Przegląd Geograficzny
2024, 96, 3, s. 395-416
https://doi.org/10.7163/PrzG.2024.3.5

Instytut Geografii i Przestrzennego Zagospodarowania
Polska Akademia Nauk

https://www.igipz.pan.pl/przeglad-geograficzny.html

Thermal extremes in February and March 2024 in Poland and their synoptical background

Katarzyna Wrona

Jagiellonian University
Doctoral School of Exact and Natural Sciences
ul. prof. S. Łojasiewicza 11, 30-348 Kraków
Institute of Geography and Spatial Management
ul. Gronostajowa 7, 30-387 Kraków
ka.wrona@doctoral.uj.edu.pl

Abstract. Extremes in air temperature are mostly studied with regards to summer period. However, the importance of above-average temperature in colder parts of the year should be highlighted too, as these extremes play an essential role for the phenological seasons and may also signalise the impacts of climate change. The aim of this work was to explore the uniqueness and synoptic background of abnormally warm February and March 2024 in Poland. The results show that during both months the inflow of rare tropical air masses determined the appearance of the highest temperature. However, the characteristics of the two months were different. During February, most days displayed the above-average daily mean temperature. In March, on the other hand, thermal situation was more complex. Both frost days and hot days were noted, with extreme minimum temperature often lower during March than in February. Under current state of knowledge, the results described in the paper represent very specific anomalies resulting from rare synoptic conditions, yet it is possible that due to climate change more events of this type will be noted in Poland and Central Europe.

Keywords: thermal extremes, Poland, circulation, synoptic conditions, climate change.

Introduction

Meteorological and climatic extremes are an integral part of the climate system with its internal variability and have accompanied people's lives for centuries (Strupczewski & Girguś, 1965; Girguś, 2022). Nowadays, there are also numerous deviations from long-term norms, which are better documented because of the increasingly more accurate measurement methods and devices. However, researchers claim that the observed increase in the number of recorded phenomena is not only related to technological progress (new types of measuring equipment, more weather stations, wider use of satellite data and development of weather reanalyses) but also is a consequence of ongoing human-induced climate change (Kundzewicz, 2017a, b; Karaczun & Kozyra, 2020; IPCC, 2023).

Extreme weather and climate events vary in nature and duration. Some of them occur suddenly and last for a few hours or even a few minutes. Such events are usually referred to in the literature as "meteorological phenomena" or "weather phenomena". These include, for example, violent downpours, storms, strong wind gusts, tornadoes and fog. Also, some longer events, with a duration of few days or even few months can be called "weather phenomena" when they exhibit the above-average or below-average values of certain weather characteristics. Some of the examples include heat and cold waves or

droughts. Meteorological phenomena often cause difficulties in everyday life, including material losses and paralysis in transport and energy supply (Piotrowicz et al., 2020).

This article focuses on an extreme meteorological phenomenon in the form of above-average air temperature that were noted in Poland in February and March 2024. Despite being a very interesting research case, winter and early spring warms spells are rarely getting attention in studies. They may not produce outcomes as disastrous as summer heat waves, but their importance is indisputable, especially for agriculture, as they may cause premature flourish of crops which then become easily susceptible to dangerous ground frosts. Also, winter sports, such as alpine skiing, are heavily affected by exceptionally warm periods in February and March. The choice of this particular study period, consisting of two months in 2024, was made in order to verify the frequently-published media information about their high thermal extremity and explore the background of this situation. The results allow for a better understanding of the causes of thermal extremes in the current Polish climate and may serve as a reference point for future analyses of exceptional weather events and their impacts on economy, ecology and nature.

Literature review

The literature on extreme meteorological phenomena is extremely rich. This issue is addressed in particular by the Intergovernmental Panel on Climate Change (IPCC) research group in its reports on the causes and effects of climate change in the world. The last of them contains the entry: "Human influence was very likely the main driver of these increases *(increases in the number of extreme phenomena – author's note)* since at least 1971. Evidence of observed changes in extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones, and, in particular, their attribution to human influence, has further strengthened since AR5" (IPCC, 2023, p. 5). For this reason, extreme phenomena are studied by numerous authors from around the world, also in the context of climate change (e.g. Tangborn, 2003; Fonseca et al., 2016; Caloiero, 2017; Feng et al., 2018; Xie, 2022), There is no shortage of regional works as well, e.g. covering the whole of Europe (de Bono et al., 2004; Benison et al., 2007; Pellegrini et al., 2007; Ballester et al., 2010; Russo et al., 2015; Twardosz & Kossowska-Cezak, 2015, 2016; Kossowska-Cezak & Twardosz, 2016; Guerreiro et al., 2018).

In relation to Poland, research is carried out both for the entire country (i.e., for all synoptic stations operating in Poland) and for selected regions and cities. Among the most recognized researchers of extreme weather and climate phenomena are: Wibig (2007, 2009a, b), Krzyżewska (2010, 2014), Krzyżewska & Wereski (2011), Kuchcik (2006a, b), Kossowska-Cezak (2010a, b), Kossowska-Cezak & Skrzypczuk (2011), Kossowska-Cezak & Wawer (2014), Kossowska-Cezak & Twardosz (2016), Kossowska-Cezak et al. (2016), Piotrowicz (2005), Piotrowicz et al. (2020) and Tomczyk et al. (2018, 2019). Examples of research in this field include a work by Zimnol and Bielec-Bąkowska (2019), who studied the occurrence of warm and cold days in Poland in the years 1966-2017. Having based their definition of warm days on the deviations of daily maximum temperature from the multi-year mean maximum temperature of that day, they extracted the above-average warm winter spells. Their number was small, amounting to about 2.9 to 4.3 spells per year. However, in almost all cases, winter warm periods appeared more frequently in Feb-

ruary and March than in December and January. Especially many sequences of warm days were noted in Świnoujście in February. The authors also indicated that the number of warm spells in winter and early spring was increasing over the years, but the tendencies were not strongly pronounced (the most significant ones being 0.36 in Rzeszów in December and 0.31 in Suwałki in March). The rise in the number of winter warm spells was also noted in a study by Tomczyk et al. (2019). These authors used percentile method to estimate the number of winter warm spells in the years 1966/67 to 2015/16 and separated around 3-5 of them per 10 years. The study focuses on Central Europe and provide an atmospheric circulation background for the observations. The results show that warm winter spells are connected with a more active and intensive baric system in Europe and a south-western advection. Also, before winter warm spells, positive anomalies in geopotential heights were observed, the greatest recorded at 250 hPa.

In the above-mentioned literature, the definition of "extreme phenomenon" is not clear. In colloquial understanding, "extreme" means "rarely encountered in a given place, time and conditions". The limit of "extreme" or "anomalous" can be defined in many different ways. One of the methods most often used by researchers are percentiles, which provide information about the percentage of phenomena that fall below, or reach above, a certain threshold (Benison et al., 2007). The threshold for an extreme phenomenon is often defined as the 5th and 95th percentile (approach used by IPCC and the Polish Institute of Meteorology and Water Management – National Research Institute IMGW-PIB), although depending on the nature of the research and the phenomenon under consideration, other limits are also encountered, e.g., 90th and 10th or 99th and 1st percentile (Benison et al., 2007; Krzyżewska, 2014; Sulikowska et al., 2016; Tomczyk et al., 2019). Another way to define extreme is to determine the probability of a given phenomenon occurring using a time interval. For example, a "hundred-year frost" means frost occurring at an approximate rate of one event every hundred years. This approach is particularly popular in hydrology, where the estimated frequency of flood events is determined. It is also possible to determine extremes based on standard deviations (usually thresholds of 2σ or 3σ are used).

In some situations, especially in relation to heat and frost waves, relative thresholds are abandoned in favour of absolute thresholds, set at a constant level. For example, Kossowska-Cezak (2010a, b), Kozłowska-Szczęsna et al. (2004) and Tomczyk et al. (2018) define a heat wave as a sequence of at least three days during which maximum temperature exceeds 30°C. Another case are record-breaking values. By definition, they have the characteristics of an extreme phenomenon, as they are the maximum or minimum values of a given parameter in a specific time period. As a rule, record-breaking values are defined in relation to the so-called normal periods – multi-year periods adopted in climatology as reference intervals. The currently used normal period is 1991-2020.

Studies on above-average air temperature most often refer to the summer period. The number of hot and very hot days is discussed, as well as the causes and effects of heat waves when the maximum daytime temperature exceeds 30°C. However, cases of extremely (above average) high air temperature during astronomical winter are extremely rarely discussed. This is because air temperature values achieved in summer are much higher, and the effects of long-term summer heat waves can be extremely severe for both humans and the environment – for example, the estimated number of victims of the 2003 heat wave was between 20,000 and 70,000 people across Europe (Robine et al.,

2008; Barriopedro et al., 2011; Christidis et al., 2015; as cited in Russo et al., 2015). The importance and threats associated with summer heat waves should be emphasized, but extremely warm winter and early spring events also have their consequences. Early breeding of birds and other animals (Belik & Beuch, 2019), as well as the faster proceedings of phenological phases, can have vital impacts – not only for our ecosystems, but also for agriculture, leading to substantial losses in crops when after a warm spell a recurrence of frost days is observed (Węgrzyn, 2008; Mager & Kępińska-Kasprzak, 2016; Xie, 2022). Other areas of life affected by abnormally warm late winters and early springs are winter sports and tourism, such as skiing, skitouring and snowboarding. These extreme weather events can also be seen as a sign of ongoing climate change and a prediction of future standard conditions in that part of the year (Tangborn, 2003; Twardosz & Kossowska-Cezak, 2016). This study aims to fill the research gap in the field of recognizing the nature and determining the synoptic causes of the occurrence of anomalously high air temperature values in winter and early spring. The analysis is based on a case study of the extremes recorded in February and March 2024 in Poland.

Data sources and methods

The main part of the analysis is based on the use of meteorological and climatic data, which included daily and monthly maximum air temperature values, monthly mean temperature values and mean monthly temperature anomalies from the years 1951-2024 (the period 1991-2020 was used as a reference period). The data was obtained for all synoptic stations in Poland from the official sources of IMGW-PIB, namely the websites imgw.pl, klimat.imgw.pl and cmm.imgw.pl, monthly Polish Climate Monitoring Bulletins (Biuletyny Monitoringu Klimatu Polski), as well as archival data available at danepubliczne.imgw.pl. As of 2024, 58 synoptic stations are in operation in Poland. They are dispersed throughout the country and in all main landforms of Poland: the coastland, the lake district, the lowlands, the highlands, the Subcarpathia and the mountains – Carpathians and Sudetes. However, historic data from the period 1991-2020 is only available for 56-57 stations, depending on the parameter, which is due to changes in location and/or the category of the station. Supplementary to the temperature data, synoptic maps of Poland and baric topography maps over Europe for levels 850 hPa, 500 hPa and 300 hPa were used. The former were obtained from IMGW-PIB resources (danepubliczne.imgw.pl), while the latter were accessed via the archive service of German Weather Service (Deutscher Wetterdienst), available at https://www.wetter3.de/archiv_gfs_dt.html and based on GFS (Global Forecast System) numeric model.

As an auxiliary research method and data source, two calendars of synoptic situations were used in the research – the modified Lityński calendar (Pianko-Kluczyńska, 2007, 2018) and Niedźwiedź calendar (Niedźwiedź, 2020). The Lityński calendar is used by IMGW-PIB in its studies. It covers the entire area of Poland. The circulation types were created based on three classes in each of the three indicators (zonal Ws, meridional Wp and air pressure Cp), resulting in a distinction of 27 circulation types. The Ws and Wp indices are calculated based on the differences in atmospheric pressure between meridians 40°-65°N and parallels 0°-35°E. A detailed description of this classification can be found, among others, in Nowosad (2019), in which paper the researcher also discusses

the shortcomings of the calendar. They include: partial basing on reanalyses, averaging pressure values over a fairly large area and dividing the values always into 3 classes, which may result in the "middle" class containing values that actually represent one dominant geostrophic wind direction. Nevertheless, the Lityński calendar of synoptic situations is a convenient tool for conducting circulation analyses. Its use by IMGW-PIB allows for an easy access to current data, as well as to data from the reference period 1991-2020, but obtaining archival data for single years is difficult, as IMGW-PIB does not share it with the users on any official platform.

The Niedźwiedź calendar of synoptic situations, unlike the Lityński calendar, is not universal for the entire country – it only covers the area of southern Poland between meridians 18 and 24°E and parallels 49 and 51°N. The calendar relies on the manual typology, created on the basis of synoptic maps of Europe (Niedźwiedź, 2017). In the basic version, it distinguishes 21 types – 8 directional cyclonic types, 8 directional anticyclonic types, as well as a high-pressure centre, a low-pressure centre, a high-pressure wedge, a low-pressure bay and an unspecified type, i.e., a baric saddle or a day with a very dynamic change of the synoptic situation. It is also possible to use a simplified version of the calendar, in which adjacent types are combined to create 11 divisions. Another interesting feature of this calendar is that the author provides the notes on which types of air masses prevailed in the southern Poland during each day up to 03/11/2018, which was useful in determining the frequency of air masses' inflows over Poland. The calendar of circulation types for southern Poland for the period 01/09/1873-14/10/2017 is available on the website of the University of Silesia. To obtain data for later years, the researchers may contact the calendar's author personally. Due to the public availability of historical data, as well as transparency and ease of interpretation, the information from this calendar was included in the analysis as part of this study.

Due to the lack of access to full historical data from the modified Lityński calendar, some of the synoptic analyses of record warm months from previous years are based solely on the classification of synoptic situations included in the Niedźwiedź calendar. The author is aware of the spatial inconsistency of this calendar with the assumed research area, as well as other imperfections characteristic of both calendars used in this study. Therefore, the types of circulation were cross-checked with the synoptic maps of Poland issued by IMGW-PIB. Also, the backward trajectories of air masses advection calculated at 850 hPa height for Potsdam, Eastern Germany, were used as a reference to air mass trajectories stated in the circulation calendars. The backward trajectories are based on the GFS reanalysis and were obtained via the archive service of German Weather Service (Deutscher Wetterdienst, 2024). The choice of German data rather than calculating specific backward trajectories for Poland, for example via the Hysplit model, was made taking into account the easy access to data and the possibility to flicker through subsequent days without the need to generate separate images. Still, despite the use of auxiliary data, the analyses of synoptic situations contained in this study should be treated rather as a general background for the presented thermal extremes than an in-depth and detailed exploration of the circulation patterns.

Results

Exceptionally warm February 2024

According to preliminary estimates of CMM IMGW-PIB (Centre for Meteorological Modelling), February 2024 was the warmest February in the history of modern measurements in Poland, i.e., since 1951. The average air temperature calculated from all synoptic stations reached 5.8°C, which is an anomaly of +5.9°C compared to the average February temperature of the 1991-2020 period, -0.1°C. (IMGW-PIB, 2024a). The average air temperature in February was clearly higher not only compared to the long-term average temperature for February, but also to the long-term average for March, which is 3.1°C (IMGW-PIB, 2024b). The anomalies at individual stations ranged from +3.3°C in Hel (average air temperature over the long term 0.7°C, in 2024 4.0°C) to +7.5°C in Krosno (average temperature over the long term -0.9°C, in 2024 6.6°C). In general, the further to the south-east of the country, the greater positive temperature anomalies were observed (Fig. 1). They exceeded 7°C at 6 stations and 6°C at 26 stations, which in total constitutes the majority of the 58 synoptic stations managed by IMGW-PIB.

According to the classification of Miętus et al. (2002), this month in Poland, both as a whole and in all physico-geographical regions (coastlands, lake districts, lowlands, highlands, Subcarpathia, Sudetes, Carpathians), should be classified as extremely warm, i.e., above the 95th percentile of deviation from the average of years 1991-2020. Previo-

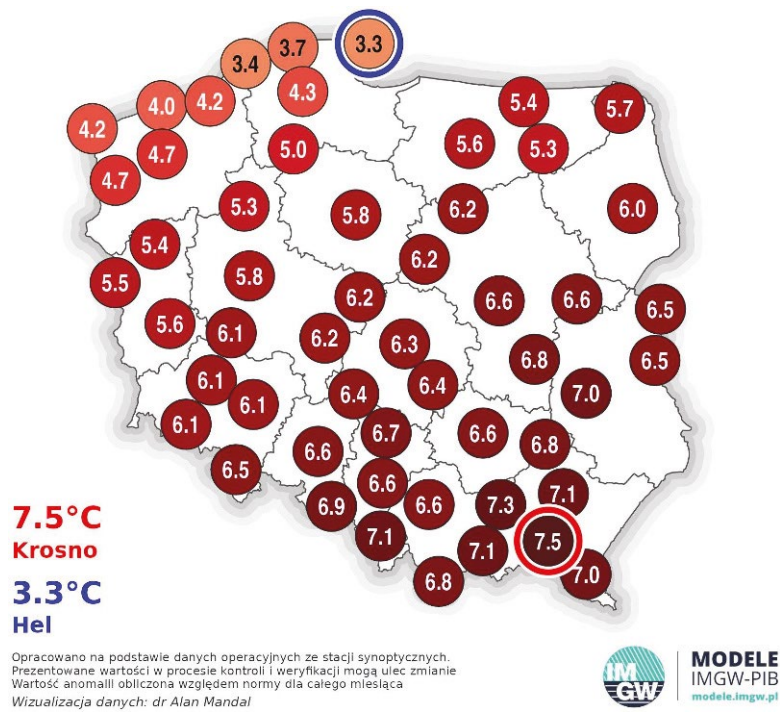

Fig. 1. Air temperature anomalies in Poland at synoptic stations in February 2024 in relation to the period 1991-2024. Source: CMM IMGW-PIB (2024).

usly, such situation occurred only twice: in 1990 and 2002 (Biuletyn Monitoringu Klimtu Polski, 2024a). At that time, anomalies at synoptic stations reached: in 1990 from +3.9°C on Kasprowy Wierch to +6.2°C in Mikołajki and Suwałki and in 2002 from +2.7°C on Śnieżka to +4.8°C in Białystok. So, up to this time, the anomaly of +7°C has never been exceeded in February, and an anomaly greater than +6°C occurred only in 1990 at two stations. This shows the unprecedented nature of the phenomenon we faced in Poland in 2024.

It is worth emphasizing that the largest temperature anomalies in 1990 and 2002 concerned the north-eastern and eastern parts of the country – including stations like Białystok, Mikołajki and Siedlce. In 2024, the largest temperature anomalies were recorded in the south-east and the south – in Krosno, Tarnów, Rzeszów and Nowy Sącz. On this basis, it can be concluded that the synoptic situation prevailing in February in Poland was different from the previous years. In the period 1991-2020, the dominant directions of air masses' advection in February were: north-west (approx. 16.5% of cases) and south-west (approx. 14% of cases) according to the modified Lityński calendar of circulation types (Biuletyn..., 2024a) or west (approx. 23%) and south-west (approx. 12.5%) according to the Niedźwiedź calendar of circulation types for southern Poland (Niedźwiedź, 2020). The total share of circulation from the western sector (NW-W-SW directions) is about 42.5% according to the modified Lityński calendar and about 47.5% according to the Niedźwiedź calendar. Therefore, it can be assumed that during approximately half of the days in February we will experience an inflow of air from the west over Poland. Advection directly from the north accounts for approximately 6% (Niedźwiedź) to 7% (Lityński) of cases. In turn, in the case of advection directly from the south, there are significant discrepancies among calendar authors – in Niedźwiedź it is only about 3.7% of the cases, while the modified version of Lityński calendar gives the value of about 10.5%. The share of the eastern sector (NE-E-SE directions) in both calendars is much smaller than that of the western sector – in Lityński it is approximately 32.5%, while in Niedźwiedź only 19%. Piotrowski (2023), who developed his own system of separating circulation types and used it to explore variability of atmospheric circulation in Poland in the period 1951-2020, states that for the central Poland, during February, advection directly from the north amounts to about 12% of all types' frequency, advection from the south – to 8%, from the eastern sector (NE-E-SE) – to 20% and from the western sector (NW-W-SW) – up to 60%. Inconsistencies in these values are a natural consequence of differences in the calendars' structure and their spatial scope, but the general patterns remain roughly the same.

By comparing the average frequency of air masses' advection from different directions in February in the reference period with the frequency recorded in the years when the largest positive air temperature anomalies occurred, it is possible to obtain information about the circulation peculiarities of these periods and then, basing on them, to seek the causes of the anomalies. In winter, air usually flows into Poland from the west and north-west as a so-called polar maritime air. Sometimes, the polar air flows inside the country from the south-west or even from the south, drawn to Poland through Mediterranean Europe via the atmospheric lows located in the Atlantic or western Europe. Such masses are then called "polar maritime warm" because they are associated with an increase in air temperature. In turn, cold arctic and polar continental air masses reach Poland usually from the north, north-east and east. Especially the latter herald a significant drop in air temperature, even below -20°C. The least frequently arriving air masses are tropical masses – of a maritime or continental nature. They flow over Poland mainly from the south

and south-east and contribute to a significant increase in air temperature, even to several degrees above zero.

In 2024, according to the modified Lityński calendar, situations with advection from the south prevailed. As many as 6 days with circulation from the south, 5 days with circulation from the south-west and 4 days with circulation from the south-east were recorded – which constitutes a total of 15 days with circulation from the southern sector, more than half of the days in the analysed month. The share of meridional circulation should therefore be described as above average. On the other hand, air masses from the north--west, north and east were characterized by a significantly lower-than-average frequency. The backward trajectories observed in Potsdam prove that air masses were coming mostly from the western sector (polar maritime air), with almost complete absence of the air masses from the east (polar continental air) and a rare occurrence of masses originating from the north (arctic air) (Deutscher Wetterdienst, 2024). This allowed the presence of very high air temperature in most parts of Poland – also in the north and east of the country, where the influence of frosty continental polar air masses in winter is usually strong. However, comparing the situation in 2024 with that in 2002, when the eastern and north-eastern parts of Poland noted the highest positive anomalies, it was the frequent inflow from the south that made the south-eastern part of Poland the warmest during February 2024. According to the Niedźwiedź calendar, the dominant direction of air masses' advection in 2002 was west, especially in the cyclonic subtype. Overall, 12 days of western cyclonic advection were noted, 5 days of western anticyclonic advection, 4 days of south-western anticyclonic advection, 2 days of north-western cyclonic advection and 1 day of south-western cyclonic advection. This means that advection of air masses from the western sector was present during 24 of the 28 days of the month. Only one day was characterised by advection directly from the north and no day with advection from the south or east was recorded. According to the author of the calendar, arctic air flowed over Poland for 6 days in February 2002, while polar continental air did not reach the country at all. Therefore, due to the simultaneous lack of inflow of air masses from the south, the highest positive air temperature anomalies were observed in the northern and north--eastern Poland, usually dominated by the cold continental advection. A similar situation occurred in 1990. During 24 days, a circulation from the western sector prevailed, most often the western anticyclonic type. This means that the weather in Poland was shaped primarily by stable high-pressure centres drawing maritime polar air over the country. No day with an inflow of arctic, polar continental or tropical air was observed then.

The genesis of above-average air temperature values in February 2024 was therefore different than in the previous cases of exceptionally high temperature during this month. This was due to the unusually large frequency of the air masses' inflow from the southern sector. According to the research of Więcław (1999), tropical air masses over Poland occur with an average frequency of 1.5-2% of days per year. They can be observed mostly in October and at the turn of May and June, while from November to the end of February their frequency is very low. Similar findings are presented in a recent study by Bartoszek and Kaszewski (2022), in which the frequency of tropical air masses is estimated for around 3% in July and almost zero in January and February (Fig. 2). This shows what a phenomenon February 2024 was in terms of circulation. According to IMGW-PIB synoptic maps, in the first half of the month the western circulation clearly dominated over Poland, with warm and transformed polar maritime air masses shaping the weather in the country.

This allowed the average daily air temperature to remain above zero. However, the path to the inflow of warmer air from the southern Europe opened several times – especially on February 10-12. During this time, the parallel arrangement of isobars over Europe was disturbed by a low-geopotential saddle spreading over the western part of the continent from the low geopotential centre over the Arctic and a high-geopotential wedge that was connected with a high from over Egypt and took over most of the Central and Eastern Europe. Between these two strong systems arose large differences in geopotential values, which was especially well pronounced at 500 hPa and 300 hPa levels. Backward trajectories from Potsdam show that the strongest inflow of southern air was noted there on February 11. Another period with the southern inflow of air masses took place during February 16 to 17. Another high-geopotential wedge, small but visible even on the height of 300 hPa, appeared in Europe, influencing the weather mostly in Central Europe. Data show that on 300 hPa, the warmest period was February 10-11, while on 500 hPa, more above-average warm periods could be distinguished. These were: February 3, February 9-11, February 16-17. All of these periods are characterised by very strong contrasts of geopotential values between the northern and southern parts of Europe (Deutscher Wetterdienst, 2024).

Subsequently, the temperature over Poland remained quite variable, but rather high, as drops below zero were rarely observed. It was only on February 27 that the warmth returned to the country. During that day, the occurrence of tropical air masses over Poland was recorded. They reached mainly the southern and eastern parts of the country because of an atmospheric front that ran through Poland, blocking the inflow of tropical air towards the north and west and resulting in significant thermal contrasts within the country. However, due to the ongoing reconstruction of the barometric situation over Europe at that time, air temperature differences in Poland gradually became even. On the last day of the month, February 29, after the passage of the cold front, the entire country once again became susceptible to tropical airflow. The increase in air temperature

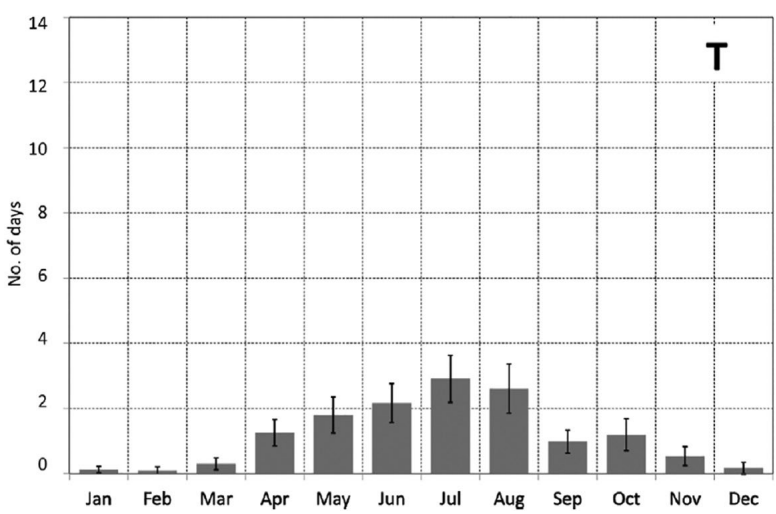

Fig. 2. Average number of days (in months) with tropical air masses in Poland and their 95% confidence intervals
Source: Bartoszek & Kaszewski (2022, p. 8220).

and geopotential values was clearly visible even on 850 hPa. On higher baric levels, i.e., 500 hPa and 300 hPa, this increase took place a little bit earlier, around February 22-23 (Deutscher Wetterdienst, 2024).

February 2024 was not entirely a homogeneous period in terms of air temperature – the synoptic situation favoured the occurrence of differences between stations. In the case of synoptic stations located in central, southern and eastern Poland, the highest air temperature was recorded on February 27, when the inflow of tropical air was observed in these regions of the country. Heat records were broken at 21 stations (including Włodawa, where an even higher air temperature was recorded the next day). The highest air temperature was noted in Tarnów, where the maximum thermometer reached 19.1°C. The previous record for maximum temperature in February at this station was 18.2°C, recorded on February 25, 2008. At two stations (Włodawa and Lublin), new heat records were established the next day, on February 28. In turn, in northern and western Poland, the warmest day was February 16, the one after the passage of the warm front from the south to the north, and before the cold front arrived from the west. The heat records were broken that day in Łeba, Olsztyn and Kętrzyn (in the case of Olsztyn and Kętrzyn, similarly as in Włodawa, another record was established later in the same month – in both cases on February 26), but many stations, such as Chojnice, Suwałki, Białystok, Lębork and

Table 1. Synoptic stations where the heat records from the period 1990-2021 were broken in February 2024

Station	Maximum T_{max} in 2024	Date	Previous maximum T_{max}	Date
Tarnów	19.1	27.02.2024	18.2	25.02.2008
Rzeszów	18.6	27.02.2024	17.2	25.02.2008
Zamość	17.9	27.02.2024	15.3	22.02.1998
Krosno	17.8	27.02.2024	15.3	25.02.2008
Częstochowa	17.7	27.02.2024	16.1	24.02.2008
Katowice	17.7	27.02.2024	16.2	24.02.1997
Kraków	17.7	27.02.2024	16.8	24.02.2008
Bielsko-Biała	17.6	27.02.2024	17.1	27.02.1994
Lesko	17.4	27.02.2024	15.9	03.02.2019
Kozienice	17.0	27.02.2024	15.1	21.02.1998
Racibórz	16.8	27.02.2024	16.2	27.02.1994
Sulejów	16.6	27.02.2024	15.1	24.02.2008
Warszawa	16.5	27.02.2024	14.3	17.02.2020
Kielce	16.5	27.02.2024	15.6	24.02.2008
Włodawa	16.5	28.02.2024	14.5	28.02.2017
Lublin	16.2	27.02.2024	13.5	22.02.1998
Terespol	15.9	27.02.2024	14.9	28.02.2017
Łódź	15.9	27.02.2024	14.8	24.02.2008
Łeba	14.9	16.02.2024	14.6	17.02.2020
Siedlce	14.7	27.02.2022	14.2	17.02.2020
Mława	14.1	27.02.2024	11.8	17.02.2020
Płock	14.1	27.02.2024	13.5	05.02.2004
Kętrzyn	13.5	26.02.2024	11.8	19.02.2019
Olsztyn	13.0	26.02.2024	12.6	09.02.2001

Source: author's own work based on Dane Publiczne IMGW-PIB (2024) and Klimat IMGW-PIB (2024).

Toruń, came very close to the maximum values recorded in previous years. In total, during February 2024, heat records were broken at 24 of IMGW-PIB synoptic stations (Table 1). The largest differences between the previous and new records occurred in Lublin (2.7°C), Zamość (2.6°C) and Krosno (2.5°C).

Exceptionally warm March 2024

March 2024 was, like February, the warmest March in the history of IMGW-PIB measurements. The average air temperature in Poland reached 6.7°C, which is 3.6°C higher than the average for the period 1991-2020 (IMGW-PIB, 2024b) and only 1.9°C lower than the long-term average for April (IMGW-PIB, 2024c). The range of anomalies for individual stations was between +2.4°C in Hel (5.1°C in 2024 compared to 2.7°C in the 1991-2020 period) to +4.7°C in Jelenia Góra (7.6°C in 2024 compared to 2.9°C in the 1991-2020 period). The highest anomalies occurred in the south-western and southern Poland (Fig. 3). The anomaly values were slightly lower than in February, but still significant. Within 13 stations, the measured anomalies were higher than +4°C. Anomalies higher than +3°C were recorded at all synoptic stations – except for Hel.

According to the classification of Miętus et al. (2002), March 2024 should be referred to as extremely warm, i.e., above the 95th percentile of deviation from the average temperature of years 1991-2020, both in the whole country and in all physico-geographic re-

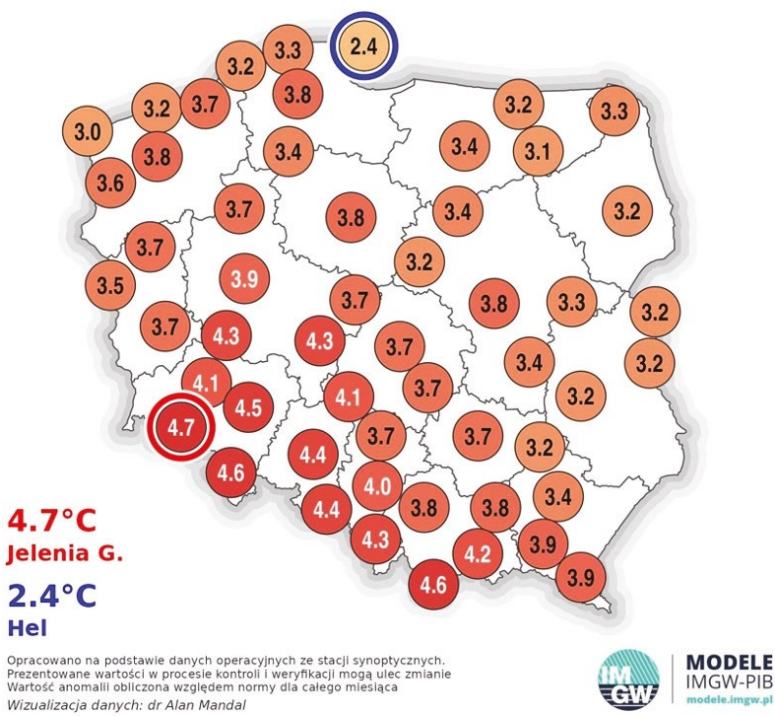

Fig. 3. Air temperature anomalies in Poland at synoptic stations in March 2024 in relation to the period 1991-2024. Source: CMM IMWM-PIB (2024).

gions (coastlands, lake districts, lowlands, highlands, Subcarpathia, Sudetes, Carpathians). In the history of measurements such situation has occurred, as in February, twice: in 1990 and in 2014 (Biuletyn Monitoringu Klimtu Polski, 2024b). During these months, the anomalies at synoptic stations reached: in 1990 from +2.5°C in Śnieżka to +4.1°C in Mikołajki and in 2014 from +2.0°C in Hel to +4.8°C in Słubice. This means that although the absolute highest anomaly of the average monthly air temperature occurred in 2014, in 2024 more stations reached very high air temperature values – hence the average temperature calculated for all synoptic stations in Poland became record-breaking.

In March during the reference period the dominant directions of air masses' advection were north-west (approx. 18%), west (approx. 13%) and north (approx. 13%) (Biuletyn..., 2024b), according to the modified Lityński calendar of synoptic situations. The least frequent air inflow to Poland came from the north-east (approx. 7%), south (approx. 8%) and south-east (approx. 8%). In total, the western sector (NW-W-SW directions) was responsible for around 43% of the frequency of air masses' inflow over Poland. This amounts to 13 days a month with air flow from the western sector and only about 8 days with air flow from the eastern sector (NE-E-SE). The inflow of air from the south lasted on average for about 5 days a month, and the inflow from the north – for 3 days. For about 2 days, a synoptic situation with no specific direction of air mass inflow prevailed. In the case of the Niedźwiedź calendar (Niedźwiedź, 2020), in the years 1991-2020, the inflow from the western sector accounted for 39.3% of cases (approx. 12 days), from the eastern sector – 22.7% (approx. 7 days), from the north – 7% (approx. 2 days) and inflow from the south – 3.7% (approx. 1 day), and days with no uniform direction of air inflow, i.e. situations when a high pressure centre or low pressure centre, a high pressure wedge, a low pressure bay or an undefined situation occurred in southern Poland, constituted 27.3% of all situations (approx. 8.5 days). Both calendars agree that the inflow of air from the western sector dominates in March, while the inflow directly from the north and south is rare. According to the Niedźwiedź calendar, the type of advection most frequently appearing in March in the 1991-2020 period was type Ka – a high-pressure wedge, and the second most common type was Bc – a low-pressure bay. The third most frequent circulation type was the western cyclonic type. The dominance of Ka and Bc types proves the high variability of weather in March and the dynamics of the synoptic situation, which is marked, among others, by numerous front crossings.

In 1990, which was the second warmest March in the history of measurements, the most common circulation types according to Niedźwiedź were: western anticyclonic (7 days), north-west anticyclonic (6 days), high-pressure wedge (6 days). This proves the dominance of high-pressure weather over Poland, with the inflow of mainly polar maritime air masses, sometimes warm or transformed. However, usually when a high-pressure wedge is stationed over Poland, continental air flow over the south of the country. Polar continental air masses were present over southern Poland for approximately 8 days. Therefore, in March that year the warmest parts of the country were generally the southwestern, western and northern Poland, where continental polar air did not reach. The highest average air temperature was measured then in Opole, Legnica and Słubice (7.7°C in each), and the highest deviations from the long-term average – in Mikołajki and Suwałki. The year 2014, in turn, clearly contrasted synoptically with 1990. The inflow of air from the east with anticyclonic circulation had the dominant share (7 days). Also relatively often, air flowed from the north-west during cyclonic circulation (5 days). The subtype with the highest fre-

quency in March 1990, i.e., Wa, appeared only once in 2014. According to Niedźwiedź, for 13 days in March 2014 continental polar air flowed over southern Poland, and for 7 days it was warm maritime polar air. The remaining days were characterized by an inflow of mainly transformed polar maritime air. The frequency of continental air inflow was therefore even higher than in 1990 – hence, again, higher mean air temperature values were recorded in the western than in the eastern and south-eastern parts of the country. The highest value was measured in Zielona Góra, amounting to 7.7°C. Referring to thermal anomalies, the distinctiveness of western Poland was less pronounced. The largest positive differences from the long-term average air temperature occurred in Słubice (western Poland), but the following places were taken by Śnieżka and Kasprowy Wierch – two mountainous stations, situated in the south. This happened even despite the fact that the inflow of air directly from the south was observed during only one day. However, the combined inflow of air from all southern directions (SW-S-SE) was observed in Poland in March 2014 during 6 days. This is significantly more than in 1990 (1 day), although similar to the multi-year mean (on average 6.6 days according to the Niedźwiedź calendar). It can be assumed that the inflow of warm and transformed polar maritime air masses from the south and polar continental air masses from the east resulted in abnormally low cloudiness over southern Poland – because of the path that those masses travelled through the continent. Low cloud cover, in turn, favours an intensive supply of energy from solar radiation, which in the mountainous stations – Śnieżka and Kasprowy Wierch – is delivered in even larger quantities. The above-average sunshine duration in Poland in March 2014 was confirmed by data from the Biuletyn Monitoringu Klimatu Polski (2014).

In 2024, according to the modified Lityński calendar of synoptic situations, the dominant directions of air masses' advection were: north-west (6 days a month) and south (5 days a month). In total, the inflow of air from the southern sector to Poland lasted for approximately 11 days and was a great deal higher than the average frequency of inflow from this sector, which according to the Lityński calendar is between 8 and 9 days. The above-average frequency of southern air masses in Poland is confirmed by the backward trajectories observed in Potsdam. Air of southern European and African origins reached Eastern Germany for about 10 days (Deutscher Wetterdienst, 2024). This situation can therefore be compared to that observed in February 2024, with the above-average share of air masses from the southern sector defining the month in terms of air temperature. The warmest days in March were March 30 and 31, when the inflow of tropical air over Poland was recorded. As mentioned earlier, while discussing the synoptic situation in February, tropical air appears extremely rarely in Poland, only during around 1.5-2% of days a year and usually in October and in the second half of May and the first half of June. Meanwhile, both in February and March 2024, the weather in Poland was partially shaped by this type of air masses. This means that by the end of 2024, the record frequency of these air masses over Poland may potentially be noted.

In March 2024, however, not only tropical but also arctic air flowed over Poland. The coldest days were March 6-8, when a wedge of high pressure reached over Poland, while the centre of the high-pressure system was located over Norway, and March 18-19, when the high from north-western Russia brought arctic maritime air into Poland. At that time, frosts were recorded in almost the entire country, and at several stations, mainly mountain ones (Kasprowy Wierch, Śnieżka, Hala Gąsienicowa, Zakopane) and those located in northern Poland (including Kętrzyn, Olsztyn, Suwałki, Łeba, Ustka), mean daily tempe-

rature below zero was recorded. In total, according to the Lityński calendar, air flowed over Poland directly from the north for approximately 3 days during March 2024 (less frequently than the average from 1991-2020), and air from the north-east reached over Poland for approximately 4 days (more often than in 1991-2020). During the remaining days, Poland was dominated by the inflow of maritime polar air masses, controlled by low pressure systems from the western sector. The frequency of air masses inflow from the west, north-west and south-west in March 2024 was similar to the 1991-2020 average. The synoptic situation during these days of the month was dynamic, and numerous atmospheric fronts passed through the country, which is visible also on higher baric levels. The beginning of the month was marked by the dominance of high-pressure system, while the rest of it was geopotential lows crossing Europe from west to east, sometimes taking more northern or southern paths. The end of the month experienced the formation of two strong baric systems with significant differences between them. The high from Africa reached Central Europe via the clearly visible wedge while the low from Arctica and the secondary low from over the British Isles formed a large bay of cold air above the western Europe (Deutscher Wetterdienst, 2024).

The inflow of arctic air over Poland for several days, confirmed by the backward trajectories from Potsdam on February 7 and February 16-19 (Deutscher Wetterdienst, 2024), did not ultimately prevent the record-breaking average areal air temperature in Poland in March 2024. This was mainly due to the unusually warm two last days of the month. During that time, heat records for March were broken at 45 IMGW-PIB synoptic stations out of 56 for which the maximum temperature records are available for the long-time period. Similar to February, the highest maximum temperature was recorded in Tarnów (25.5°C in 2024 compared to the previous record of 22.6°C). However, records were broken all over the country: in the north (Hel, Gdańsk, Elbląg, Resko), in the east (Suwałki, Białystok, Terespol, Siedlce), in the west (Zielona Góra, Gorzów Wielkopolski), in the south (Nowy Sącz, Kraków, Zakopane, Wrocław) and in central Poland (Warsaw, Kozienice, Kielce, Łódź) (Table 2). This is what made March 2024 stand out compared to February 2024, when new maximum values were noted mainly in the southern and central Poland, with a few exceptions. In March, only mountainous stations (Śnieżka, Kasprowy Wierch), some stations in the north (Piła, Szczecin, Łeba, Ustka, Świnoujście, Kołobrzeg) and Słubice did not note new records on their thermometers. Also, although no new records were broken in Kłodzko and Koszalin, the previous maximum values were equalized. Breaking the previous records by the highest values took place in eastern Poland – in Suwałki the record was beaten by 5.3°C, in Białystok by 4.5°C, and in Terespol by 4.2°C.

What is unusual is the fact that during March 2024 hot days were recorded at three synoptic stations – Tarnów, Warsaw and Nowy Sącz. According to the IMGW-PIB definition, a hot day is "a day on which the maximum air temperature reaches at least 25°C (Tmax ≥ 25°C)" (Agrometeo IMGW-PIB, 2024). The occurrence of such days is typical of the summer period. They appeared mostly in July and, except mountains, amount to about 5.1 days in Kołobrzeg and Łeba to 17.7 days in Opole and Tarnów. In the period 1991-2020, there has not been a single hot day in March at any of the synoptic stations. The first rare hot days (maximum mean 1.3 days per station) start to appear in April. Their recording in March 2024 is therefore an unprecedented event, which emphasize the thermal uniqueness of this period.

Table 2. Synoptic stations where the heat records from the period 1990-2021 were broken in March 2024

Station	Maximum T_{max} in March 2024	Date	Previous maximum T_{max}	Date
Tarnów	25.5	30.03.2024	22.6	21.03.2014
Warszawa	25.3	31.03.2024	22.4	21.03.2014
Nowy Sącz	25.2	30.03.2024	22.3	18.03.2004
Terespol	24.8	31.03.2024	20.6	27.03.2015
Białystok	24.8	31.03.2024	20.3	21.03.2014
Kozienice	24.2	31.03.2024	22.3	21.03.2014
Kraków	24.2	31.03.2024	22.0	21.03.2014
Kielce	24.2	30.03.2024	21.5	21.03.2014
Łódź	24.0	31.03.2024	21.2	21.03.2014
Rzeszów	23.9	30.03.2024	20.9	31.03.2010
Suwałki	23.9	31.03.2024	18.6	27.03.1999
Sandomierz	23.9	30.03.2024	21.0	21.03.2014
Siedlce	23.7	31.03.2024	21.5	21.03.2014
Sulejów	23.7	31.03.2024	20.7	21.03.2014
Włodawa	23.6	31.03.2024	20.4	27.03.2015
Toruń	23.6	30.03.2024	22.1	21.03.2014
Mława	23.5	30.03.2024	20.6	21.03.2014
Kalisz	23.4	31.03.2024	21.6	21.03.2014
Zielona Góra	23.4	30.03.2024	22.4	26.03.2010
Lębork	23.4	31.03.2024	23.0	26.03.2010
Wrocław	23.3	31.03.2024	22.5	21.03.2014
Częstochowa	23.3	30.03.2024	21.6	18.03.2004
Wieluń	23.2	30.03.2024	20.9	17.03.2012
Jelenia Góra	23.2	31.03.2024	21.6	26.03.2010
Leszno	23.1	30.03.2024	22.9	21.03.2014
Opole	23.0	30.03.2024	22.4	17.03.2012
Legnica	23.0	31.03.2024	22.2	21.03.2014
Płock	23.0	31.03.2024	21.1	21.03.2014
Katowice	23.0	30.03.2024	20.9	31.03.1994
Zamość	22.8	30.03.2024	19.8	27.03.1999
Krosno	22.6	30.03.2024	20.3	27.03.2015
Racibórz	22.6	30.03.2024	20.8	18.03.2004
Gorzów Wlkp.	22.5	31.03.2024	22.0	26.03.2010
Poznań	22.5	30.03.2024	21.8	21.03.2014
Olsztyn	22.5	30.03.2024	20.9	21.03.2014
Lublin	22.5	30.03.2024	20.1	21.03.2014
Lesko	22.1	31.03.2024	20.1	25.03.2010
Resko	22.1	30.03.2024	21.6	26.03.2010
Kętrzyn	22.0	31.03.2024	20.1	21.03.2014
Bielsko-Biała	21.6	31.03.2024	21.0	18.03.2004
Gdańsk	20.5	31.03.2024	19.5	27.03.1999
Elbląg	20.4	31.03.2024	20.1	26.03.2010
Chojnice	20.4	30.03.2024	20.1	26.03.2010
Zakopane	19.6	30.03.2024	18.7	24.03.1991
Hel	17.7	31.03.2024	16.5	27.03.1999

Source: author's own work based on Dane Publiczne IMGW-PIB (2024) and Klimat IMGW-PIB (2024).

Discussion

February and March 2024 in Poland should certainly be perceived as extremely warm months, with the average area air temperature clearly exceeding the average values over the period 1991-2020. Moreover, these were record months in terms of maximum temperature values – in February, new highest air temperature values were recorded at 25 IMGW-PIB synoptic stations, and in March – at as many as 45 stations. Also, in March 2024, the first historical occurrence of hot days for this month has been recorded.

In both months, the synoptic situation that led to record air temperature values was similar – an above-average frequency of air masses flowing from the south. During these days, the weather in Poland was shaped primarily by warm polar maritime air masses, as well as the tropical air masses, the occurrence of which is statistically extremely rare in this part of the year. Their inflow meant that the largest positive air temperature anomalies were recorded in southern Poland – stations in Tarnów, Kraków and Rzeszów – although in the rest of the country deviations from the average were also significant.

It is worth emphasizing the difference in circulation in February and March 2024 from the previous record months of 1990, 2002 and 2014. During those years, positive thermal anomalies resulted primarily from the lack or limited inflow of continental polar air and arctic air over Poland, which are the coldest masses in winter and spring that shape the weather in the country. With their absence, the weather was dominated by polar maritime air masses, including warm polar maritime air, flowing into Poland along with the western circulation (Niedźwiedź, 2020). With such synoptic conditions, the warmest areas of the country became those that remained beyond the reach of the locally interacting continental polar air masses (the highest air temperature values in 2014 recorded in western Poland) or those where the weather is usually shaped by air masses from the north and east which were missing this time (northern and eastern Poland in 1990 and 2002). Additionally, the high positive thermal anomalies in March 2014, even despite relatively many days with the inflow of continental polar air over southern Poland compared to the years 1990 and 2002, were influenced by the high dryness of air masses and the resulting above-average insolation.

Not many works dealing with the issue of thermal extremes in February and March from a climatological and circulation perspective have been published up to 2024, as this topic is not among the most popular in literature. Yet, some papers explore this phenomenon further and allow for a comparison. Particularly, research by Tangborn (2003), Twardosz and Kossowska-Cezak (2016), Tomczyk et al. (2019), Zimnol and Bielec-Bąkowska (2019) and Bartoszek and Kaszewski (2022) can give a valid reference point for the issues covered in this article.

The research by Twardosz and Kossowska-Cezak (2016) focuses on the exceptionally cold and exceptionally mild winters in Europe. The authors mostly pay attention to the frequency of those situations rather than their synoptic background, but they note that most of the warm extremes occur during predominantly western cyclonic circulation and the positive phase of NAO, as, for example, in 1990. From their study it is clearly seen that the frequency of extremely mild winters is increasing since the 1980s, but still mostly in the western and southern parts of the continent – with rare occurrence in places like Poland, Belarus or the Baltic states. However, the increase in number of warm spells during winter in Poland has been mentioned in two other works (Tomczyk et al., 2019; Zimnol & Bielec-Bąkowska, 2019). The authors have proven that periods with above-ave-

rage air temperature occur more frequently in February and March than in December and January, although they tend to appear most frequently in north-western Poland (Zimnol & Bielec-Bąkowska, 2019), while in this study southern and eastern parts of the country noted most thermal records and maximum differences from the previous record-breaking temperatures. The occurrence of high temperature values was related to an increase in geopotential values on higher baric levels of the atmosphere, although on the level of 300 hPa the anomalies sometimes developed earlier than on lower levels, which is in consistence with Tomczyk et al. (2019). A broad analysis by Tangborn (2003) connects all the winter positive thermal anomalies observed in the Northern Hemisphere from 1932 to 1999. The author proves that since 1985, a significant rise in positive anomalies of winter (from winter solstice to spring equinox) temperatures has been observed, and most of them are synchronised in time. In addition to that, Bartoszek and Kaszewski (2022) found out that since 1951, Poland has experienced more frequent appearances of polar maritime warm air masses during the whole year and tropical air masses during summer. Although no significant increase in the number of days with tropical air inflow in winter or early spring was noted, a change in the overall temperature of air masses was highlighted, with virtually all of them becoming gradually warmer over the years. This evidence suggests that data from Poland is probably a part of a broader picture which shows the constant warming of winters in the Northern Hemisphere due to the climate change.

Works raising the issue of extremely warm months on the verge of winter and spring are often centred around the ecological and phenological impacts of such events – some of them can also be found in Poland. Belik and Beuch (2019) discovered that during an exceptionally warm March 2014, an abnormally early breeding of a bird species Scolopax rusticola took place in Upper Silesia. Also, Mager and Kępińska-Kasprzak (2016) proved the influence of positive thermal anomalies in February and March 2014 on the beginning of the wild plants' phenophases, with 90% of them growing faster than in the years 1946-1960 and 78% growing faster than in the years 2007-2012. Węgrzyn (2008) listed the year 1990 as "abnormally long" in terms of the duration of the vegetation period in Puławy and as "long" under the same criterion in Bezek and Felin (all of these places located in the Lublin Highland, south-eastern Poland). These examples prove that thermal anomalies of late winter and early spring are altering the standard process of the phenological phases. They also allow to predict that ecological and phenological changes similar to those observed in 1990 and 2014 also took place in 2024. Early start of phenological phases can be very dangerous, especially in agriculture, as plants begin to flourish and then, with a return of colder weather, they become vulnerable and easily freeze, ruining the harvest. Other sectors of the economy that can be heavily affected by abnormally warm winters are winter sports and tourism. According to press releases, skiing season 2023/24 was terribly bad, with some ski resorts closing as early as the beginning of February and reporting substantial losses (Ciryt, 2024; Dziennik Polski, 2024).

However, more studies are needed to appropriately address the issue of warm spells in winter and early spring in Poland. The research should continue in the following years so as to establish the occurrence of long-term patterns. This study was aiming to be a starting and reference point for further observations. Some conclusions that were made could be valuable, but they should not be generalised, as the study refers to a fairly small number of cases. However, with the consideration of other works in the field, it can be said that more above-average warm winter and early spring periods should be expected

in the following years and one reason for that may be the more common occurrence of tropical air masses, but the most probable and expected cause should be the increase in temperature of all air masses due to climate change.

Conclusions

February and March 2024 stand out as exceptionally warm months in comparison with the 1991-2020 mean. However, the anomalies that occurred during this period were of different nature than those occurring during the previous record-breaking years. In 2024, due to the increased frequency of advection from the south and the inflow of tropical air, the warmest areas of Poland were the southern and eastern parts of the country, while warm winter spells are more typical of western Poland. It should also be noted that although in February 2024 the average temperature deviations from the multi-year period's mean were higher than the values of these deviations in March, this second month turned out to be much more record-breaking in terms of maximum temperature values recorded on synoptic stations. While February was a clearly warmer month compared to the period 1991-2020, it was also characterized by greater thermal stability, with positive deviations in the average daily air temperature recorded during most days. March, in turn, was characterized by greater fluctuations in daily temperature, including frost days, but also hot days, especially the last two in the month.

The months discussed in this paper will certainly go down in the history of Poland's climate monitoring as extremely warm and unique in terms of circulation. However, the evidence provided by other authors (Tangborn, 2003; Tomczyk et al., 2019; Zimnol & Bielec-Bąkowska, 2019; Bartoszek & Kaszewski, 2022) suggests that temperature anomalies from February and March 2024 show the direction in which Poland's and the whole Northern Hemisphere's climate may be heading under the influence of ongoing global warming. Only measurements and observations carried out in the coming years will prove if this assumption was right, nevertheless we shall be prepared for all the impacts that may be caused by this change – most notably, the ecological and agricultural ones and those related to winter tourism.

References

Agrometeo IMGW-PIB. (2024). *Słownik pojęć*. Retrieved from: https://agrometeo.imgw.pl/slownik_pojec (22.05.2024).

Ballester, J., Rodó, X., & Giorgi, F. (2010). Future changes in Central Europe heat waves expected to mostly follow summer mean warming. *Climate Dynamics*, *35*, 1191-1205. https://doi.org/10.1007/s00382-009-0641-5

Barriopedro, D. Fischer, E.M, Luterbacher, J., Trigo, R.M., García-Herrera, R. (2011). The hot summer of 2010: redrawing the temperature record map of Europe. *Science, 332*(8), 220-224. https://doi.org/10.1126/science.1201224

Bartoszek, K., & Kaszewski, B.M. (2022). Changes in the frequency and temperature of air masses over East-Central Europe. *International Journal of Climatology*, *42*, 8214-8231. https://doi.org/10.1002/joc.7704

Belik, K., & Beuch, S. (2019). Wyjątkowo wczesny lęg słonki Scolopax rusticola w Lasach Lublinieckich (woj. śląskie). *Ptaki Śląska, 26*, 127-131.

Benison, M., Stephenson, D.B., Christensen, O.B., Ferro, C.A.T., Frei, C., Goyette, S., Halsnaes, K., Holt, T., Jylhä, K., Koffi, B., Palutikof, J., Schöll, R., Semmler, T., & Woth, K. (2007). Future extreme events in European climate: an exploration of regional climate model projections. *Climate change*, *81*, 71-95. https://doi.org/10.1007/s10584-006-9226-z

Biuletyn Monitoringu Klimatu Polski. (2014). *Marzec 2014*. Retrieved from: https://klimat.imgw.pl/pl/biuletyn-monitoring/#2014/03 (31.05.2024).

Biuletyn Monitoringu Klimatu Polski. (2024a). *Luty 2024*. Retrieved from: https://klimat.imgw.pl/pl/biuletyn-monitoring/#2024/02 (30.05.2024).

Biuletyn Monitoringu Klimatu Polski. (2024b). *Marzec 2024*. Retrieved from: https://klimat.imgw.pl/pl/biuletyn-monitoring/#2024/03 (31.05.2024).

de Bono, A., Peduzzi, P., Kluser, S., & Giuliani, G. (2004). Impacts of summer 2003 heat wave in Europe. *UNEP/DEWA/GRID European Environmental Alert Bulletin*, 2, 1.

Caloiero, T. (2017). Trend of monthly temperature and daily extreme temperature during 1951-2012 in New Zealand. *Theoretical & Applied Climatology*, *129*, 111-127. https://doi.org/10.1007/s00704-016-1764-3

Christidis, N., Gareth, S.J. & Stott, P.A. (2015). Dramatically increasing chance of extremely hot summers since the 2003 European heatwave. *Natural Climate Change, 5,* 46-50. https://doi.org/10.1038/nclimate2468

Ciryt, B. (2024). *Stacje narciarskie pod Krakowem liczą straty. Nie ma śniegu, narciarzy, zabawy. Większość tras zamkniętych, działają nieliczne szkółki*. Retrieved from: Gazeta Krakowska, https://gazetakrakowska.pl/stacje-narciarskie-pod-krakowem-licza-straty-nie-ma-sniegu-narciarzy-zabawy-wiekszosc-tras-zamknietych-dzialaja-nieliczne/ar/c1-18306953 (21.09.2024).

CMM IMGW-PIB. (2024). *Materiały wizualne (Visual materials)*. Retrieved from: https://cmm.imgw.pl/ (04.06.2024).

Dane Publiczne IMGW-PIB. (2024). *Dane archiwalne (Archive data)*. Retrieved from: https://danepubliczne.imgw.pl/ (04.06.2024).

Deutscher Wetterdienst. (2024). *Archiv GFS*. Retrieved from: https://www.wetter3.de/archiv_gfs_dt.html (18.09.2024).

Dziennik Polski. (2024). *Czynne stacje narciarskie w Małopolsce. Białka i Jaworzyna jeszcze się trzymają. Gdzie można pojeździć na nartach?* Dziennik Polski, 7.03.2024. Retrieved from: https://dziennikpolski24.pl/czynne-stacje-narciarskie-w-malopolsce-bialka-i-jaworzyna-jeszcze-sie-trzymaja-gdzie-mozna-pojezdzic-na-nartach-7032024/ar/c3-18325257 (21.09.2024).

Feng, R., Yu, R., Zheng, H., & Gan, M. (2018). Spatial and temporal variations in extreme temperature in Central Asia. *International Journal of Climatology*, *38*(S1), 388-400. https://doi.org/10.1002/joc.5379

Fonseca, D., Carvalho, M.J., Marta-Almeida, M., Melo-Gonçalves, P., & Rocha, A. (2016). Recent trends of extreme temperature indices for the Iberian Peninsula. *Physics and Chemistry of the Earth, Parts A/B/C*, *94*, 66-76. https://doi.org/10.1016/j.pce.2015.12.005.

Girguś, R. (2022). *Wyjątki ze źródeł historycznych o nadzwyczajnych zjawiskach hydrologicznych i meteorologicznych na ziemiach polskich w latach 1601-1920*. Warszawa: Seria Publikacji Naukowo-Badawczych IMGW-PIB.

Guerreiro, S.B., Dawson, R.J., Kilsby, C., Lewis, E., & Ford, A. (2018). Future heat-waves, droughts and floods in 571 European cities. *Environmental Reseach Letters*, *13*. https://doi.org/10.1088/1748-9326/aaaad3

IMGW-PIB. (2024a). *Charakterystyka wybranych elementów klimatu w Polsce w lutym 2024 roku*. Retrieved from: https://www.imgw.pl/wydarzenia/charakterystyka-wybranych-elementow-klimatu-w-polsce-w-lutym-2024-roku (04.06.2024).

IMGW-PIB. (2024b). *Charakterystyka wybranych elementów klimatu w Polsce w marcu 2024 roku*. Retrieved from: https://www.imgw.pl/wydarzenia/charakterystyka-wybranych-elementow-klimatu-w-polsce-w-marcu-2024-roku (04.06.2024).

IMGW-PIB. (2024c). *IMGW-PIB: Charakterystyka wybranych elementów klimatu w Polsce w kwietniu 2022 roku.* Retrieved from: https://imgw.pl/wydarzenia/imgw-pib-charakterystyka-wybranych-elementow-klimatu-w-polsce-w-kwietniu-2022-roku (04.06.2024).

IPCC. (2023). Summary for Policymakers. In: Core Writing Team, H. Lee, & J. Romero (eds.), *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva: IPCC Switzerland (p. 1-34). https://doi.org/10.59327/IPCC/AR6-9789291691647.001.

Karaczun, Z.M., & Kozyra, J. (2020). *Wpływ zmiany klimatu na bezpieczeństwo żywnościowe Polski*. Warszawa: Wydawnictwo SGGW.

Klimat IMGW-PIB. (2024). *Normy klimatyczne 1991-2020*. Retrieved from: https://klimat.imgw.pl/pl/climate-normals/TSR_AVE (04.06.2024).

Kossowska-Cezak, U. (2010a). Fale upałów i okresy upalne – metody ich wyróżniania i wyniki zastosowania. *Prace Geograficzne*, *123*, 143-149.

Kossowska-Cezak, U. (2010b). Występowanie pogody gorącej w Warszawie (1951-2009). *Przegląd Geograficzny*, *1-2*, 61-75.

Kossowska-Cezak, U., & Skrzypczuk, J. (2011). Pogoda upalna w Warszawie (1947-2010). *Prace i Studia Geograficzne*, *47*, 139-146.

Kossowska-Cezak, U., & Wawer, J. (2014). Skrajności termiczne w klimacie Warszawy (1947-2013). *Prace i Studia Geograficzne*, *56*, 119-145.

Kossowska-Cezak, U., & Twardosz, J., (2016). Zależność liczby niezwykle zimnych i niezwykle ciepłych miesięcy w Europie (1951-2010) od liczby uwzględnionych stacji meteorologicznych. *Przegląd Geofizyczny*, *61*, 3-4, 225-237.

Kossowska-Cezak, U., Pełech, S., & Twardosz, J. (2016). Niezwykle zimne miesiące zimowe w Europie (1951-2010). *Przegląd Geofizyczny*, *61*, 1-2, 45-72.

Kozłowska-Szczęsna, T., Krawczyk, B., & Kuchcik, M. (2004). Wpływ środowiska atmosferycznego na zdrowie i samopoczucie człowieka. *Monografie IGiPZ PAN*, *4*, 124-129.

Krzyżewska, A. (2010). Fale upałów jako zjawisko ograniczające turystykę w dużych miastach świata. In: A. Richling (ed.) *Krajobrazy rekreacyjne – kształtowanie, wykorzystanie, transformacja*. Problem Ekologii Krajobrazu, 27, 239-244.

Krzyżewska, A. (2014). Przegląd metod wydzielania fal upałów i fal mrozów. *Przegląd Geofizyczny. Przegląd zagadnień naukowych, 59*(3-4), 157-173.

Krzyżewska, A., & Wereski, S. (2011). Fale upałów i mrozów w wybranych stacjach Polski na tle regionów bioklimatycznych (2000-2010). *Przegląd Geofizyczny*, *56*, 1-2, 99-109.

Kuchcik, M. (2006a). Defining heat waves – different approaches. *Geographica Polonica*, *79*(2), 47-63.

Kuchcik, M. (2006b). Fale upałów w Polsce w latach 1993-2002. *Przegląd Geograficzny*, *78*(3), 397-412.

Kundzewicz, Z.W. (2017a). Wielkoskalowa zmiana klimatu (obserwacje, interpretacja, projekcje). In: Z.W. Kundzewicz, Ø. Hov, T. Okruszko (eds.), *Zmiany klimatu i ich wpływ na wybrane sektory w Polsce* (p.14-30). Poznań: ISRL PAN.

Kundzewicz, Z.W. (2017b). Konsekwencje zmian klimatu i adaptacja do nich. In: Z.W. Kundzewicz, Ø. Hov, T. Okruszko (eds.), *Zmiany klimatu i ich wpływ na wybrane sektory w Polsce* (p. 31-45), Poznań: ISRL PAN.

Mager, P., & Kępińska-Kasprzak, M. (2016). Pojawy fenologiczne w 2014 roku w Trzebawiu koło Poznania na tle wcześniejszych obserwacji fitofenologicznych na obszarze środkowej Wielkopolski. *Acta Scientiarum Polonorum Formatio Circumiectus*, *15*(2), 93-103. http://doi.org/10.15576/ASP.FC/2016.15.2.93

Miętus, M., Owczarek, M., & Filipiak, J. (2002). Warunki termiczne na obszarze Wybrzeża i Pomorza w świetle wybranych klasyfikacji. *Materiały Badawcze IMGW. Seria Meteorologia*, *36*, 1-56.

Niedźwiedź, T. (2017). *Kalendarz typów cyrkulacji atmosfery dla Polski południowej*. Sosnowiec: Uniwersytet Śląski. Retrieved from: https://klimatologia.us.edu.pl/kalendarz-typow-cyrkulacji-calendar-of-circulation-types/ (20.05.2024).

Niedźwiedź, T. (2020). *Kalendarz typów cyrkulacji atmosfery dla Polski południowej* (unpublished document).

Nowosad, M. (2019). O problemach związanych z wyznaczaniem typów cyrkulacji atmosferycznej Lityńskiego. *Prace Geograficzne*, *159*, 49-66, https://doi.org/10.4467/20833113PG.19.019.11487

Pellegrini, E., Lorenzini, G., & Nali, C. (2007). The 2003 European Heat Wave: which role for ozone? Some data from Tuscany, Central Italy. *Water, Air and Soil Pollution*, *181*, 401-408. https://doi.org/10.1007/s11270-006-9310-z

Pianko-Kluczyńska, K. (2007). Nowy kalendarz typów cyrkulacji atmosfery według J. Lityńskiego. *Wiadomości Meteorologii, Hydrologii, Gospodarki Wodnej*, *61*(1, 4), 65-85.

Pianko-Kluczyńska, K. (2018). *Kalendarz typów cyrkulacji atmosferycznej według J. Lityńskiego*. IMGW-PIB.

Piotrowicz, K. (2005). Ekstremalne warunki termiczne w Krakowie. In: E. Bogdanowicz, U. Kossowska-Cezak, J. Szkutnicki, J. (eds.). *Ekstremalne zjawiska hydrologiczne i meteorologiczne* (p. 89-96). Warszawa: Polskie Towarzystwo Geofizyczne/IMGW.

Piotrowicz, K., Bielec-Bąkowska, Z., & Krzyworzeka, K. (2020). *Groźne zjawiska meteorologiczne w Krakowie i powiecie krakowskim w świetle interwencji straży pożarnej i policji*. Kraków: IGiGP UJ.

Piotrowski, P. (2023). The variability of atmospheric circulation over Poland in the years 1950-2021. *Acta Geographica Lodziensia*, *113*, 77-88. https://doi.org/10.26485/AGL/2023/113/4

Robine, J.M., Cheung, S.L, Le Roy, S., Van Oyen, H., Griffiths, C., Michel, J.P. & Herrmann, F.R. (2008). Death toll exceeded 70,000 in Europe during the summer of 2003, *C. R. Biologies, 331,* 171-178. https://doi.org/110.1016/j.crvi.2007.12.001

Russo, S., Sillmann, J., & Fischer, E.M. (2015). Top ten European heatwaves since 1950 and their occurrence in the coming decades. *Environmental Research Letters*, *10*(12). https://doi.org/10.1088/1748-9326/10/12/124003

Strupczewski, W., & Girguś, J. (1965). *Wyjątki ze źródeł historycznych o nadzwyczajnych zjawiskach hydrologiczno-meteorologicznych na ziemiach polskich w wiekach od X do XVI*, Warszawa: Instrukcje i Podręczniki PIHM, 87.

Sulikowska, A., Wypych, A., & Woszczek, I. (2016). Fale upałów latem 2015 roku i ich uwarunkowania cyrkulacyjne. *Badania Fizjograficzne*, *7*(A67), 205-223. https://doi.org/10.14746/bfg.2016.7.16

Tangborn, W. (2003). Winter warming indicated by recent temperature and precipitation anomalies. *Polar Geography*, *27*(4), 320-338.

Tomczyk, A.M., Bednorz, E., Półrolniczak, M., & Kolendowicz, L. (2018). Strong heat and cold waves in Poland in relation with the large-scale atmospheric circulation. *Theoretical and Applied Climatology*, *137*, 1909-1923. https://doi.org/10.1007/s00704-018-2715-y

Tomczyk, A.M., Sulikowska, A., Bednorz, E., & Półrolniczak, M. (2019). Atmospheric circulation conditions during winter warm spells in Central Europe. *Natural Hazards*, *96*, 1413-1428. https://doi.org/10.1007/s11069-019-03621-4

Twardosz, J., & Kossowska-Cezak, U. (2015). Exceptionally hot and cold summers in Europe (1951-2010). *Acta Geophysica*, *63*, 275-300. https://doi.org/10.2478/s11600-014-0261-2

Twardosz, J., & Kossowska-Cezak, U. (2016). Exceptionally cold and mild winters in Europe (1951-2010). *Theoretical and Applied Climatology*, *125*(1), 399-411. https://doi.org/10.1007/s00704-015-1524-9

Węgrzyn, A. (2008). Typowe i anomalne długości okresu wegetacyjnego na Lubelszczyźnie. *Acta Agrophysica*, *12*(2), 561-573.

Wibig, J. (2007). Fale ciepła i chłodu w środkowej Polsce na przykładzie Łodzi. *Acta Universitatis Lodziensis. Folia Geograhica Physica*, *8*, 27-61.

Wibig, J., Podstawczyńska, A., Rzepa, M., & Piotrowski, P. (2009a). Coldwaves in Poland – frequency, trends and relationships with atmospheric circulation. *Geographica Polonica, 82*, 47-59.

Wibig, J., Podstawczyńska, A., Rzepa, M., & Piotrowski, P. (2009b). Heatwaves in Poland – frequency, trends and relationship with atmospheric circulation. *Geographica Polonica*, *82*, 33-46.

Więcław, M. (1999). Przestrzenne zróżnicowanie częstości występowania mas powietrza nad Polską w latach 1971-1990. *Badania Fizjograficzne nad Polską Zachodnią*, *A50*, 175-188.

Xie, J. (2022). Record high warm 2021 February temperature over East Asia. *Bulletin of the American Meteorological Society*, *103*, 2917-2922. https://doi.org/10.1175/BAMS-D-22-0139.1

Zimnol, J., & Bielec-Bąkowska, Z. (2019). Dni ciepłe i chłodne w Polsce (1966-2017). *Prace Geograficzne*, *159*, 67-86. https://doi.org/10.4467/20833113PG.19.020.11488

[Wpłynęło: 9 lipca 2024; poprawiono: 23 września 2024]