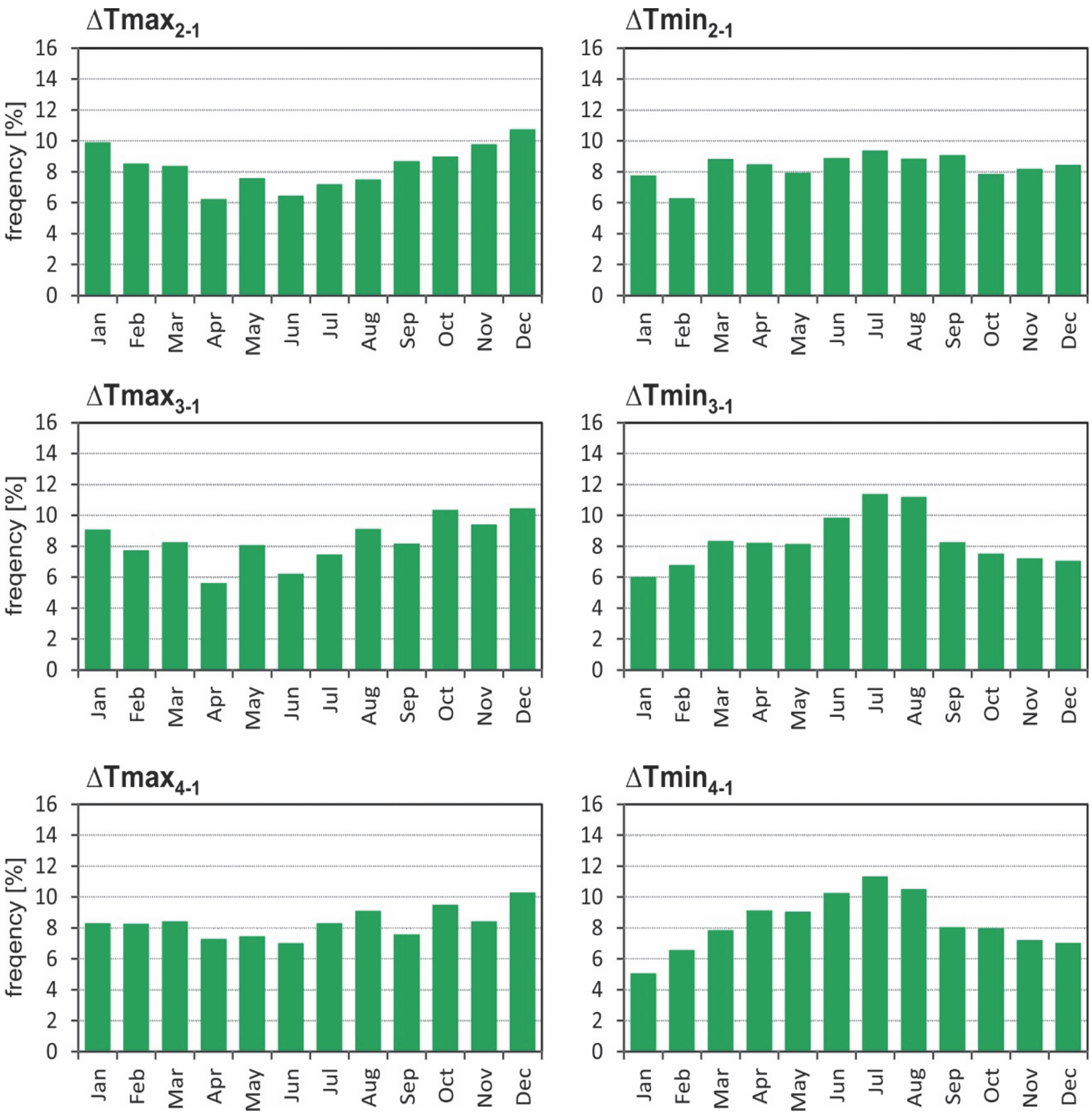

Fig. 2. Frequency of cases with no short-term variations in air temperature ($\Delta T = \pm 0.1$ °C) of day-to-day (ΔT_{2-1}), over three (ΔT_{3-1}) and four (ΔT_{4-1}) days in Krakow in the period 1826–2015.

4. Multi-annual variability of short-term variations in air temperature

The mean annual values of Tmax and Tmin of increases and decreases in the analyzed period spanning 190 years have been shown in *Fig. 3*. All trends indicate a decrease in the values of short-term variations in temperature, and they are statistically significant at the level of 0.05. The most significant changes in the analyzed period were recorded for Tmin, especially regarding its decreases over three and four consecutive days (*Fig. 3*). Somewhat lower values of short-term temperature variations could be seen at the turn of the 20th century (1886–1905) and around 1970–1976.

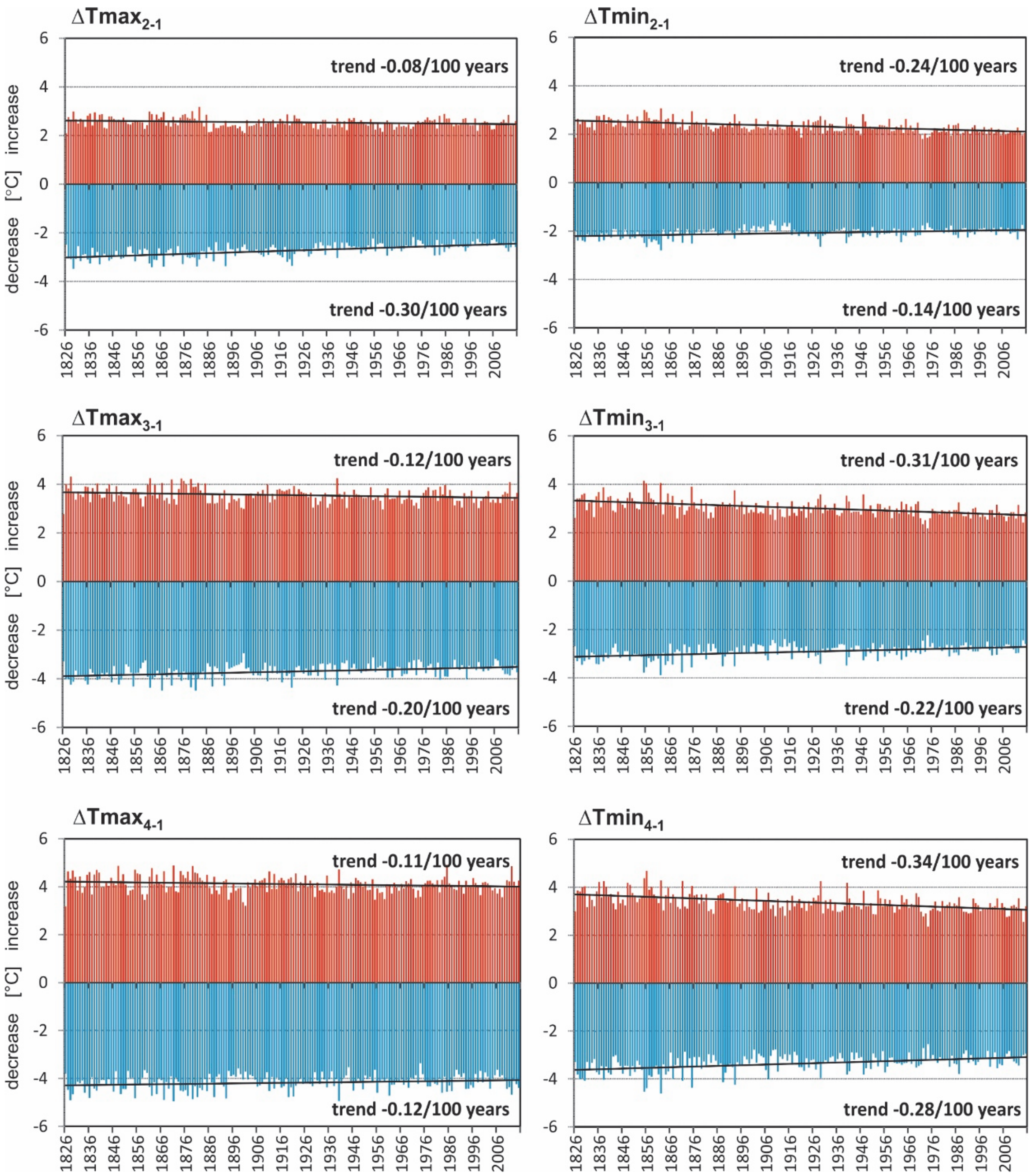

Fig. 3. Multi-annual variability and trends of increases and decreases in maximum and minimum air temperature of day-to-day (ΔT_{2-1}), over three (ΔT_{3-1}), and four (ΔT_{4-1}) days in Krakow in the period 1826–2015.

The long-term variability of the number of cases with no changes in temperature ($\Delta T = \pm 0.1$ °C) did not exhibit a clear trend (*Fig. 4*). The only statistically significant trend which suggests a decrease in the number of the analyzed cases was observed for day-to-day variations in Tmax (1.05/100 years).

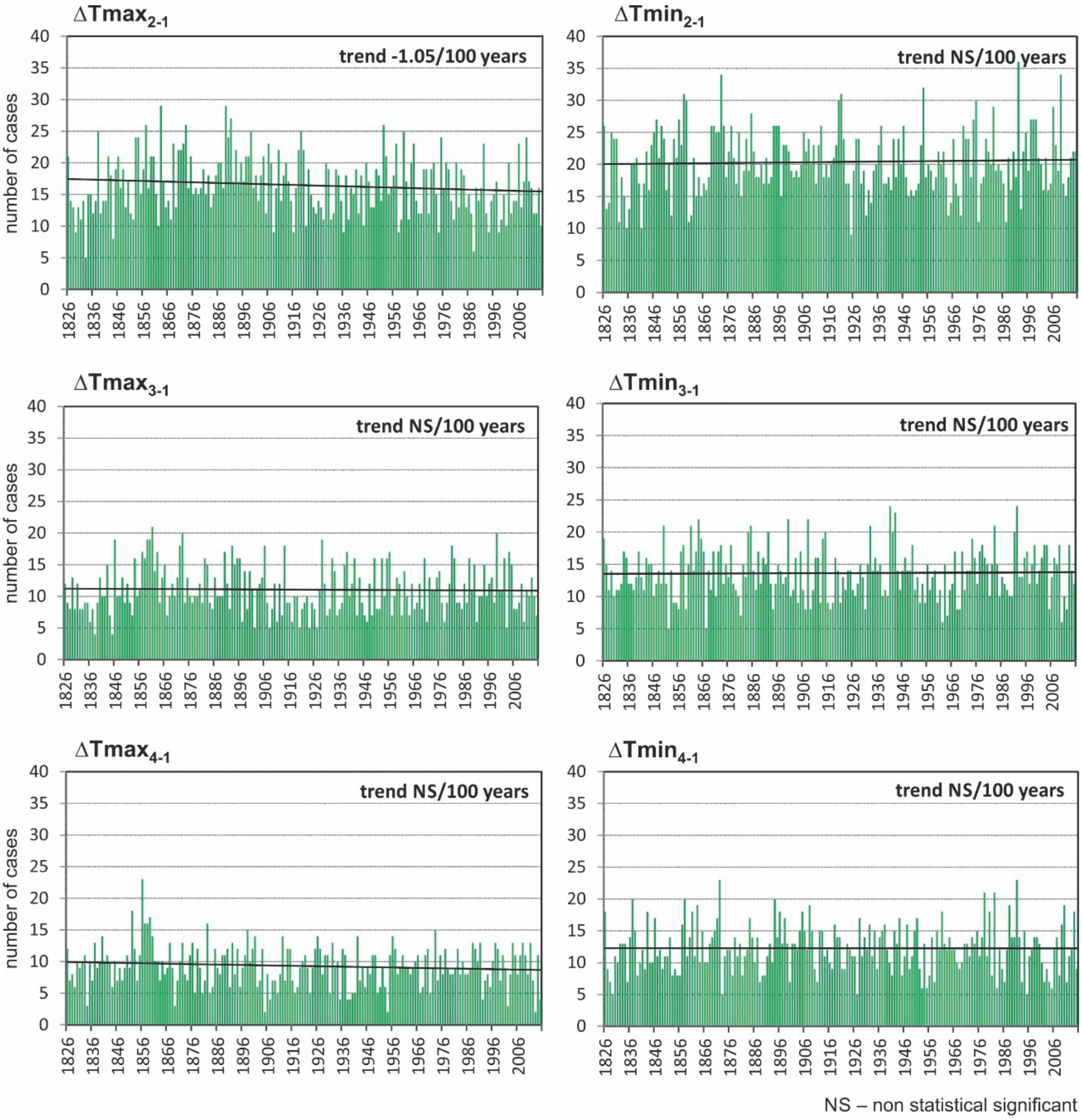

Fig. 4. Multi-annual variability and trends of no-variation (ΔT=±0.1 °C) in maximum and minimum air temperature of day-to-day (ΔT_{2-1}), over three (ΔT_{3-1}), and four (ΔT_{4-1}) days in Krakow in the period 1826–2015.

5. Significant (>±10 °C) short-term variations in air temperature

Regarding to day-to-day variation, significant decreases in Tmax were more numerous (410 cases) than in Tmin (95), whereas the opposite was true for significant increases – they were more numerous in the case of Tmin (297 cases) than for Tmax (163). During the year, a clear difference is visible between the frequency of occurrence of significant variations in Tmin in winter (Dec-Feb) and March, and in the remaining months of the year (*Fig. 5*). More than 90% of such cases (91.2% of increases, 90.5% of decreases) occurred in those four months. Day-to-day abrupt changes in Tmax occurred with a similar frequency in all seasons, with significant increases being much more frequent in spring (31.9%) and winter (34.4%), and significant decreases prevailing in spring (35.4%) and summer (35.4%). Significant variations in temperature over three and four days, as compared to day-to-day changes, only differed in terms of the number of cases, as they were much more frequent. However, their frequency of occurrence over the year was quite similar (*Fig. 5*).

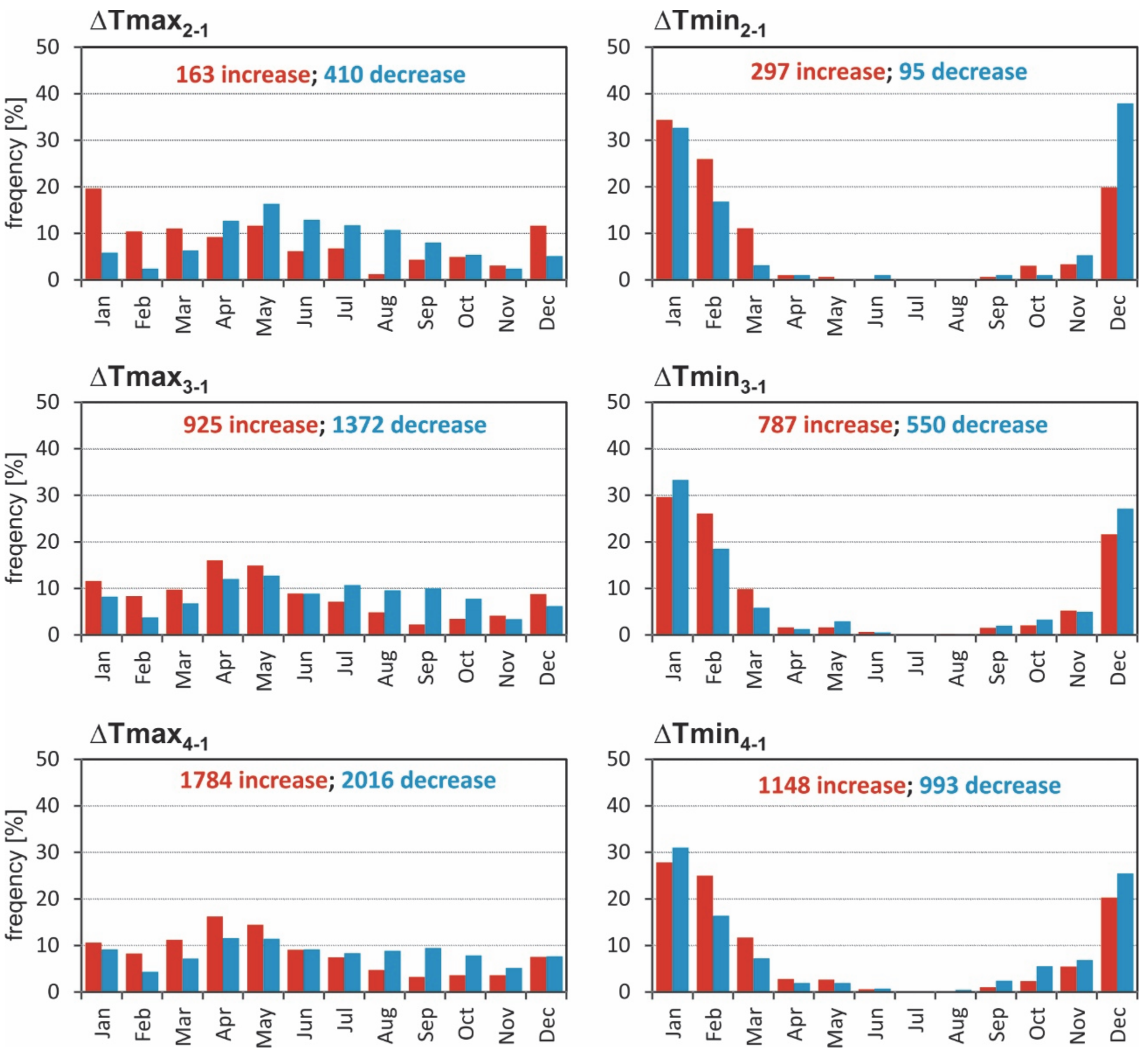

Fig. 5. Frequency of occurrence of short-term variations of >±10 °C in extreme temperatures in Krakow in the period 1826–2015.

The multi-annual trend of significant variations in temperature, including both increases and decreases, suggests that they are becoming smaller (*Fig. 6*).

In terms of day-to-day changes, there were significantly fewer cases of Tmax differing by –10 °C (2.08/100 years) and Tmin by +10 °C (1.47/100 years). Regarding the variations in Tmax over a slightly longer time interval (3–4 days), greater trends appeared in the case of differences exceeding –10 °C, while regarding the Tmin, trends in both significant decreases and increases were quite significant (from 2.64 to 3.08/100 years).

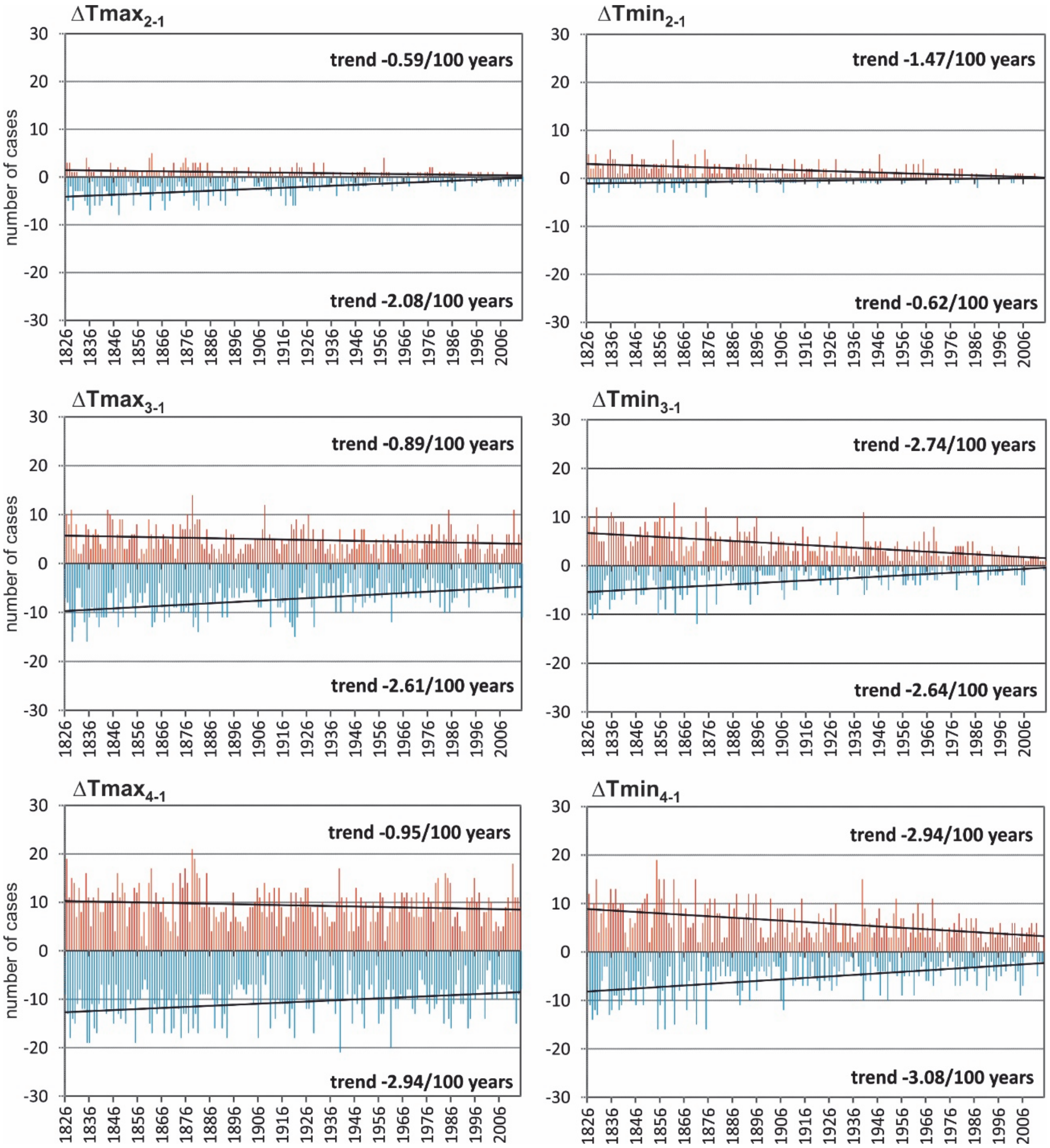

Fig. 6. Multi-annual variability and trends in significant maximum and minimum air temperature increases (>10 °C) and decreases (<–10 °C) in day-to-day (ΔT_{2-1}), over three (ΔT_{3-1}) and four (ΔT_{3-1}), consecutive days in Krakow in the period 1826–2015.

6. Sequences of day-to-day variations in maximum and minimum air temperatures

The variability of temperature in short time intervals can also be identified by analyzing sequences of days when the difference in temperature values was denoted with the same sign, i.e., when temperature decreased (–), increased (+), or remained stable, i.e., $\Delta T_{2-1}=\pm 0.1$ °C.

Most frequently, day-to-day temperature increases and decreases occurred in isolation, i.e., from one day to the next. Such cases accounted for between 46% and 54% of all cases (*Fig. 7*). In 43–49% of all cases, temperature increases and decreases persisted for 2–4 consecutive days. *Fig. 7* also shows that there were some cases where the same direction of change was recorded for up to 10–12 consecutive days. Such long sequences occurred in January, February, April, July, October, November, and December, i.e., in almost all seasons, but they were predominant in winter. Temperature increases and decreases were equally frequent in such series.

In 93% of all cases no variations in Tmax were recorded in one-day sequences (*Fig. 7*); however, such slight temperature fluctuations occurred in up to 4-day-long sequences. Therefore, also in this case, defining short-term variations in temperature as changes in temperature values occurring for up to four days turned out to be right.

The multi-annual variability of the analyzed sequences leads to the conclusion that in the case of day-to-day variations in Tmax, the average annual number of all sequences (regardless of their length) in which the temperature increased (91.5 sequences) and decreased (91.0) was almost the same (*Fig. 8*). The situation was similar for Tmin, although the number of cases was slightly higher. The respective values amounted to 94.3 and 95.2 (*Table 2*).

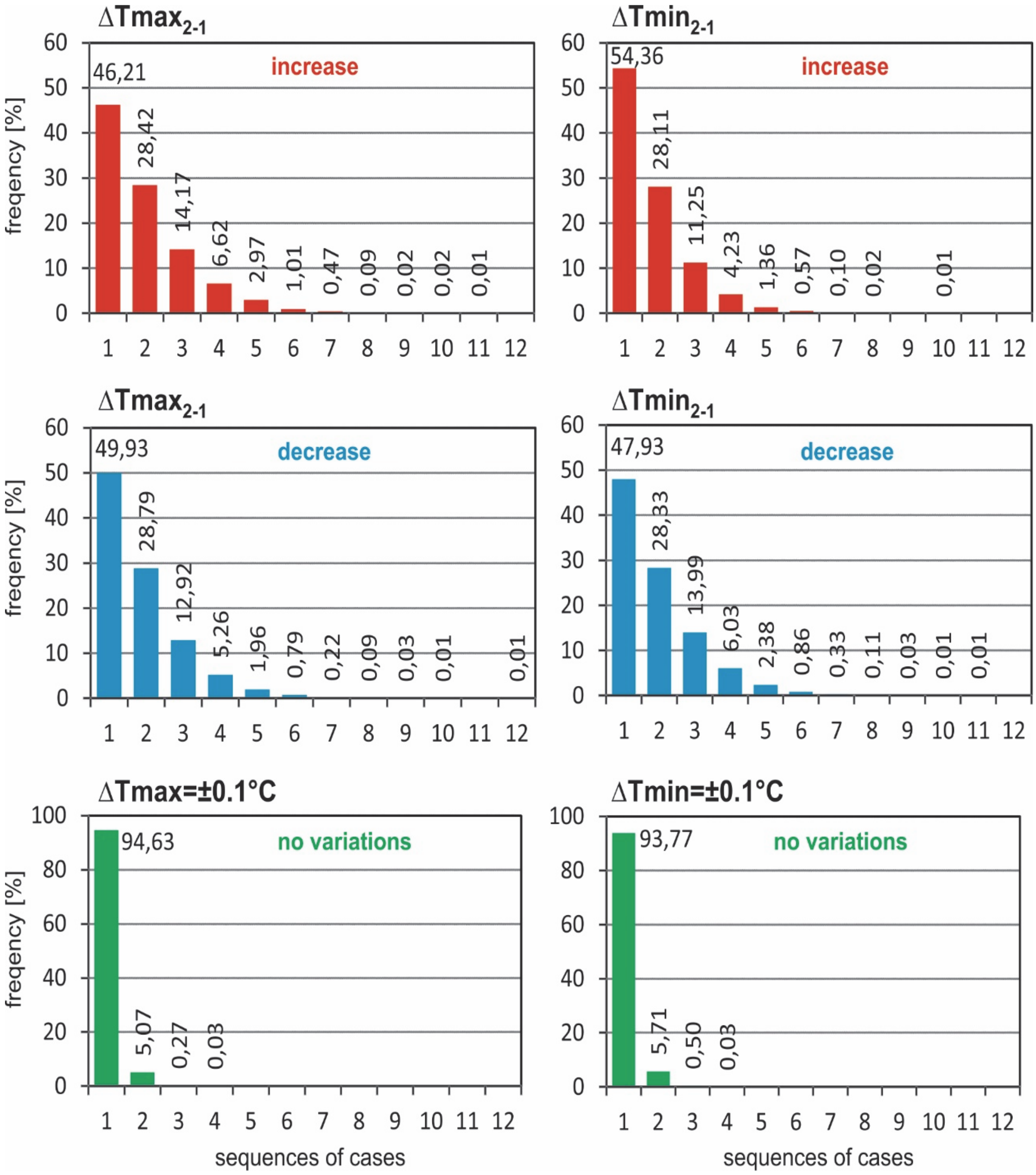

Fig. 7. Frequency of occurrence of sequences of days with day-to-day variations (and no-variations) in air temperature, broken down by length in Krakow in the period 1826–2015.

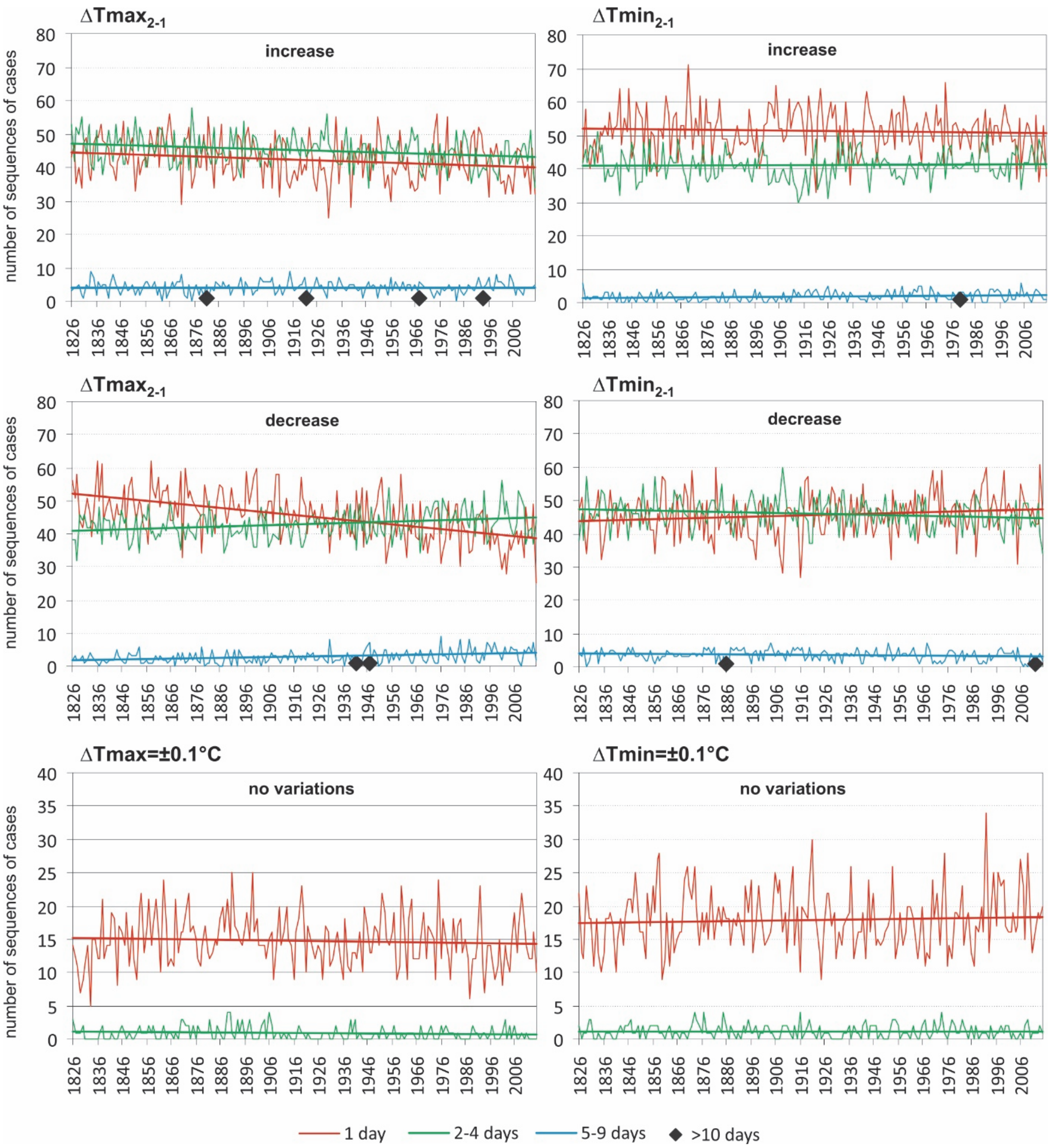

Fig. 8. Multi-annual variability of sequences of days with day-to-day variations (and no-variations) in air temperature, broken down by length in Krakow in the period 1826–2015.

Table 2. Average number of sequences of days with day–to–day variations (and no-variations) in air temperature, broken down by length and trends (trend/100 years) in Krakow in the period 1826–2015

Sequences	Tmax – increase		Tmin – increase	
	Mean number in the year	**Trend/100 years**	**Mean number in the year**	**Trend/100 years**
One-day	42.3	–2.18	51.2	NS
2–4 days	45.0	–2.18	41.1	NS
5–9 days	4.2	NS	1.9	+0.52
all	91.5	–4.33	94.3	NS
	Tmax – decrease		Tmin – decrease	
One–day	45.4	–6.90	45.6	+1.72
2–4 days	42.7	+2.11	46.0	–1.46
5–9 days	2.8	+1.18	3.6	–0.41
all	91.0	–3.61	95.2	NS
	Tmax – with no variations		Tmin – with no variations	
One–day	14.7	NS	17.9	NS
2–4 days	0.8	NS	1.2	NS
all	15.6	NS	19.1	NS

In the analyzed period, the overall number of all sequences in Tmax clearly decreased (*Table 2*). This was mainly due to a reduced number of 1-day sequences, as well as a reduced number of short sequences (2–4 days) in which temperature increased. Therefore, recently there have been fewer cases of alternating day-to-day increases and decreases of temperature. Thus, Tmax more frequently increases or decreases over several consecutive days.

In the case of Tmin, statistically significant trends, albeit small ones, were only noticed when the multi-annual variability of some sequences was analyzed (*Table 2*). Over the last 190 years in Krakow, Tmin has changed from one day to the next in quite similar sequences of days. On average during the year, the Tmin increases in one-day sequences were most numerous, while decreases were most frequent in 2–4 day sequences. The latter, however, exhibited a slight downward trend, and thus, one can still expect frequent day-to-day variation in the direction of change (increase and decrease) of Tmin (i.e., in one-day long sequences).

No clear trends in the multi-annual period were observed for the other previously analyzed parameter, i.e., the no-variation in temperature (*Table 2*, *Fig. 8*). On average during the year, such cases of no-variation are grouped in 15.6 (Tmax) and 19.1 (Tmin) sequences, and one-day long sequences are the most frequent.

7. Discussion

In the analyzed multi-annual period (1826–2015), there was a clear decrease both in the values of short-term Tmax and Tmin changes, and in the number of cases with significant changes (±10 °C). Similar conclusions were drawn by *Rebetez* (2001), who relied on data from Switzerland (Neuchatel and Davos), stating that an increase in temperature in the 20th century was accompanied by its reduced day-to-day variation. *Moberg et al.* (2000) point out that the day-to-day variations in temperature in England, Stockholm, Uppsala, and Saint Petersburg were 10% greater in the 19th century than between 1961 and 1990.

Analyzes conducted by *Kossowska-Cezak* (1987, 1988, 2003) suggest that significant variations in temperature in Poland may co-occur with various types of atmospheric circulation. Moreover, the same type of circulation may lead to both a decrease and an increase in temperature. Rather than with changes in atmospheric circulation, short-term variations in temperature should then be linked to the advection of air masses and local conditions, such as the inflow of air from areas with contrasting thermal conditions (e.g., coastal areas), night-time temperature inversion near the ground, and adiabatic heating of air. Unfortunately, it is impossible to measure the strength of this relationship due to a lack of long-term data on the frequency of occurrence of particular air masses over Krakow. Undoubtedly, changes in temperature in the city are influenced by local conditions, such as land relief, and especially its location in the inversion valley of the Vistula River, the influence of foehn winds in the mountain range located ca. 100 km away, and the built-up urban land (urbanization), including the urban heat island (UHI).

In Krakow, more than half of all days of the year have an inverse temperature distribution, and in the case of Tmin, that frequency raises even up to 92% (*Matuszko et al.*, 2015). Inversions are especially intense in the cool half-year (Oct-Mar) and particularly in winter (Jan-Feb). At the same time, abrupt temperature increases may occur in connection with the occurrence of the foehn wind. Over the last 190 years (1826–2015), the impact of these factors did not demonstrate any significant changes. Increasing urbanization and the urban heat island may have a much greater influence on temperature and also on its short-term variation. The UHI phenomenon has been examined in detail in Krakow since the 1950s. Currently, the UHI extends over an area which is almost three times greater than it was in the mid-20th century, but its intensity is considered to reach an average of 1.2 °C and a maximum of 5–7 °C (*Lewińska*, 1996). Research into the impact of the city on day-to-day variations in temperature has been conducted by *Kossowska-Cezak* (1988) in Warsaw, *Olejniczak* (2003) in Krakow, and *Tam et al.* (2015) in USA and Canada. The authors observed lower Tmin variability in the city center, which resulted from the influence of urban built-up land. The effect is especially noticeable in the evening and at night, i.e., during the time when daily minimum temperature values are most frequently recorded. Differences in day-to-day temperature variability in Krakow turned out to be quite small. For Tmin, they amounted to 0.7 °C on average, while for the daily mean and for Tmax they equalled to 0.3 °C (*Olejniczak*, 2003).

8. Conclusions

When discussing short-term variation in Tmax and Tmin in Krakow – which is representative of the wider area of Central Europe – the authors used relatively rarely applied methodology. Besides day-to-day variation in temperature, they also examined changes occurring over three or four consecutive days. The latter were taken into account due to the observed highest frequency of occurrence (over 95%) of day-to-day variations over 4-day-long periods. The analysis also included cases where there were no day-to-day variations in temperature.

An analysis of short-term variations in temperature in Krakow between 1826 and 2015, as well as of significant temperature increases and decreases (±10 °C) has found that both the size of such variations and the number of cases are decreasing. However, it is worth noting that Tmax more frequently increased from one day to the next and over several consecutive days, while Tmin more frequently decreased.

Significant short-term variations in temperature most frequently occur in the cooler half of the year, when the air masses over Poland are most thermally diverse and weather fronts are most frequent (*Kossowski*, 1970). In the summer months, such shifts are smaller and happen less frequently, while changes in cloud cover, which influence night-time radiation cooling, become a contributing factor (*Moberg et al.*, 2000). As a result, significant day-to-day variations in Tmax occur in summer.

Short-term variation in Tmax and Tmin decrease has been gradual over the entire analyzed long-term period, without clear and sudden changes to the overall trend. It seems that it was largely influenced by anthropogenic factors, such as increasing population size and urban sprawl, which in Krakow took place in several clear-cut stages. However, even when an entire new city district with a steel mill was erected in 1949–1954, the expansion did not result in abrupt changes to thermal conditions. Certainly, however, more detailed studies would be required to determine the impact of urbanization on thermal conditions using the values of day-to-day variations in temperature (and especially in Tmin). This has previously been pointed out by *Kossowska-Cezak* (1988). This, however, requires data from a pair of weather stations (one located in the city and another one outside the city) for a long period of time. Data from at least several large cities would be recommendable.

The causes of the analyzed changes in thermal conditions are still unclear and it is impossible to be certain whether they are permanent or a reversal of the trend should be expected. It seems that short-term variations in temperature are largely influenced by natural factors – mainly by the advection of air masses and to a lesser extent by local conditions, which have been compounded by the human impact, including the urban heat island.

If this trend persists, in the upcoming years a further reduction in the dynamics of changes in thermal conditions can be expected, i.e., short-term variations in temperature may more often be only slight, i.e., around ±0.1–4.0 °C.

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