THE ROLE OF INCREASED SUNSHINE IN SHAPING AIR TEMPERATURE RISE IN KRAKÓW (1951–2020)

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Abstract: Since the late 1980s, air temperature in Kraków (southern Poland) has increased by ~2.2–2.3°C compared to the 1951–1988 average. Over the same period, a significant increase in sunshine duration (SD) (by about 500 hr) has been observed relative to the 1951–1988 baseline. This pattern of temperature change in Kraków is representative of trends observed across Poland. The aim of this study is to determine the impact of SD on the increase in air temperature in Kraków. The analysis indicates that the strong rise in SD has resulted from changes in cloud structure since the late 1980s. During this period, the frequency of frontal stratiform clouds (*As*, *Ns*, *St*) decreased, while the occurrence of *Sc*, *Cu*, and *Cb* clouds increased. These shifts in cloud structure, driven by changes in mid-tropospheric macro-circulation, have led to an increase in SD. An analysis of the combined influence of three factors – annual SD, the NAO PC DJFM index (Hurrell), and radiative forcing (ΔF) – on annual temperature trends between 1951 and 2020 shows that the variability of these factors explains 67.3% of the variance in annual air temperature ($R = 0.83$, $p << 0.001$), fully accounting for the observed temperature increase within the margin of estimation error. Of this, SD variability explains 58% of the variance, NAO index variability accounts for 7.7%, and ΔF variability contributes 3.6%. These findings indicate that the primary driver of air temperature increase in Kraków is the rise in SD (solar radiation influx) rather than radiative forcing (ΔF).

Keywords: climate change, temperature, sunshine duration, NAO index, radiative forcing, Kraków, Poland

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Introduction

The air temperature in Kraków, as well as across Europe, is steadily rising (Ustrnul et al. 2021, Matuszko et al. 2023). This increase is occurring at a faster rate than the global temperature rise. In contemporary global climatological literature and in subsequent IPCC Reports (2007, 2013, 2023), the main cause of the global temperature rise is often attributed to the anthropogenic increase in CO_2 concentration in the atmosphere, which leads to the intensification of the greenhouse effect.

In numerous works by Matuszko (2012a, b, 2014) and Matuszko with co-authors (Matuszko, Węglarczyk 2014, 2015, 2018, Bartoszek, Matuszko 2021, Matuszko et al. 2022b), attempts were made to establish the relationships between

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cloud cover, cloud genera, and sunshine duration, as well as the impact of changes in sunshine on air temperature in Kraków. For this purpose, a unique dataset from the climatological research station of the Jagiellonian University was used. This station represents the climatic conditions of an urbanised area in Central Europe, located below 300 m above sea level. The regularities observed in the analysis of the long-term variability of selected climate elements based on data from Kraków may serve as a sensitive indicator of climatic fluctuations in a larger area (Matuszko, Węglarczyk 2014). Kraków is one of the few cities in Europe where measurements of sunshine, air temperature, and cloud observations are made at the same location throughout the entire measurement period, providing an uninterrupted series of climatological data. Air temperature has been measured since 1792. The registration of sunshine with the Campbell-Stokes heliograph began in June 1883, just 2 years after the construction of this instrument and its introduction into the international network of heliographic measurements. The cloud cover data series has no gaps since December 1862, and the series of cloud genera observations has been continuous since January 1906. The observational series of cloud cover and cloud genera (Matuszko 2012a, b, Matuszko, Węglarczyk 2018), the heliographic series (Lewik et al. 2010), and the temperature measurement series from this station are fully homogeneous (Ustrnul et al. 2021).

The existing publications based on the unique climatological dataset from Kraków present a vast amount of material, but their results, especially in evaluating the impact of changes in cloud cover and sunshine on air temperature changes in Kraków, yield ambiguous results. These studies have shown that the amount of cloud cover (N) has a relatively small impact on sunshine duration (SD) (Matuszko, Węglarczyk 2015). The variability in cloud type structure has a much stronger and clearer influence on the variability of sunshine than the amount of cloud cover (Matuszko, Węglarczyk 2018). A particular role in shaping the variability of SD is played by changes in the frequency of frontal stratiform clouds (*As*, *Ns*, *St*), whose frequency of occurrence is statistically significantly negatively correlated with SD (Matuszko, Węglarczyk 2015), while being strongly positively and statistically highly significantly associated with the variability of cloud cover (N).

The aim of this study is to determine the impact of changes in SD in Kraków on observed changes in air temperature in the city, considering that changes in sunshine are not the only factor driving temperature changes. Therefore, the influence of atmospheric circulation and the effect of radiative forcing, which is an energetic measure of the increase in CO_2 concentration in the atmosphere, were also analysed.

According to Brázdil et al. (1994), changes in SD during the period of global warming should be of particular interest. Understanding the trends in SD and air temperature, as well as determining the relationships between them, could help explain the natural causes of contemporary warming.

Material and methods

This study analysed data on the monthly and annual average values of air temperature (T), total cloud cover (N), cloud type frequency, and SD collected from the scientific station at Jagiellonian University over a 70-year period (1951–2020). The analysis only included cloud genera observations from 12:00 GMT, as this is the only time of day when observations are made in daylight every day of the year in Kraków, ensuring optimal accuracy in cloud recognition. Marsz et al. (2024) provided a detailed explanation for the choice of this time slot.

The time series of the winter (DJFM) NAO index based on principal components (PC) from Hurrell et al. (2003) was retrieved from the NCAR/UCAR *Climate Data Guide website*.

The values of radiative forcing (denoted following IPCC as ΔF; $W \cdot m^{-2}$) were calculated using the formula provided by the IPCC (2001, Chapter 6.1, Table 6.2):

$$\Delta F_k = 4.841 \times \ln(C_k/C_0) + 0.0906 \times ((C_k)^{0,5} - (C_0)^{0,5}), \quad (1)$$

where ΔF_k – radiative forcing in year k, C_0 – pre-industrial concentration of CO_2, assumed to be 280 ppm according to IPCC (2001), C_k – CO_2 concentration in year k, and ln – natural logarithm.

The annual CO_2 concentration values required for calculating the annual ΔF values for the period 1951–2011 were obtained from the Global *Mean CO2 Mixing Ratios* (ppm). The remaining data for the years 2012–2020 were supplemented with data from the Mauna Loa CO_2 annual mean data.

For the analysis, an annual time resolution was adopted. The average temperature of a given year (annual) synthetically averages seasonal changes, eliminating the need to consider annual cyclicity. This approach avoids delving into seasonal variations that often occur with opposing signs. The same applies to the other climatic elements. Preliminary analysis of the relationships between the climatic parameters in Kraków suggests that they are linear; therefore, the simplest statistical methods were used in the study, mainly linear correlation analysis and regression analysis. All calculations were performed using the Statistica PL software package by StatSoft. The values of correlation coefficients, as well as the intercepts and regression coefficients in the linear equations, were tested using the *t*-test, and the significance of the equations was tested using the Fisher-Snedecor *F*-test. A significance level of $p \leq 0.05$ was considered, with $p \leq 0.001$ indicating high statistical significance.

Multiannual course of air temperature and sunshine duration in Kraków

The increase in air temperature can result from two processes: the increased influx of solar electromagnetic radiation (sunlight) to the surface and the increased horizontal heat flux brought into the area by atmospheric circulation. In both cases, these energy fluxes must exceed the sum of the losses. Sunshine, or the duration of sunlight exposure, is a direct measure of the amount of solar energy received at a given point. The course of the annual air temperature and the annual sums of sunshine in Kraków are shown in Figure 1. It can be observed that both trends are highly similar to each other, and the linear correlation coefficient between them is strong and highly statistically significant ($r = 0.76$, $p < 0.000$).

From the perspective of elementary physics, sunshine, as a simplified measure of the influx of solar electromagnetic radiation to the surface, is absorbed and converted into heat. This heat is then transported from the surface to the atmosphere through turbulent exchange processes, causing the air temperature to rise. On the other hand, the temperature in the near-surface air layer has minimal or no effect on sunshine. Therefore, it can be argued that the variability in annual sunshine is one of the (radiative) causes of changes in air temperature, which explains 58% of the annual variance in air temperature in Kraków from 1951 to 2020 ($r^2 \cdot 100\%$).

The temperature and sunshine patterns (Fig. 1) are very similar to the average area-wide sunshine and air temperature patterns over Poland (Matuszko et al. 2020, 2022a, Marsz, Styszyńska 2021, 2022). Both patterns show a weak, insignificant negative trend between 1951 and 1988, with a sharp increase in temperature and sunshine between 1987 and 1989, followed by a statistically significant positive trend in the subsequent period (1988–2020). This explains the fact that the increase in temperature in Poland only occurred after 1988. This abrupt shift in temperature and sunshine trends coincided with a phase change in the North Atlantic thermohaline circulation from negative to positive (1987–1989; Marsz, Styszyńska 2022) and a change in the mid-tropospheric circulation epoch in the Atlantic-European circulation sector, according to Wangengejm-Girs classification (Wangengejm 1952, Girs 1964), from the meridional E epoch to the zonal W epoch. This suggests that, despite certain local peculiarities, the temperature and sunshine duration trends in Kraków generally reflect large-scale changes. Therefore, the variability of temperature, cloud cover, cloud type structure, and sunshine

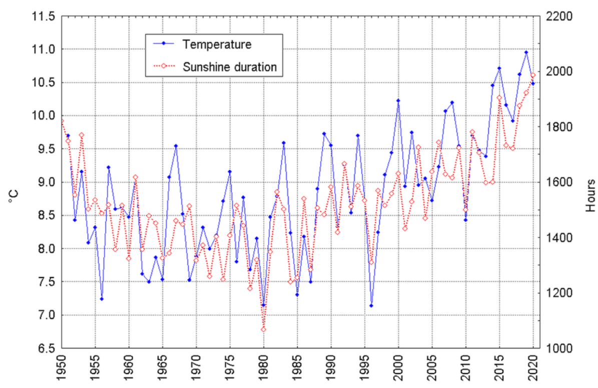

Fig. 1. Course of average annual air temperature (°C) and annual totals of sunshine duration (SD in hours) in Kraków (1951–2020).

duration in Kraków will be analysed in these two time periods: 1951–1988 and 1988–2020.

In the first period (1951–1988), the trend in annual air temperature in Kraków was not significant (p = 0.287) and equalled −0.011 (±0.010)°C per year. The trend in annual sunshine in Kraków was negative, statistically significant (p = 0.002), and equalled −6.28 (±1.89) hr per year. In the second period (1988–2020), the trend in annual air temperature was positive and highly statistically significant (p < 0.000), equal to 0.052 (±0.012)°C per year. The trend in annual sunshine was also positive and highly statistically significant (p < 0.000), equal to 11.5(±1.97) hr per year. The ranges of variability in air temperature and sunshine in Kraków during both periods are shown in Figure 2.

The multi-year average values, when a trend is present, do not adequately describe the scale of changes taking place. A comparison of the average air temperature over the last 3 years of the second period (2018–2020), which was 10.7°C, with the average temperature of the 1951–1988 period (8.3°C), showed that the temperature in Kraków at the end of the 2020s had increased by 2.3–2.4°C compared to the 1951–1988 period. The same applies to sunshine. The average annual sunshine over the last 3 years (2018–2020) was 1927.4 hr, whereas the average from 1951 to 1988 was 504 hr lower (1423.2 hr). The increase in sunshine in recent years constitutes about 1/3 of the average sunshine value from the previous period (1951–1988).

Evaluating the scale of climatic changes that occurred in Kraków between the two periods, it can be concluded that there has been a radical shift, encompassing not only air temperature but also sunshine.

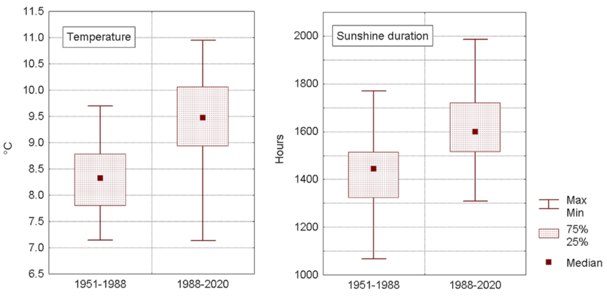

Fig. 2. Ranges of variability of annual air temperature (°C) and annual sums of sunshine duration (SD in hours) in Kraków in the years 1951–1988 and 1988–2020.

The influence of cloud cover and the frequency of cloud genera in Kraków on sunshine duration and air temperature

The problem arises regarding which factors influence the variability of sunshine duration and, consequently, air temperature in Kraków. Clearly, the main factor influencing the variability of sunshine is the changes occurring in cloud cover during the daytime. The amount of cloudiness (N) defines the degree of sky coverage by clouds of all types and heights. It does not consider the differentiation of cloud types. For example, a total cloud cover of N = 8 can occur with the complete sky cover by *Cirrostratus (Cs)* clouds or *Altostratus opacus (As op)*. These two clouds, due to their extremely different optical densities, give completely different responses on a sunshine measuring instrument. During *Cs*, sunshine will be registered by the instrument, while during *As op*, the instrument will not register sunshine. Even more complications arise when clouds of small horizontal size (such as *Cu*) are present in the sky. Many of these clouds (N = 5–6) may be present in the sky, but the measured sunshine will be high, only interrupted when a cloud is between the sun's disc and the measuring instrument. These complexities are more broadly described by Matuszko (2012a, b, 2015). For these reasons, the relationships between cloud cover (N), sunshine (SD), and air temperature (T), although statistically significant, are relatively weak. In the case of the relationship between T and N, the correlation coefficient is −0.45 (p < 0.000), and in the case of the relationship between SD and N, the coefficient is −0.43 (p < 0.000). It is noteworthy that the values of both correlation coefficients are quite similar (with a difference of 0.02, which is not meaningful). This means that the variability in N explains the variance of SD and T to a similar extent (18–20%). The amount of cloudiness in both periods shows slight differentiation. The average annual cloudiness from 1951 to 1988 was 5.5(±0.06) oktas, and in the subsequent period (1988–2020), it slightly decreased to 5.2(±0.04) oktas. This small difference of about 0.3 oktas is statistically significant. The ranges of variability of total cloudiness in Kraków are shown in Figure 3.

The relationships between the cloud genera structure and sunshine duration and air temperature differ significantly. These relationships were

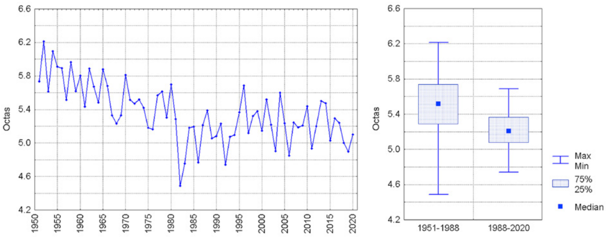

Fig. 3. Course of annual cloudiness values (oktas) in Kraków in the period 1951–2020, and ranges of its variability in periods 1951–1988 and 1988–2020.

detected and described earlier by Matuszko and Węglarczyk (2015, 2018). Generally, only three cloud genera (*As*, *Ns*, and *St*) show a negative correlation with sunshine and temperature. The remaining cloud genera are positively correlated with temperature. In the period from 1951 to 2020, the distribution of correlation coefficients is presented in Table 1.

Due to the different periods of the analyses, the strength of these relationships (Table 1) differs from those presented in the works of Matuszko and Węglarczyk (2015, 2018), but they are generally similar. It is noteworthy that only the occurrence of stratiform clouds is negatively correlated with both sunshine and air temperature. Additionally, changes in the frequency of these clouds (*As*, *Ns*, *St*) have a relatively strong impact on the variability of cloud cover (N), although not as strong as might be expected (positive correlations). The sum of occurrences of clouds *As*, *Ns*, and *St* is negatively correlated with changes in sunshine duration ($r = -0.46$, $p < 0.000$), also negatively, but more strongly, with air temperature ($r = -0.58$, $p < 0.000$), and most strongly, but positively, with cloud cover ($r = 0.68$, $p < 0.000$).

In both periods, 1951–1988 and 1988–2020, specific changes in the cloud type structure occurred (Fig. 4). In the second period, compared to the first, there was a significant decrease in the

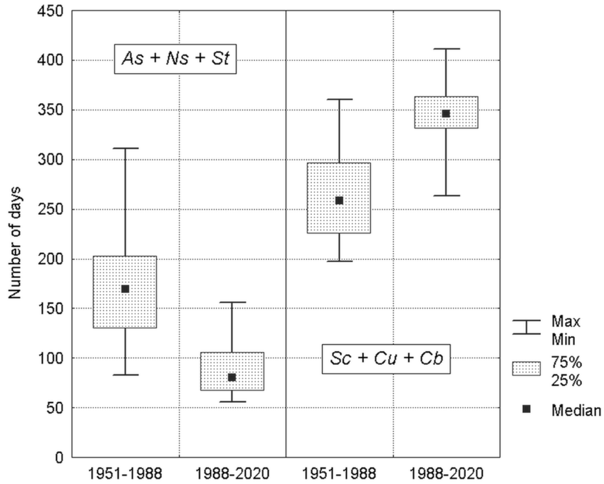

Fig. 4. Ranges of variability in the number of days with observations of frontal clouds (*As*, *Ns*, *St*) and clouds occurring in unstable weather conditions in Kraków during the periods 1951–1988 and 1988–2020.

total number of observations with frontal clouds (*As*, *Ns*, *St*), while the number of observations of clouds associated with unstable weather conditions (*Sc*, *Cu*, *Cb*) significantly increased. This mutual 'replacement' of the two groups of cloud genera resulted in a relatively small decrease in the value of N in the second period compared to the first.

The data presented in Table 1 clearly indicate that the decrease in the frequency of stratiform clouds (*As*, *Ns*, *St*) in Kraków, as shown by Matuszko and Węglarczyk (2018) and Matuszko et al. (2020), must be the cause of the reduction in cloud cover (N) and the increase in sunshine (SD), and thus, indirectly, the rise in air temperature in Kraków.

Changes in overall cloud cover and the cloud genera present in the sky are the result of atmospheric dynamics (atmospheric circulation), which determines the course of synoptic situations. Thus, the influence of atmospheric

Table 1. Correlation coefficients (r) and their statistical significance (p) between the annual frequency of cloud types and annual sunshine duration (SD), average annual air temperature (T), and cloudiness (N) in Kraków in the years 1951–2020 (bold values are significant in level $p < 0.05$).

Element		Cloud genera										Cloudless sky
		Ci	Cc	Cs	Ac	As	Ns	Sc	St	Cu	Cb	
SD	r	**0.61**	**0.62**	0.10	0.01	**−0.45**	**−0.37**	**0.25**	**−0.41**	**0.59**	0.14	−0.03
	p	0.000	0.000	0.395	0.942	0.000	0.002	0.040	0.000	0.000	0.264	0.800
T	r	**0.49**	**0.40**	0.01	0.08	**−0.53**	**−0.46**	**0.38**	**−0.55**	**0.52**	0.30	−0.17
	p	0.000	0.001	0.913	0.491	0.000	0.000	0.001	0.000	0.000	0.012	0.149
N	r	−0.02	0.16	**0.48**	0.01	**0.58**	**0.60**	−0.09	**0.64**	−0.04	**−0.48**	**−0.52**
	p	0.851	0.190	0.000	0.966	0.000	0.000	0.456	0.000	0.735	0.000	0.000

circulation manifests in short-term synoptic processes (weather changes), while long-term climatic effects are only the outcome of the interactions of synoptic-scale processes. The clouds *As, Ns,* and *St*, which have the greatest impact on changes in sunshine, are frontal clouds. Meteorological fronts occur exclusively in low-pressure systems. Frontal stratiform clouds typically have large horizontal extensions and relatively slow movement, which results in a long duration of sky coverage. It is evident that the reflection of incoming solar radiation from the upper surface of these clouds (albedo), followed by strong scattering and absorption of radiation within the cloud mass, significantly reduces the radiation reaching the Earth's surface (amount of energy). As a result, there is a decrease in surface temperature, weakening of turbulent exchange, and, consequently, a reduction in air temperature.

The changes in cloud genera for Kraków described by Matuszko and Węglarczyk (2015, 2018), as well as Wibig (2008) for Łódź, Filipiak (2021), and Matuszko et al. (2022b) for Poland, involving a decrease in the frequency of frontal clouds, can therefore be clearly interpreted as a reduction in the number of low-pressure systems passing over Central Europe, accompanied by an increase in anticyclonic synoptic situations. It can thus be argued that the underlying cause of the observed changes in solar radiation and air temperature in Kraków is the change in the nature of large-scale atmospheric circulation, leading to alterations in the structure of synoptic situations. These changes in large-scale atmospheric circulation, in turn, are influenced by the variability of the thermal state of the North Atlantic, regulated by changes in thermohaline circulation in the ocean. These processes are explained in detail in the works of Marsz et al. (2024) and Marsz and Styszyńska (2024a, b). It is also worth noting that a decrease in cloud cover and changes in cloud genera across the Northern Hemisphere or Europe in the past 20–30 years have been highlighted by other researchers (e.g., Veretenenko, Ogurtsov 2016, Pfeifroth et al. 2018, Dübal, Vahrenholt 2021, Sfîcă et al. 2021, Post, Aun 2024).

The role of changes in sunshine duration, atmospheric circulation, and radiative forcing in shaping air temperature changes in Kraków

The relationship between annual air temperature in Kraków and annual sunshine duration in the city is strong, highly significant ($r = 0.76$, $p < 0.001$), and explains 58% of the variance in annual air temperature over the entire period from 1951 to 2020. The relationships between monthly mean air temperature in Kraków and the annual total solar radiation are statistically significant in all months of the year except for February and October (Table 2), with the strongest correlations in the warm half of the year (April–September, r ranging from 0.29 in May to 0.68 in August). This indicates a relatively strong and consistent influence of sunshine duration (SD) on the course of

Table 2. Correlation coefficients (r) and their statistical significance (p) between monthly and annual air temperature and the annual sunshine duration (SD) in Kraków, the North Atlantic Oscillation PC DJFM Hurrell index (NAO), and radiative forcing (ΔF) during the years 1951–2020 (bold values are significant in level p < 0.05).

Month	SD		NAO		ΔF	
	R	p	r	p	r	p
I	**0.35**	0.003	**0.51**	0.000	**0.24**	0.045
II	0.22	0.074	**0.40**	0.001	**0.28**	0.020
III	**0.26**	0.027	**0.54**	0.000	**0.33**	0.006
IV	**0.51**	0.000	**0.24**	0.043	**0.43**	0.000
V	**0.29**	0.014	0.07	0.593	**0.36**	0.002
VI	**0.63**	0.000	0.13	0.292	**0.45**	0.000
VII	**0.59**	0.000	0.19	0.112	**0.45**	0.000
VIII	**0.68**	0.000	**0.28**	0.019	**0.55**	0.000
IX	**0.49**	0.000	0.18	0.130	0.21	0.074
X	0.16	0.187	0.08	0.526	0.16	0.175
XI	**0.29**	0.014	−0.16	0.176	0.20	0.105
XII	**0.25**	0.036	0.18	0.145	0.17	0.154
Year	**0.76**	0.000	**0.54**	0.000	**0.64**	0.000

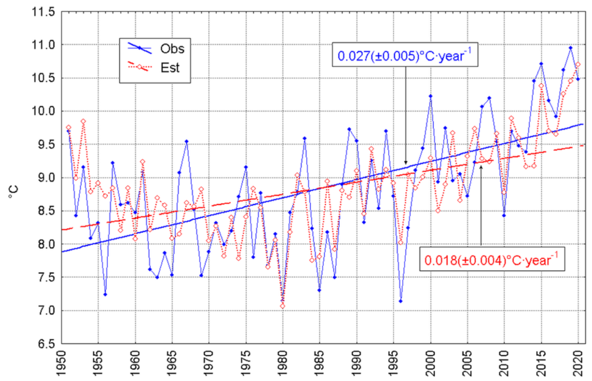

Fig. 5. The course of the observed mean annual air temperature (°C) in Kraków (Obs) and the estimated air temperature based on sunshine duration (Est) from 1951 to 2020. The trend values are marked in boxes (with the standard error of estimation values in parentheses).

annual air temperature (T) in Kraków. Regression analysis (T = a + b × SD) shows that this relationship is linear. Estimated annual air temperature values in Kraków based on annual sunshine duration reproduce the interannual variability quite well, and a discontinuity in the estimated temperature trend is evident in the second half of the 1980s (Fig. 5). The estimated values show a positive trend of 0.018(±0.004)°C · year^{-1}, which is lower than the observed trend in Kraków for the same period (0.027(±0.005)°C · year^{-1}). The difference between the two trend values is statistically significant.

The relationship between the annual air temperature in Kraków and the annual sunshine duration (SD) in the city during the years 1951–2020 takes the form of:

$$T = 2.8457(\pm 0.6277) + 0.0040(\pm 0.0004) \times SD \qquad (2)$$

(values provided with increased precision). This means that an increase in the annual sunshine duration (SD) in Kraków by 1 hr led to an increase in the annual air temperature by ~0.004°C. Considering that between the periods 1951–1988 and 2018–2020 there was an increase in SD by approximately 500 hr, the increase in sunshine duration during this period, without the influence of other factors, resulted in an air temperature rise of about 2.0°C in Kraków.

As mentioned earlier, the variability in air temperature in Kraków is a function of several variables, not just changes in solar radiation. In addition to solar radiation, at least two other factors should be considered: large-scale atmospheric circulation, which transfers heat along with air mass transport, and radiative forcing (ΔF).

The relationships between atmospheric circulation and cloudiness (N), SD, and air temperature (T) in Kraków have typically been considered as connections between local atmospheric circulation indices (Niedźwiedź 1981) and the previously mentioned elements (Matuszko, Węglarczyk 2018). Generally, large-scale circulation, which operates across the entire Atlantic-European circulation sector, was not taken into account, with some exceptions (Matuszko 2007). The shaping of air temperature variability in Kraków demonstrates the separate influence of two factors. During the warm season, the primary role is played by the changes in solar energy influx regulated by the variability in SD. This is understandable, given the influence of the astronomical factor (day length, Sun's altitude). In the cold season, the role of radiative influx takes a back seat to the horizontal heat transport. The form of atmospheric circulation that most strongly influences the shaping of air temperature in the cold season, particularly during the 'extended winter' period (December–March; DJFM), is the North Atlantic Oscillation (NAO). The NAO index (Hurrell et al. 2003) is significantly correlated with temperature trends from January to April (Table 2). The correlation between the NAO index and the annual air temperature in Kraków is 0.54, which is highly significant ($p < 0.001$), meaning that the variability of the winter NAO index explains 29% of the variance in the annual air temperature. In the period 1951–2020, a statistically significant positive trend of 0.020(±0.006) ($p = 0.002$) can be observed in the NAO. The variability of the NAO index also shows significant

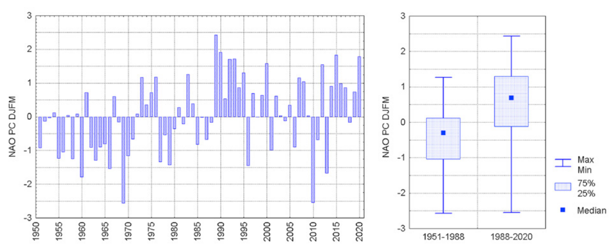

Fig. 6. The course of the North Atlantic Oscillation principal components (NAO PC) DJFM Hurrell index from 1951 to 2020 and the ranges of its variability in the periods 1951–1988 and 1988–2020.

differences between the periods 1951–1988 and 1988–2020 (Fig. 6). This indicates that the increase in the intensity of westerly (zonal) circulation in the winter period after 1988 is one of the reasons for the observed rise in annual temperature in Kraków.

The estimated annual temperature (T) in Kraków, based on the NAO index values (T = a + b × NAO), shows a discontinuity at the end of the 1980s and a positive trend of 0.009°C · $year^{-1}$. This trend is significantly smaller than the trend observed in the actual air temperature data (0.027°C · $year^{-1}$). Additionally, the interannual variability of the temperature in the estimated course is clearly underestimated, and the standard error of estimation (SEE) is substantial (±0.80°C).

The combined effect of changes in annual sunshine (SD) in Kraków and the winter (DJFM) NAO index (NAO) is expressed by the equation:

$$T = 3.730(\pm0.620) + 0.003(\pm0.000) \times SD + 0.250(\pm0.066) \times NAO \qquad (3)$$

statistical characteristics of which are as follows: R = 0.807, adj. R^2 = 0.641, SEE = 0.563, p < 0.001. This equation is highly significant ($F(2, 67)$ = 62.6; p << 0.001). The distribution of residuals from the estimated values is normal, indicating a very good fit of the estimated temperature values to the observed ones. The combined effect of both variables explains 64% of the variance in the observed air temperature. Variance analysis shows that the variability of sunshine (SD) in this equation explains 57.7%, while the variability of the NAO index explains 7.4% of the variance in the observed annual temperature in Kraków. The trend of the estimated annual temperature from Eq. (3) is 0.020(±0.004)°C · $year^{-1}$. This trend value is higher than the trend estimated from sunshine alone but lower than the trend in the analysed air temperature series (0.027(±0.005)°C · $year^{-1}$).

The comparison of the estimated values from Eq. (3) and the observed temperature values indicates a good fit of the estimated values to the observed ones (Fig. 7), as well as the presence of a discontinuity in the series at the end of the 1980s.

Radiative forcing (ΔF), a function of CO_2 concentration in the atmosphere, is widely considered (IPCC Reports 2007, 2013, 2023) as the most important factor causing anthropogenic

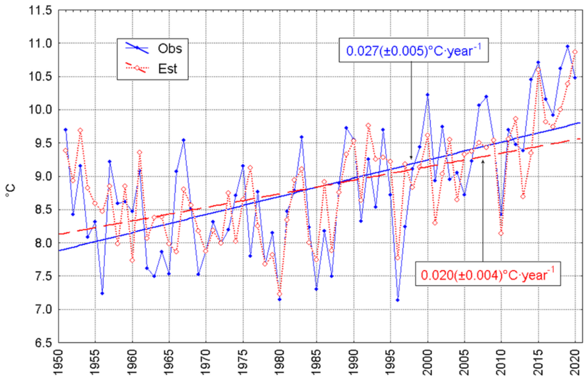

Fig. 7. Course of the observed mean annual air temperature (°C) in Kraków (Obs) and the estimated (Est) from the course of two variables: sunshine duration (SD) and North Atlantic Oscillation (NAO) in the years 1951–2020. The trend values are marked in the boxes (with standard error of estimation values in parentheses).

global warming. In the period 1951–2020, ΔF systematically increased from 0.592 in 1951 to 2.224 W · m^{-2} in 2020. This increase is monotonic, and the course is weakly exponential. The correlation coefficient between ΔF and the annual air temperature (T) in Kraków is 0.64, highly significant (p < 0.001), and explains 40% of the variance in the observed air temperature. This is a high explanation. Regression analysis (T = a + b × ΔF) shows (Fig. 8) that the estimated air temperature course based on ΔF variability does not reveal any interannual variability or a change in temperature regime in the 1980s. In the first period (1951–1988), when the temperature trend in Kraków is zero, the estimated temperature trend is positive. The regression merely ‘rescaled’ the ΔF values to match the air temperature values. This pattern suggests that the main cause of the strong correlation between these values is the common trend observed in both series. Interpreting this relationship, it can be considered either a statistical artefact or that ΔF only contributes to the positive trend observed in the temperature course.

A more detailed analysis of the relationships between ΔF and the monthly air temperature course in Kraków reveals significant statistical relationships between these variables only from January to August (inclusive) (Table 2). The strongest correlations are observed during the summer months (June, July, August), when the highest air temperatures (as well as the highest solar radiation) are recorded.

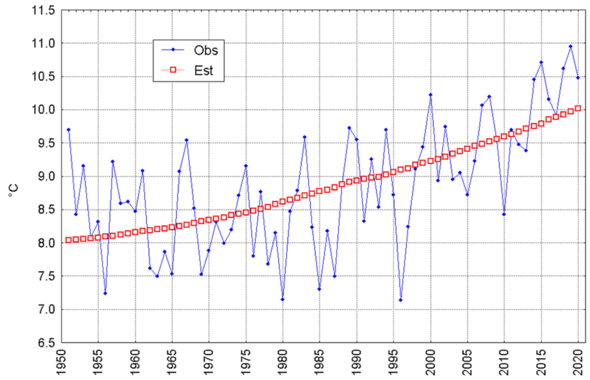

Fig. 8. Course of the observed mean annual air temperature (°C) in Kraków (Obs) and the estimated (Est) from the course of radiative forcing in the years 1951–2020.

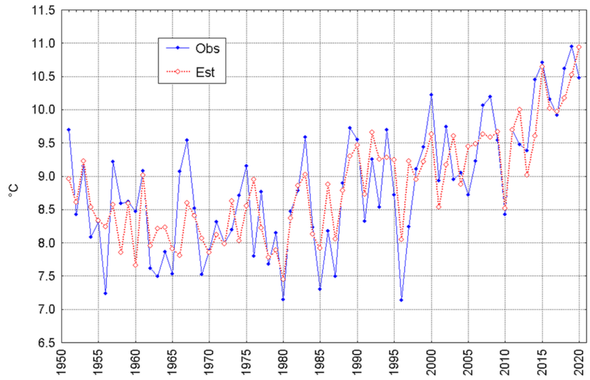

Fig. 9. The course of the observed annual average air temperature (°C) in Kraków (Obs) and the estimated (Est) temperature based on the course of three variables: sunshine duration (SD), North Atlantic Oscillation (NAO), and ΔF from 1951 to 2020.

The estimation of the annual air temperature (T) course in Kraków using the three explanatory variables – solar radiation (SD), the winter NAO Hurrell PC index (NAO), and radiative forcing (ΔF) – resulted in a statistically highly significant equation ($F(3.66) = 48.3$; $p << 0.001$) in the form of:

$$T = 4.145(\pm 0.610) + 0.003(\pm 0.000) \times SD + 0.218(\pm 0.064) \times NAO + 0.454(\pm 0.165) \times \Delta F \quad (4)$$

with the following characteristics: R = 0.829, adj. $R^2 = 0.673$, SEE = 0.538. The estimation of the intercept and all regression coefficients is statistically significant. The residual analysis shows that they follow an almost perfect normal distribution, and there is no trend in the series. Variance analysis shows that in Eq. (4), the variability of SD explains 57.7%, NAO explains 7.7%, and ΔF explains 3.6% of the observed annual temperature variance in Kraków (T). A remaining 32.7% of the variance remains unexplained. Such an explanation of the variability in annual air temperature in Kraków through the combined action of the three variables should be considered high (Fig. 9). The smaller explanation of temperature variance by NAO and ΔF in the multiple regression Eq. (4), compared to each variable individually in the single-variable regression equations, results from the covariance (redundancy) between the independent variables.

The estimated trend of air temperature based on Eq. (4) is 0.028(±0.003)°C · year^{-1}, which is not statistically different from the observed trend of annual air temperature in Kraków (0.027(±0.005)°C · year^{-1}). This stage of the analysis explains that the ΔF contributes only a sole, very weak positive trend (on the order of thousandths of a °C per year) to the variability of air temperature. The combined effect of solar radiation variability, the winter NAO index, and radiative forcing thus satisfactorily explains the increase in air temperature in Kraków, although it does not fully explain the entire pattern of this variability (Fig. 10).

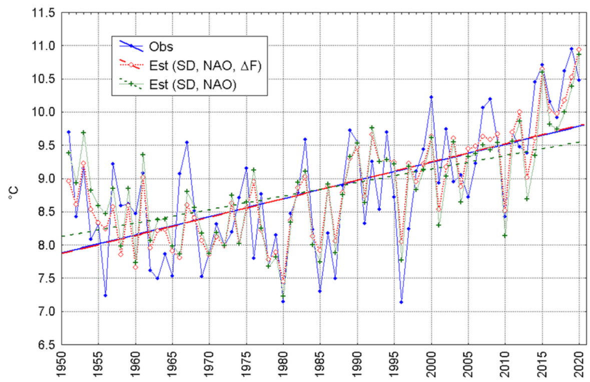

Fig. 10. Course of the observed average annual air temperature (°C) in Kraków (Obs) and the estimated temperature (Est) based on the course of two variables sunshine duration (SD) and North Atlantic Oscillation (NAO) and three variables (SD, NAO, and ΔF) in the years 1951–2020. Trend lines are marked. The differences between the observed temperature trend and the estimated temperature trend based on three variables are so small (0.001°C · year^{-1}) that they overlap in the graphical representation

Discussion of results and conclusions

The analysis conducted shows that the combined effect of the considered variables (SD, NAO, ΔF) explains just over two-thirds of the observed annual air temperature variability in Kraków. About one-third of the unexplained variance is attributed to factors not considered in this analysis. Among these, changes in atmospheric transparency, which influence solar radiation intensity but have little or no effect on SD, should be mentioned first. The authors do not have data on changes in atmospheric transparency or aerosol concentrations over Kraków during this period. However, it can be assumed that in the 21st century, due to the reduction and eventual cessation of production at the metallurgical complex in Nowa Huta (Bokwa 2010, Matuszko et al. 2023) and measures taken to limit both gas and particulate emissions, the transparency of the atmosphere in Kraków has increased. A second factor not considered in this analysis is likely the development of the urban heat island in Kraków. It existed before 1951 (Morawska-Horawska 1991), and its spatial shape and intensity changed with the ongoing urban development and the location of anthropogenic heat sources. Its intensity averages 1.2°C, but in extreme cases, it can reach even 5–7°C (Lewińska 2000, Bokwa 2009, 2010, Matuszko et al. 2023).

The regression analysis revealed that the variability of the three considered factors – SD, the intensity of the western circulation in winter (NAO), and radiative forcing (ΔF) – completely explained (within the estimation errors) the observed increase in annual air temperature in Kraków. The true value of the trend of the observed annual air temperature in Kraków falls within the range of 0.022–0.032°C per year, while the trend of the estimated temperature is within the range of 0.025–0.031°C per year. This difference is not statistically significant.

The research indicates that the most important factor influencing the increase in air temperature in Kraków is the increase in SD. This increase occurred as a result of changes in cloud cover structure – specifically a reduction in the frequency of frontal clouds (*As*, *Ns*, *St*), while the overall cloud cover decreased only slightly. A less significant factor in shaping the temperature increase in Kraków is the rise in the intensity of the western circulation during the winter period, as described by the winter NAO index. Both factors are natural, not anthropogenic, and result from changes in macro-circulation conditions in the Atlantic-European circulation sector. Between 1987 and 1989, a shift in the middle tropospheric circulation epochs occurred, moving from the meridional circulation epoch (E) to the zonal circulation epoch (W) according to the Wangengejm-Girs classification (Savichev et al. 2015, Marsz, Styszyńska 2022). This caused a shift in the trajectories of low-pressure systems to the north, an increase in the frequency of high-pressure systems south of 55–60°N, and consequently, an increase in the occurrence of 'high-pressure weather' with no frontal clouds (Marsz, Styszyńska 2023, 2024a, b, Marsz et al. 2024).

The role of the anthropogenic factor, namely the increase in CO_2 concentration in the atmosphere, described by radiative forcing, in driving the increase in air temperature in Kraków is statistically significant but marginal in terms of its importance. It does not introduce interannual variability and only slightly increases the trend of temperature rise. Similarly, in Wrocław, located ~250 km from Kraków, a small impact of radiative forcing on temperature increase (~6%) was detected (Marsz et al. 2021). There, the main factor driving the rise in temperature after 1988 was also a radical increase in sunshine. These results indicate the fundamental role of changes in cloud structure, and consequently sunshine, in shaping the observed rise in air temperature. Research by Norris and Slingo (2009) suggested that even small changes in cloud cover can have a greater effect on Earth's radiation balance than corresponding changes in greenhouse gas concentrations. They note that a 15–20% increase in low cloud cover can cause changes in the radiation balance comparable to doubling the CO_2 concentration. Additionally, van Wijngaarden and Happer (2025) estimated that the role of low cloud cover in shaping the transfer of solar energy to Earth's surface is even greater, and a reduction in low cloud cover by just a few percent produces the same effect as doubling the CO_2 concentration.

Based on the results of this study, the role of increasing CO_2 concentrations in the atmosphere in raising air temperature (global warming) appears to be overestimated. Thus, the actual contribution of increased CO_2 concentrations to the magnitude of the greenhouse effect in the atmosphere requires further research based on empirical data rather than relying solely on models.

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Author's contribution

AM: Conceptualization; methodology; writing-review & editing; AS: Visualization; writing-original draft; writing-re-view & editing; DM: Project administration; supervision; writing-review & editing.

Data availability statement

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