

CHARACTERISTICS OF BIOCLIMATIC CONDITIONS OF THE WARMIA-MASURIA LAKE DISTRICT, POLAND

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Abstract

The study analysed the temporal variability and spatial diversity of bioclimatic conditions in the Warmian-Masurian Lake District from 2015 to 2024. The UTCI index was used to assess these conditions, with values calculated for five stations assigned to specific human heat stress categories. The results are presented in the form of the annual course of UTCI, the frequency of categories by seasons, and the existence of a temporal trend were also examined. The average annual UTCI value was 6.8°C, which is classified as “slight cold stress.” In spatial distribution values varied depending on location, from the lowest one in Elbląg (3.8°C) to the highest in Lidzbark Warmiński (9.4°C). Linear trends for average, maximum and minimum UTCI values were examined; a statistically significant positive trend was observed only for Elbląg, with a mean value of 0.3°C per decade. Statistically significant trends in the number of days for two heat stress categories were also obtained: a negative trend with “moderate cold stress” for Elbląg (2.4 days per decade), Olsztyn, and Mikołajki (2.0 days per decade), and a positive trend for the “moderate heat stress” category for Elbląg and Kętrzyn, with 2.2 and 2.7 days per decade, respectively. The analysis also took into account the frequency of occurrence of different heat stress categories, with the highest frequency of the “no thermal stress” category (0) in summer at 57–72%, in spring at 34–44% and in autumn at 32–45%, and in winter at only 0.3–3%. Conditions associated with severe cold stress dominated in winter, particularly in Elbląg, and with burdensome heat stress in summer in Lidzbark Warmiński and Kętrzyn. In summary, the most favourable conditions for recreation and relaxation occur from April to September, and even October (in Lidzbark Warmiński). Based on the calculated parameters, it can be concluded that although bioclimatic conditions in the Lake District are generally similar, there are significant differences between specific periods and parts of the region. This variation within a relatively small area confirms the need for further, more detailed research and analysis of bioclimatic conditions.

Keywords: bioclimatic conditions, Universal Thermal Climate Index (UTCI), Warmia-Masuria Lake District, Poland

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1. Introduction

In view of its unique natural features, the Region of Warmia and Masuria has a high environmental potential for the development of agriculture and tourism. Until the late 1990s, Warmia and Masuria had the status of a predominantly agricultural region owing to an abundance of fertile soils. Tourism is the second most rapidly developing branch of the local economy. Great scenic beauty and relatively low levels of environmental degradation make Warmia and Masuria one of the top tourist destinations in Poland (Gwiaździńska-Góraj, Góraj, 2013). For this reason, the evaluation of the climate and its temporal changes in this region are focused on agricultural and touristic aspects, i.e. agroclimatic and bioclimatic studies. Agroclimatic issues were dealt with by, among others, (Szwejkowski et al., 2008 and 2017; Gwiaździńska-Góraj and Góraj, 2013; Kocur-Bera and Dudzińska, 2015; Kocur-Bera, 2019; Kuchar et al., 2021; Cymes et al., 2022), while bioclimatic problems in the aspect of tourism and human health and welfare were the subject of research by, among others, (Batyk, 2013; Dębniewska and Skorwider-Namiołko, 2015; Romaszko et al., 2022).

According to the IPCC report [IPCC 2023], in the years 2011–2020, the average temperature of the Earth was 1.09°C higher than in the years 1850–1900 (considered as temperature of the pre-industrial era), with temperature of lands increasing by 1.59°C and the ocean by 0.88°C. Each of the last four decades has been warmer than the previous one, and the researchers highlight that each of the recent three decades has become warmer than any other period prior to 1980 (Kambezidis et al., 2021; NOAA, 2018; Rozbicka et al., 2025).

The scientific goals of this paper can be defined in three aspects of bioclimatic analysis: (1) The study area is in Poland (central Europe) in a temperate climate zone, one of the most sensitive areas to climate change caused by global warming (Brecht et al., 2020). (2) The results of such an analysis can provide information on the response of bioclimatic conditions to changing climate conditions in the last decade – the most dynamic in respect to the air temperature increase. (3) This region covers the specific, coldest part of Poland, with forest areas and numerous lakes, very attractive for tourism, especially for boat touring, caravanning, bicycle touring and agritourism. (4) Due to the complexity of the research, the results may also contribute to discussions on a new classification of Poland's bioclimatic regions.

2. Study area, materials and methods

According to the bioclimatic regionalisation of Poland, published by Kozłowska-Szcześna et al, 2002, the study area of this paper is the Lake District Region (type II). Bioclimatic conditions there are milder than in the Coastal Region. This area is characterised by a moderately stimulating bioclimate, which should be understood

as an intermediate between the weakly and mildly stimulating climate of lowlands and uplands, and the strongly stimulating climate of mountain and coastal areas (Kozłowska-Szczęśna et al., 1997). From the administrative point of view study area is situated in the Warmian-Masurian Province. According to geographical division of Poland by Kondracki, it covers a geographical macroregion in north-eastern Poland, being a part of the Eastern Baltic Lake District (Kondracki, 2002). The study area contains a few mesoregions including the major cities. It borders the Vistula Żuławy and the Elbląg Upland, which is part of the Gdańsk Coast to the west. The main city in this region is Elbląg. The Masurian Lake District includes, among others, the Olsztyn Lake District, with cities of Olsztyn and Lidzbark Warmiński. At the junction of the Mrągowo Lake District, the Sępopol Lowland, and the Great Masurian District lies Kętrzyn, and the town of Mikołajki is in the Great Masurian Lake District. The analysed area is one of the most attractive tourist and recreational areas in Poland. This is due to its diverse post-glacial landscape (moraine hills, plateaus, and glacial-fluvial valleys), rich in fauna and flora, including broad forest complexes and numerous lakes (there are approximately 2,500 lakes with areas exceeding 1 hectare), marshes and peat bogs.

According to the Köppen-Geiger climatological classification, the analysed area is situated within the humid continental climate zone (Dfb) The climate is defined as moderately continental, characterised by cold winters and warm summers. Based on climate normal CLINO from the years 1991-2020 for the studied meteorological stations, evident seasonal changes are observed throughout the year, giving this area a special nature. The average annual temperature is approximately 8.0°C. The mitigating influence of the sea causes increasing temperatures over the Vistula Bay. The warmest month is July with 18.3°C, and the coldest is January with -2.5°C. The highest monthly sum of precipitation is 85 mm and occurs in July and the lowest sum of precipitation is 28 mm and occurs in February (Arnfield, 2020; IMWMNRI, 2025).

This work is based on complete hourly data of five meteorological stations situated in the following locations: Elbląg ($\varphi = 54^{\circ}13' N$; $\lambda = 19^{\circ}32' E$, $H = 189$ m AMSL), Olsztyn ($\varphi = 53^{\circ}47' N$; $\lambda = 20^{\circ}25' E$, $H = 133$ m AMSL), Kętrzyn ($\varphi = 54^{\circ}04' N$; $\lambda = 21^{\circ}22' E$, $H = 107$ m AMSL), Mikołajki ($\varphi = 53^{\circ}47' N$; $\lambda = 21^{\circ}35' E$, $H = 127$ m AMSL) and Lidzbark Warmiński ($\varphi = 54^{\circ}08' N$; $\lambda = 20^{\circ}36' E$, $H = 71$ m AMSL) (Fig.1). Spatial variation has not been shown on the maps due to the small number of weather stations. In terms of population Olsztyn is the largest city with 166 thousand, Elbląg (112 thou) and then Kętrzyn (28 thousand), Lidzbark Warmiński (16 thousand) and Mikołajki (3.3 thousand) (IMWM-NRI, accessed on 25 July 2025).

Standard meteorological data for the period 2015–2024 recorded at 12:00 UTC (14:00 CEST/13:00 CET) at stations of the Institute of Meteorology and Water Management – National Research Institute (IMWM-NRI accessed on 5 June 2025) were used to analyse the variability of perceived bioclimatic conditions in the

Warmia-Masuria Lake District. These included air temperature ($^{\circ}\text{C}$) 2m AMGL, relative humidity (%), wind speed ($\text{m}\cdot\text{s}^{-1}$) 10 m AMGL, and cloudiness (0–8). The meteorological stations are situated in representative locations within the administrative boundaries of cities but they are mostly synoptic stations (and one of them is climatological station - Lidzbark Warmiński) and represent climatic conditions at a mesoregional scale.



Figure 1. Locations of the stations of the Warmia-Masuria Lake District in Poland

UTCI is defined as the equivalent air temperature at which the basic physiological parameters of the human organism would adopt the same values as in real conditions. It is a one-dimensional value reflecting the response of the organism to multidimensionally described meteorological and physiological information. This approach assumption is that the heat exchange between human body and their surroundings depends only on air temperature (T_a) at a constant level of the remaining meteorological parameters (Błażejczyk et al., 2012a). The index is based on the multifactorial thermoregulation model of the human organism by Fiala et al., 1999 and Bröde et al., 2012. It includes two heat exchange regulation subsystems: passive one and active one. UTCI values are a measure of the heat stress of the organism and are expressed in $^{\circ}\text{C}$. To calculate UTCI values, BioKlima 2.6 software was used with default parameters (Fiala et al., 2001) with implemented computation algorithms with the application of the sixth-degree exponential function. The

BioKlima software automatically calculates the mean radiant temperature (T_{mrt}) from standard data required to calculate the UTCI index. It is not calculated directly, but indirectly by the software (BioKlima ver. 2.6, accessed on 5 June 2025).

For the obtained UTCI values, an appropriate heat load was assigned according to the categories of human heat stress scale (Table 1). The obtained results are presented as relative frequency of occurrence of individual heat loads in various time intervals (in %): months, calendar seasons, individual years, and for all considered period 2015–2024. Additionally, the relative frequency of occurrence of individual classes of UTCI values was calculated (in %).

For each station considered, linear trend equations were determined for the average, maximum and minimum UTCI values and their coefficient of determination R^2 . Linear trends and coefficients of determination were also determined for the number of days and the frequency of individual heat load categories. The statistical significance of the trends was verified using the Student's t -test using Statistica 13.3 software.

Table 1. UTCI assessment scale of human heat stress (Błażejczyk et al. 2013a)

UTCI (°C) Range	Number Category	Stress Category
above 46.0	4	extreme heat stress
38.1–46.0	3	very strong heat stress
32.1–38.0	2	strong heat stress
26.1–32.0	1	moderate heat stress
9.1–26.0	0	no thermal stress
0.1–9.0	–1	slight cold stress
–12.9–0.0	–2	moderate cold stress
–26.9–13.0	–3	strong cold stress
–39.9–27.0	–4	very strong cold stress
below –40.0	–5	extreme cold stress

3. Results

In the 2015–2024 research period, the average annual UTCI value in the Warmia-Masuria Lake District calculated on the basis of five analysed stations was 6.8°C, which is classified as “slight cold stress” (category –1). The index values, however, are spatially diversified, the lowest ones are in the north-west in Elbląg 3.8°C, increasing towards the east in Kętrzyn 6.0°C and Mikołajki 6.8°C, reaching the

highest values in the central part of the District in Olsztyn 7.9°C and Lidzbark Warmiński 9.4°C (Table 2). A similar tendency is visible in the spatial distribution of the maximum UTCI value, with the highest values above 38.0°C, classified as category 3 “very strong heat stress”, occurring only in Lidzbark Warmiński 38.6°C and Kętrzyn 38.1°C, and the lowest maximum value in Elbląg 35.6°C and usually occurring in August. The spatial distribution of the lowest minimum UTCI value differs from the distribution of mean and maximum values presented above. The most severe conditions occur in the western part of the region in Elbląg (-41.3°C), classified as -5 “extreme cold stress,” while the remaining stations are characterised by category -4 “very strong cold stress”. The mildest conditions occur in the eastern part the region in Mikołajki (-33.9°C) and the lowest values occurred in various winter months from December to February (Fig. 2).

Table 2. Annual average values of UTCI [°C] in stations, 2015–2024

Stations	Annual Average Values of UTCI [°C]
Olsztyn	7.9
Kętrzyn	6.0
Mikołajki	6.8
Elbląg	3.8
Lidzbark Warmiński	9.4
2015–2024	6.8

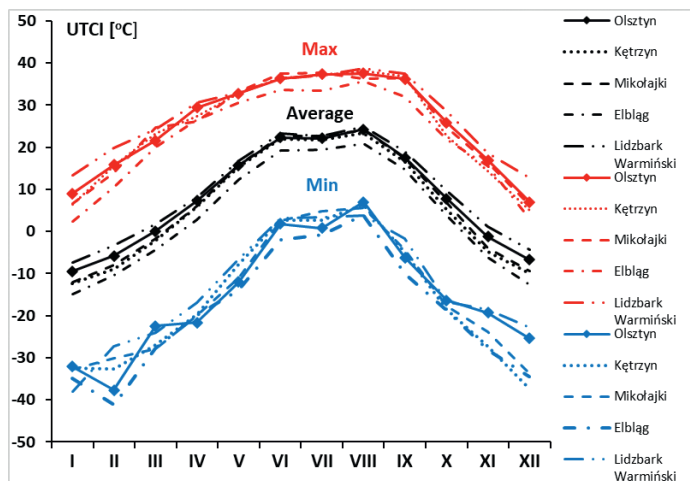


Figure 2. Annual course, average, maximum and minimum of UTCI values of the Warmia-Masuria Lake District in Poland, 2015–2024

A linear trend occurrence was checked for the average, maximum, and minimum

values of the UTCI (Fig. 3). For the average value, the trend line equation is statistically significant at $p < 0.05$ only for Elbląg, where a positive trend is observed with the coefficient of determination R^2 is 0.44, and the rate of increase is $0.3^\circ\text{C}/\text{decade}$ (the trend equation is $y = 0.336x + 1.923$). At the remaining stations, an upward trend was observed, but it is not statistically significant. In case of the maximum and minimum UTCI values is similar. The trends occur for all stations but are statistically insignificant. For the maximum UTCI value, a slight negative trend is observed for Elbląg and Kętrzyn, while the remaining stations indicate an upward trend for both the maximum and minimum UTCI values.

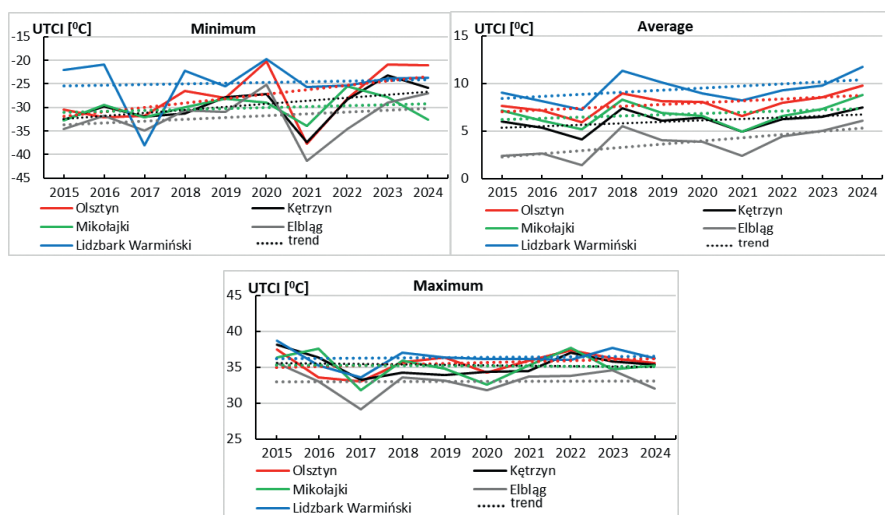


Figure 3. Variability of average, maximum, and minimum values of UTCI index with trends (dotted line) in analysed stations in 2015–2024

In the next step, linear trend equations were determined for the number of days in individual heat load categories (Fig. 4). The determined trends are statistically significant ($p < 0.05$) only for category (–2) “moderate cold stress” in Elbląg and Olsztyn, and Mikolajki, and for category (1) “moderate heat stress” in Elbląg and Kętrzyn. As expected, negative trends were obtained for the cold stress categories and positive trends for heat stress ones. For the number of days in the “moderate cold stress” category (–2), a negative trend was observed for Elbląg with a coefficient of determination $R^2 = 49\%$ and for Olsztyn and Mikolajki 48%. For the “moderate heat stress” category (1), a positive trend was obtained with $R^2 = 45\%$ and 40% for Elbląg and Kętrzyn, respectively. According to the linear trend equation, the number of days in the (–2) “moderate cold stress” category decreases by 2.4 days per decade in Elbląg and by 2.0 days per decade in Olsztyn and Mikolajki, while in the (1) “moderate heat stress” category number of days increases by 2.2 days per decade for Elbląg and by 2.7 days per decade for Kętrzyn.

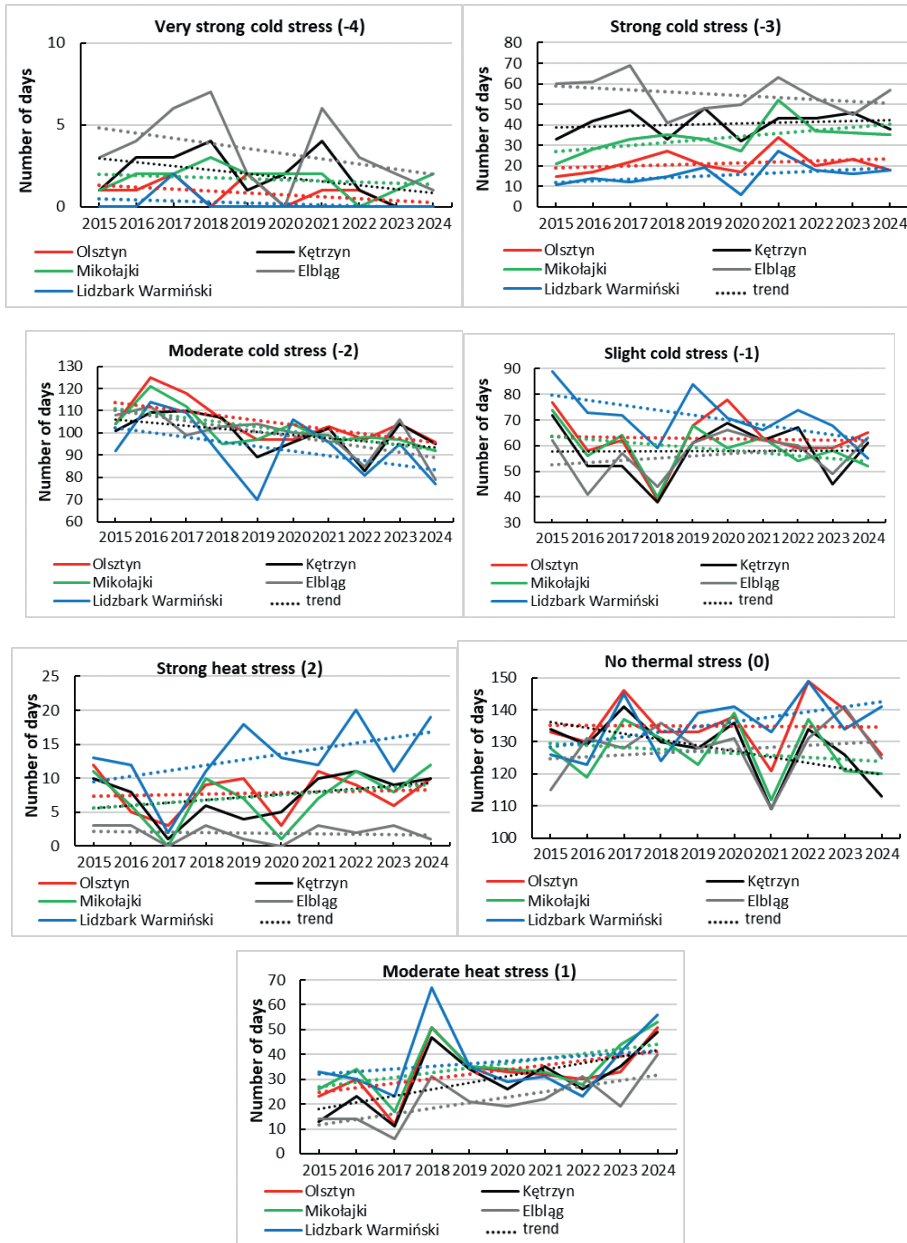


Figure 4. Annual number of days with thermal stress categories according to UTCI in the succeeding years of 2015–2024 in analysed stations with trend (dotted lines)

Apart from an analysis of Universal Thermal Comfort Index, another important parameter characterising bioclimatic conditions was examined, and namely the relative frequency of individual heat stress categories. For each station, a calculation was made of the frequency for different time intervals. Fig. 5 shows the relative

frequency throughout the analysed period 2015–2024; Fig. 6 in individual calendar seasons; Fig. 7 in months and Fig. 8 in individual years. The most frequent category in the 2015–2024 period was the “no thermal stress” (0) within a range of approximately 35–37%, which, together with the categories “moderate heat stress” (1) and “slight cold stress” (–1), are called sparing conditions and do not cause any heat stress in the human body. Their total frequency is above 55% for all stations (from 56% in Elbląg to 67% in Lidzbark Warmiński).

The second most frequent category of occurrence was (–2) “moderate cold stress” (–2), which ranged from 25.4% (Lidzbark Warmiński) to 28.7% (Olsztyn). In the case of burdensome heat loads, i.e. categories 2 and 3 – “strong” and “very strong heat stress”, they occur in total at a frequency ranging from 0.5% (Elbląg) to 3.6% (Lidzbark Warmiński). On the other hand, the category “very strong heat stress” (3) occurred only at two stations with a frequency of 0.03% in Lidzbark Warmiński and Kętrzyn once at the same time on 8 August 2015. However, category 4, i.e. “extreme heat stress”, which is the most burdensome for the human body, was not found to occur at any station at all. The categories associated with strong cold stress and occurring in all cities considered include: category “strong cold stress” (–3) which ranges widely from 4.3% in Lidzbark Warmiński to 15.0% in Elbląg, and category “very strong cold stress” (–4) within the range of 0.1%–0.9%, with a similar distribution in Lidzbark Warmiński and Elbląg, respectively. The most burdensome category of “extreme cold stress” (–5) occurred only once in the studied period in Elbląg (0.03%). This case occurred on February 8, 2021. At the other stations on that day, apart from Lidzbark Warmiński, the category of “very strong cold stress” (–4) occurred.

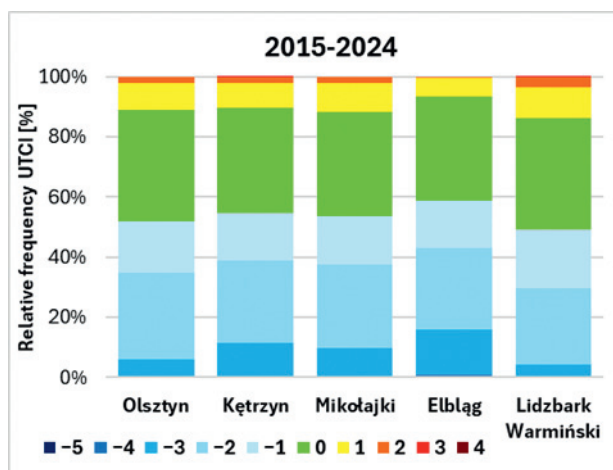


Figure 5. Relative frequency (%) of thermal stress categories according to UTCI index at 12 UTC in analysed stations, 2015–2024

Figure 6 shows the frequency of occurrence of heat load categories in each season. The most favourable bioclimatic conditions, i.e., those that do not burden the human organism, tend to occur with the highest frequency in all seasons except winter. Conditions that do not burden the body, i.e., the three categories (-1, 0, 1), called sparing conditions, range from 60–81% in spring and autumn, and up to 98% in summer. It is worth noting that in the summer, the frequency of sparing conditions is very high at every station, ranging from 87% in Lidzbark Warmiński to 98% in Elbląg.

Comparing the transitional seasons, autumn is more favourable (milder) for the human organism (62-81%) than spring (60-74%). In winter, such non-stressful conditions range from only 4% (Elbląg) to 23% (Lidzbark Warmiński), while conditions associated with significant cold stress in winter (total categories from -2 to -5, i.e., from “moderate” to “extreme” cold stress) range from 77% (Lidzbark Warmiński) to 96% (Elbląg).

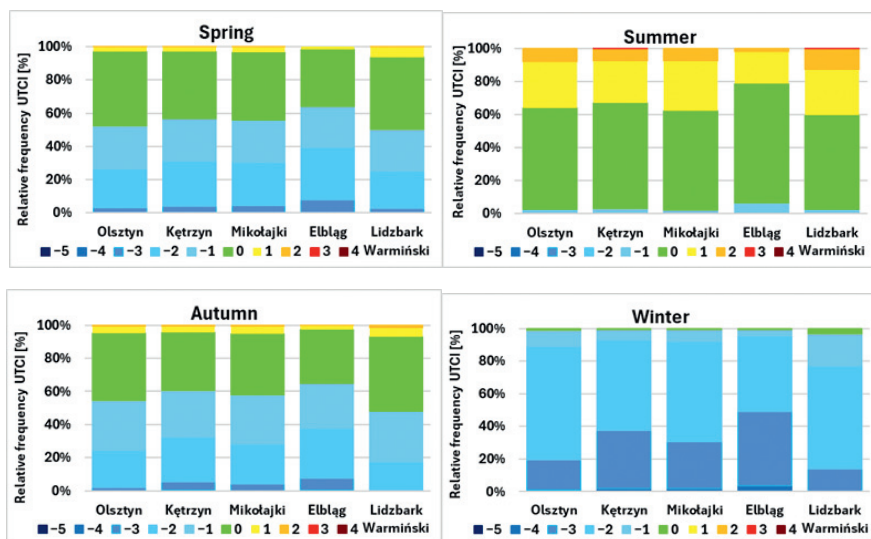


Figure 6. Relative frequency (%) of thermal categories according to UTCI values at 12 UTC in 2015–2024.

In the final step, the frequency of heat load categories was examined by month (Fig. 7) and subsequent years of the analysed period (Fig. 8) for each station. Months with the most favourable bioclimatic conditions, called sparing ones, i.e., those encompassing three categories from 1 to -1 occur at the analysed stations for a relatively long time, up to nine months, as in Lidzbark Warmiński (from March to November), with the highest frequency of occurrence in 2019 (71%). But at most stations, however, this period lasted most often seven months, from April to October, with a frequency of 60-98% of favourable conditions. On the other hand

the lowest frequency of favourable conditions was noted January and December, with a frequency of only 1-9%. The only exception was Lidzbark Warmiński, with a higher frequency of 14–24%.

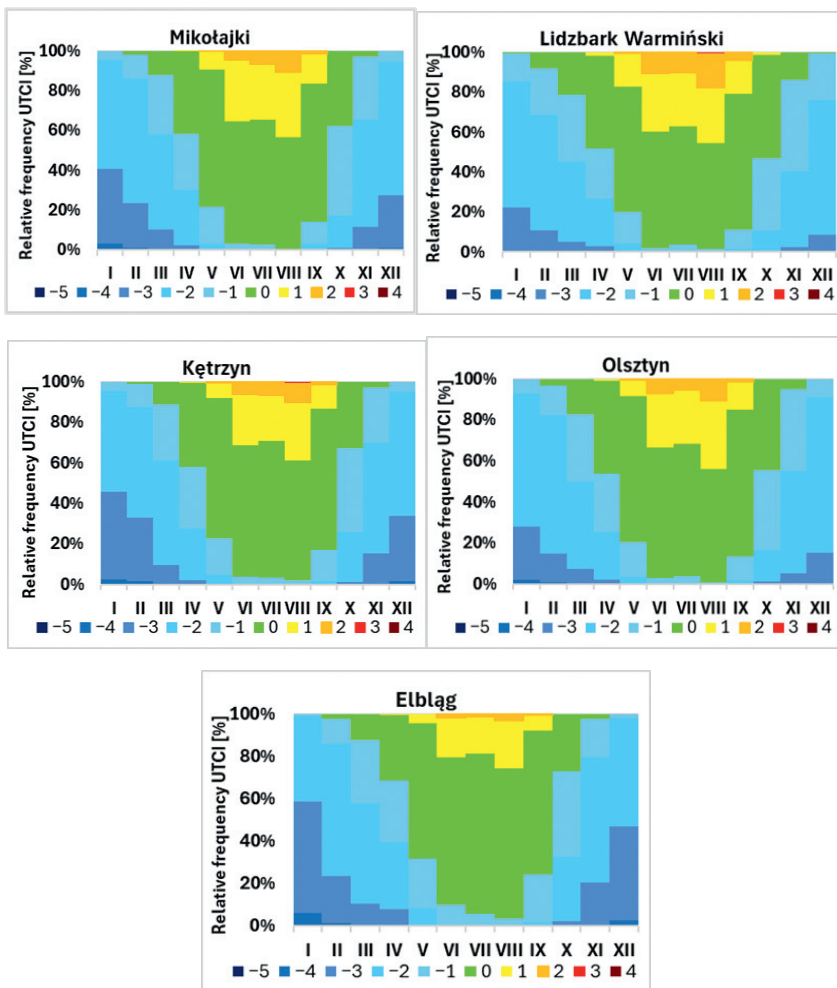


Figure 7. Relative frequency (%) of thermal stress categories by UTCI index at 12 UTC in particular months in analysed stations, 2015–2024

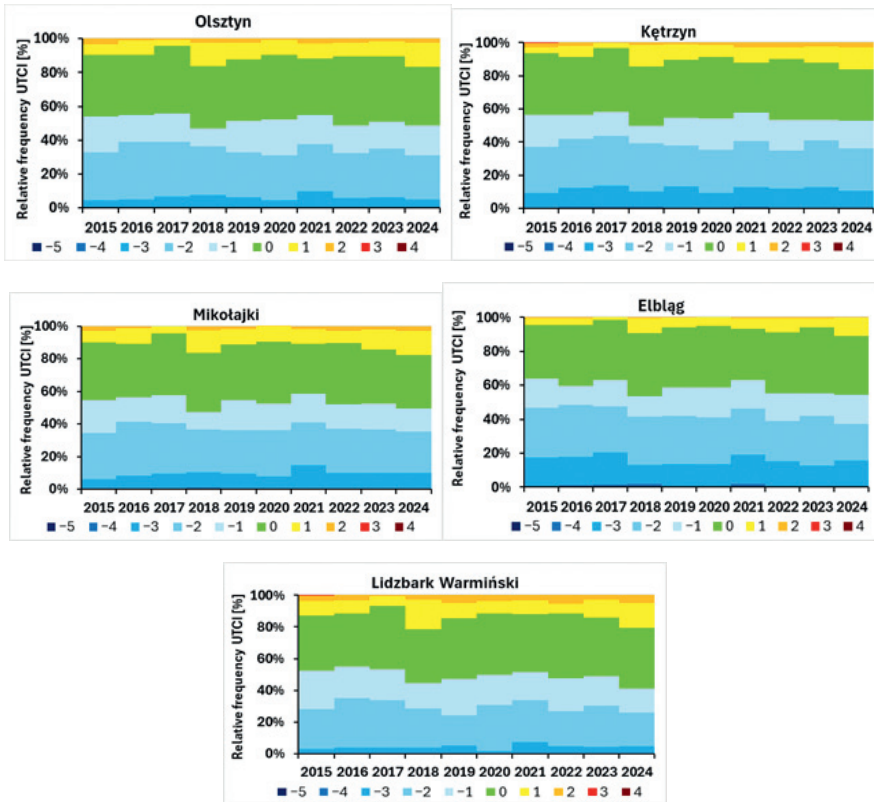


Figure 8. Relative frequency (%) of thermal stress categories according to UTCI index at 12 UTC in particular years in analysed stations, 2015–2024

Discussion

Studies of bioclimatic conditions carried out for various regions in Poland show there are both similarities and differences to the area of the Warmia-Masuria Lake District analysed in this article. These studies found the lowest UTCI values on the Baltic Sea coast and in north-eastern Poland, and the highest ones in the southern and western regions. Diverse biometeorological conditions were observed, which should be taken into account when planning tourist activities (Wereski et al., 2020; Kuchcik et al., 2021; Krzyżewska et al., 2021; Okoniewska, 2021; Tomczyk, 2021; Tomczyk and Mendel, 2023). Conditions that do not burden the body, i.e., the three categories (–1, 0, 1) known as sparing conditions, range from 60–81% in spring and autumn, and up to 98% in summer. It is worth noting that in summer the frequency of sparing conditions is very high at every station in Warmia and Masuria, ranging from 87% in Lidzbark Warmiński to 98% in Elbląg. However, autumn is slightly more favourable and milder for humans (62–81%) than spring (60–74%). In other studies for the Central Bioclimatic Region of Poland, the frequency of such days ranges between 10 and 80% in spring and autumn, and

even reaches 92% in summer. Category 0 “no thermal stress” occurs in Warsaw 43–67% (Lindner, 2011; Rozbicka & Rozbicki, 2018, 2023; Rozbicka et al., 2025), while on the Baltic Sea coast the frequency of such days is 27–42% (Półrolniczak et al., 2016; Koźmiński & Michalska, 2019) and in south-eastern Poland in Lesko and Lublin 35–37.8% (Nowosad et al., 2013; Dobek et al., 2013).

The similarity of results applies primarily to temporal tendencies. In all regions of Poland, positive trends are observed in the frequency of heat stress conditions (categories 2, 3, 4) and negative trends in the frequency of cold stress categories (-2, -3, -4). The studies by Błażejczyk et al. (2012b) and Kuchcik (2017) carried out in the years 1973–2014 show that the tendency of number of days with strong heat stress was increasing and indicated a high variability from year to year, ranging from 1 to 21 days. In this study, the range of year-to-year fluctuations in the number of days with strong heat stress is 1–18 days, similarly to the range of 1–13 given in the study by Nidzgorzka-Lencewicz & Mąkosza (2013) and Mąkosza (2021) and for Szczecin. The forecast for Poland for 2000–2100 prepared by Błażejczyk et al. (2013b) confirms these trends. For example, for Warsaw, based on UTCI, an increase in the number of heat stress days is predicted by 0.9 days/decade. A similar trend in the frequency of heat stress days can be expected in other regions of Poland. Studies by Tomczyk (2021), Rozbicka & Rozbicki, (2021), Tomczyk & Bednorz (2023) also show that an increase in the frequency of hot days associated usually with strong heat stress is expected by the end of the 21st century. The greatest changes are predicted for southern and central Poland, which is also confirmed by this study for the Warmia and Masuria region.

In the paper by Tomczyk and Bednorz (2023) proposed a new biometeorological classification for Poland, based on the variability of average annual and seasonal UTCI values and their standard deviations. It seems that both the existent classification by Kozłowska-Szczęśna et al. (2004), based on the frequency of selected characteristic days with stressful conditions and in addition on biothermal conditions, as well as the new proposal, could allow a more entire and objective definition of bioclimatic regions in Poland. Therefore, it would be worthwhile to create a new classification based on the criteria of both classifications in the future.

Conclusions

- Based on the biometeorological parameters from five analysed stations: Elbląg, Olsztyn, Mikołajki, Lidzbark Warmiński and Kętrzyn situated in the Warmia-Masuria Lake District, an extremely picturesque area of our country, with lakes being one of the greatest attractions (ca. 3,000 lakes, including the so-called Great Masurian Lakes Trail) and forests, it can be stated that the bioclimatic conditions in the District are similar, although there are certain differences in individual periods and parts of the region.

- The most favourable conditions for recreation and relaxation are from April to September, or even October (in Lidzbark Warmiński). These periods are dominated by conditions that do not cause any thermal stress (category 0 “no thermal stress”), with frequencies ranging from 31% in April to over 70% in May, July, August and September.
- Moreover, the maximum and minimum monthly UTCI values over the annual course show a large amplitude. One case of “extreme cold stress” (category -5) was recorded in February in Elbląg (UTCI -41.3°C), while in the remaining stations the minimum UTCI values were slightly higher, indicating “very strong cold stress” (category -4). In the same period 2015-2024 the index reached the maximum value above 38°C in Lidzbark Warmiński (38.6°C) and Kętrzyn (38.1°C) indicating “very strong heat stress” (category 3), while the lowest value was recorded in Elbląg (35.6°C), which is associated with the conditions of “strong heat stress (2).
- As regards the occurrence of the most frequent thermal stress in individual seasons, the most frequently recorded conditions were as follows: in summer (category 0) “no thermal stress” 57-72%, in winter (category -2) “moderate cold stress” 47-69%, in spring and autumn (categories -1 and -2) “slight and moderate cold stress” 23-27% and 17-31%, respectively. The most favourable conditions, “no heat loads” (category 0), were also observed in summer at 57-72%, in spring at 34-44% and in autumn at 32-45%, and in winter at only 0.3-3%.
- The spatial distribution shows that Elbląg stands out from the other stations for its most extreme thermal loads in terms of cold stress, while Lidzbark Warmiński stands out for its extreme thermal loads in terms of heat stress. Stations located in the central part of the region (Lidzbark Warmiński, Olsztyn) are characterised by milder, more favourable bioclimatic conditions (above 60% comfort conditions).
- The diversity of biometeorological conditions in a relatively small region (e.g. as compared to the whole Polish Lowland Region), such as the Warmia-Masuria Region, confirm the need for further research and analyses of bioclimatic conditions in Poland, as well as other regions, on a new maybe more detailed classification. It is therefore it is reasonable to attempt to update or refine the bioclimatic subdivision of Poland, taking into account the spatial and temporal distribution of present-day available parameters.

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