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Climatic and bioclimatic conditions at high-altitude meteorological stations in the Carpathian Mountains and the Sudetes in years 2005–2022

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Abstract— The subject of the analysis were the climatic and bioclimatic conditions of the mountainous areas in Central Europe from 2005 to 2022. The study was conducted based on meteorological data from 4 stations located in 2 mountain ranges in Central Europe, which were obtained from the Ogimet database. The analysis examined the course of mean air temperature, winter days, precipitation, snow cover, wind speed, horizontal visibility, as well as the number of days with thunderstorms and fog. Subsequently, bioclimatic indices were analyzed based on the wind chill index (WCI) and the climate severity index by Osokin (So). The results confirm an increase in mean air temperature and a decrease in the number of winter days. The most significant change in mean annual air temperature was recorded at the Carphatian stations: Varful Omu (0.59 °C/10 years) and Łomnica (0.49 °C/10 years). The largest change in the WCI value was recorded at the Carpathian station Varful Omu (51 W/m^2/10 years), while the So index was 1.4/10 years.

Key-words: bioclimate, mountain areas, Europe, climate changes

1. Introduction

Contemporary climate changes, characterized by a significant increase in air temperatures resulting from human activities, no doubts are raised (*IPCC*, 2021). These changes are observed both on global and regional scales. Mountainous areas are particularly sensitive ecosystems in the context of climate change. Many scientists (*Giorgi et al*., 1997; *Westerling et al*., 2006) believe that the alterations occurring in mountain ecosystems can serve as early warning systems for recognizing future changes in lowland environments. Climate changes in mountainous regions have been the subject of numerous studies (*Beniston*, 2006; *Żmudzka*, 2009; *Negi* and *Mukherjee*, 2020). In his work, *Beniston* (2006) demonstrated a rising trend in air temperatures at selected alpine meteorological stations. The most significant increase in the analyzed stations was observed in the 1990s, especially at the high-altitude Saentis station. *Żmudzka* (2009) showed an increase in the average air temperature and a rise in the number of hot days, along with a decrease in the number of cold days in the Polish Tatra Mountains between 1966 and 2006. *Negi* and *Mukherjee* (2020), in their study on the impact of climate change on Himalayan mountain ecosystems, confirmed an increase in the average air temperature, resulting in an extended growing season at the foot of the mountainous region. The subject of climate change in mountainous areas has also been addressed by *Głowicki* (2008). In his work on extreme thermal phenomena in the Sudetes, the author conducted a detailed analysis of extreme air temperature values at four selected Sudeten meteorological stations. The results showed an increase in air temperature in almost all months of the year. The highest changes in maximum air temperature occurred in May (0.6 °C/10 years). Additionally, the author demonstrated a decrease in the number of frosty and very frosty days, along with an increase in the number of hot and very hot days. It is a fact that mountainous areas are characterized by a harsh, challenging climate that impacts human comfort and well-being.

The scientific discipline concerned with the impact of weather and climatic conditions on living organisms, including humans, is known as bioclimatology. The primary goal of bioclimatic research is to determine the direct influence of atmospheric factors on living organisms and to assess living conditions from a climate perspective (*Kozłowska-Szczęsna et al*., 2004). This field of study is gaining increasing interest among researchers. A very popular focus of bioclimatic studies is the identification of conditions leading to heat stress in living organisms. To achieve this, researchers employ various bioclimatic indices to assess the degree of thermal discomfort experienced by humans. One such index is the Humidex, which was applied in the study by *Charalampopoulos et al*. (2006). It gauges the perceived heat by considering the combined effects of fundamental elements such as temperature and humidity. Another commonly used index in bioclimatic research is the UTCI (universal thermal climate index). It evaluates human thermal loads by taking into account several meteorological parameters, including wind speed, humidity, and solar radiation. The UTCI index has been employed in numerous bioclimatic studies, including those by *Błażejczyk et al.* (2021) and *Miszuk* (2021). In colder regions, the wind chill index (WCI) is often utilized, which incorporates wind speed and air temperature values. This index was adopted in the research conducted by *Coronato* (1993), *Przybylak* and *Araźny* (2005), and *Dogan et al*. (2020). In the work of *Przybylak* and *Araźny* (2005) concerning bioclimatic conditions on the Svalbard archipelago, conditions at three meteorological stations were compared. The most severe conditions in terms of the WCI index were observed at the northernmost station, Ny-Alesund, where the average annual value was 1028 W/m^2, whereas at Svalbard Lufthavn, it was 937 W/m^2, and at the Hornsund station, it was 942 W/m^2. When analyzed by months, the most severe conditions were recorded in January, while the mildest conditions were in July.

The objective of this study was to characterize and assess the climatic and bioclimatic conditions at high-altitude meteorological stations in Central Europe, specifically in the Sudetes and the Carpathian Mountains. Additionally, the study aimed to determine the direction and rate of climatic changes over the investigated multi-year period.

2. Study area, source material, and study methods

The analysis utilized data from four high-altitude meteorological stations located in two mountain ranges in Central Europe (*Fig. 1, Table 1*). These stations are situated in the Sudetes, a mountain range on the border of southern Poland and northern Czech Republic. Two stations were used for the study, one at Śnieżka, the highest peak in the Sudetes and the entire Czech Republic, and another station at Serak in the Eastern Sudetes. The study also considered the Carpathian Mountains, one of the longest and northernmost mountain ranges in Europe associated with the Alpine orogenesis. Two meteorological stations were selected for analysis, one at the summit of Łomnica in the Tatras and another in the Southern Carpathians at Varful Omu (*Makowski*, 2006).

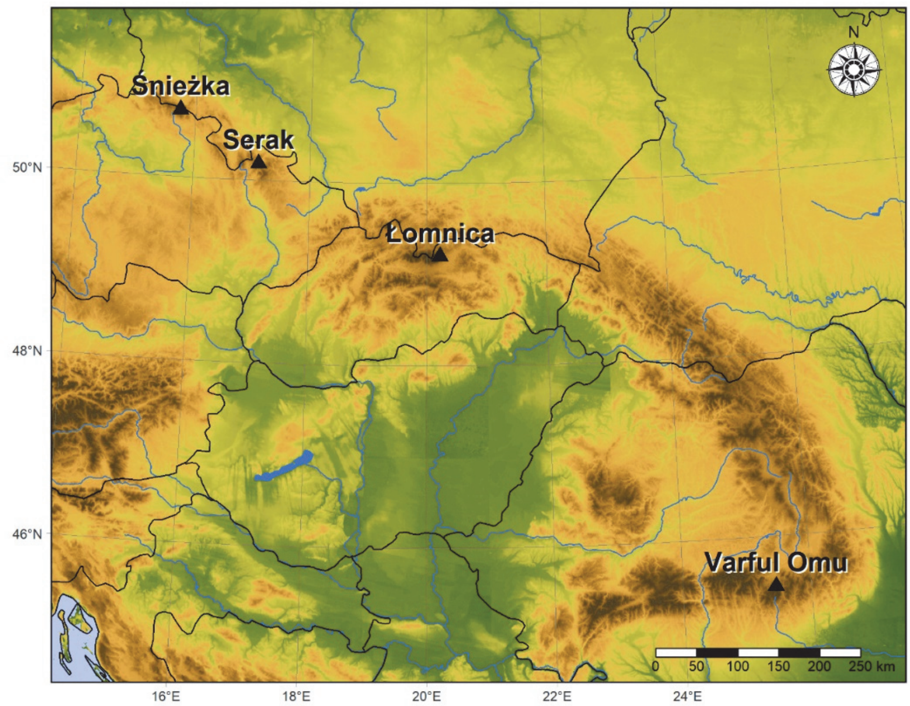

Fig. 1. Location of the stations.

Tab. 1. List of meteorological stations

Station name	**Mountain range**	**Altitude [m a.s.l.]**	**Coordinates**
Łomnica	Carphatians	2632	49°20N 20°21E
Serak	Sudetes	1370	50°18N 17°11E
Śnieżka	Sudetes	1602	50°73N 15°73E
Varful Omu	Carphatians	2503	44°81N 14°98E

In this study, daily meteorological data were acquired from the OGIMET dataset (https://www.ogimet.com/home.phtml.en). The research encompasses a multi-year period spanning from 2005 to 2022, with a rigorous station selection process based on data completeness criteria. The analysis hinged on daily data, encompassing parameters such as air temperature (average, minimum, maximum), mean wind speed, relative humidity, total precipitation, snow cover depth, horizontal visibility, and the count of days with thunderstorms and fog. From these datasets, fundamental climatic characteristics were computed, including the annual mean air temperature, winter mean air temperature, number of winter days (cold and very cold), annual precipitation totals, count of snow-covered days, and maximum snow depth during the season. Additionally, for each examined year, the average wind speed, horizontal visibility, and the annual count of days with thunderstorms and fog were determined. The winter period was defined as a three-month interval from December of the previous year to February of the following year, with winter days categorized as cold (tmax ≤ -10.0 °C) or very cold (tmax < -10.0 °C). Subsequently, bioclimatic conditions were analyzed using selected indices on both annual and winter scales. Two indices were considered: the wind chill index (*WCI*) (*Table 2*) and the Osokin climate severity index (*So*) (*Table 3*), the latter being exclusively applied during the winter period (*Kozłowska-Szczęsna et al*., 1997, from *Gregorczuk*, 1976; *Osokin*, 1968). The calculation of the WCI utilized the following formula:

$$WCI = (10\ v^{-2} + 10.45 - v) * (33 - t)\ 1.163, \qquad (1)$$

where: is the – air temperature (°C) and *v* is the wind speed (m/s). The resulting value of the *WCI* indicates the sensation experienced by a person dressed in clothing with a thermal insulation value of 4.0 clo (clo is the unit of thermal insulation that is comfortable for a person).

Table 2. WCI scale

WCI (Wm^{-2})	Thermal sensation
≤ 58.2	extremely hot
58.3–116.3	hot
116.4–232.6	excessively warm
232.7–581,5	comfortably
581.6–930.4	cool
930.5–1628.2	cold
1628.3–2326.0	frosty
> 2326.0	extremely frosty

Source: *Gregorczuk* (1976) and *Kozłowska-Szczęsna et al.* (1997).

The Osokin climate severity index (*So*) is computed using the following formula:

$$S_o = (1 - 0.06\, t)\,(1 + 0.20\, v)\,(1 + 0.0006\, H_k)\, F\, A_t\,, \qquad (2)$$

where t is the air temperature (°C), *v* is the wind speed (m/s), H_k is the absolute elevation of the measurement station, *F* is the coefficient characterizing the humidity of the air, and A_t is the daily air temperature amplitude. The values for the humidity coefficient (F) are assigned as follows: relative humidity < 60% — *F* = 0.90; 61–70% — *F* = 0.95; 71–80% — *F* = 1.0; 81–90% — *F* = 1.05; > 90% — *F* = 1.10. Similarly, the daily air temperature amplitude (A_t) is assigned values as follows: air temperature < 4.0 °C — A_t = 0.85; 4.1–6.0 °C — A_t = 0.90; 6.1–8.0 °C — A_t = 0.95; 8.1–10.0 °C — A_t = 1.00; 10.1–12.0 °C — A_t = 1.05; 12.1–14.0 °C — A_t = 1.10; 14.1–16.0 °C — A_t = 1.15; 16.1–18.0 °C — A_t = 1.20; > 18.1 °C — A_t = 1.25.

Table 3. Osokin climate severity index scale

S_o	**Climatic severity**
< 1.0	mild
1.0–2.0	low severe
2.01–3.0	moderately severe
3.01–4.0	severe
4.01–5.0	very severe
5.01–7.0	extremely severe
> 7.01	exceptionally severe

Source: *Osokin* (1968) and *Kozłowska-Szczęsna et al.* (1997).

For each of the parameters, the direction and rate of change over the multi-year period under investigation were determined. Additionally, the statistical significance of these changes was assessed using a t-student test at a significance level of $p < 0.05$. All maps, charts, and calculations were generated using the R programming language.

3. Results

3.1. Climatic conditions

The climate of the mentioned stations exhibits significant thermal variability. There are notably lower average air temperatures in the Carpathian Mountains compared to the Sudetes. The annual average air temperature at high-altitude stations in the Carpathians was -2.5 °C at Łomnica and -1.4 °C at Varful Omu (*Fig. 2*). The difference in the average air temperature between these stations is due to the lower geographical latitude of Varful Omu. On the other hand, in the Sudetes, the annual average air temperature on Śnieżka during the study period was 1.7 °C, which is nearly 2 °C lower than at Serak (3.6 °C). The significantly higher elevation of Śnieżka results in much harsher thermal conditions compared to Serak. The lowest annual air temperature values ranged from -3.3 °C at Łomnica in 2005 to 2.6 °C at Serak in 2013. In three out of four stations, the warmest year occurred in 2014 at Łomnica (-1.3 °C), Śnieżka (2.7 °C), and Serak (4.7 °C). On Varful Omu, the warmest year was recorded in 2018 (-0.2 °C). From the analysis conducted, it can be concluded that there was an increase in the annual average air temperature at all the considered stations during the study period. This increase was most pronounced at Łomnica, with a rate of 0.49 °C/10 years, and at Varful Omu, with a rate of 0.59 °C/10 years. These changes were statistically significant only at the Carpathian stations.

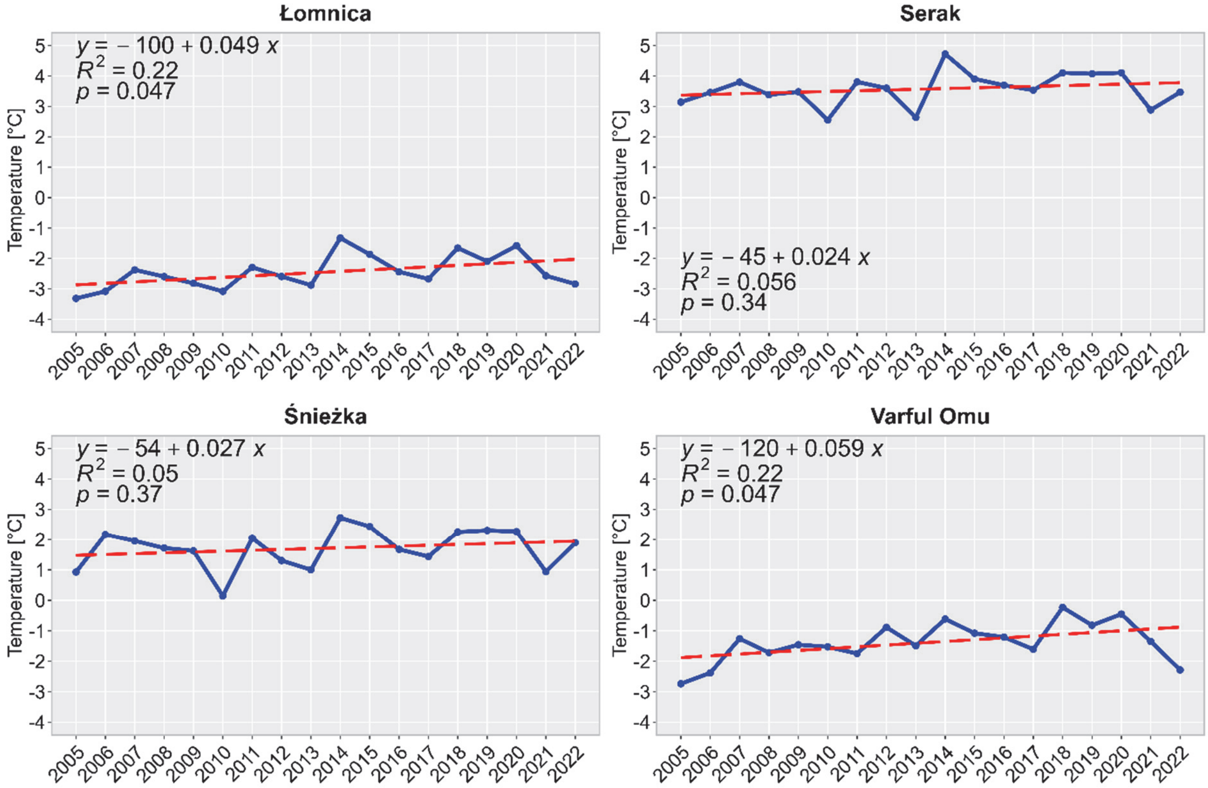

Fig. 2. The course of the average annual air temperature.

Particular attention should be given to the winter air temperature patterns. Over the study period, there was a relatively large difference in thermal conditions between the selected stations in Central Europe. The average winter air temperature at Łomnica was -9.6 °C, while at Varful Omu, it was -9.1 °C (*Fig. 3*). Noticeably milder winters were observed at Śnieżka (-5.6 °C) and Serak (-4.5 °C). The coldest winter was recorded during the 2011/12 season at Łomnica, with an average temperature of -13.4 °C. In the same season, the coldest winter at Varful Omu was slightly milder with an average air temperature of -12.,3 °C. In the Sudeten stations, the coldest winter occurred one year earlier during the 2009/10 season (-8.0 °C) at Śnieżka and (-7.8 °C) at Serak. The warmest winter was recorded during the 2007/08 season at Łomnica (-7.8 °C) and Serak (-2.7 °C). On Śnieżka and Varful Omu, the warmest winter occurred during the 2013/14 season, with average air temperatures of -3.2 °C and -6.9 °C, respectively. The study revealed that the increase in average winter air temperature was more pronounced than for the entire year. The most significant changes were observed at Serak, with a rate of 0.63 °C/10 years, and at Varful Omu, with a rate of 0.73 °C/ 10 years. However, these changes were not statistically significant.

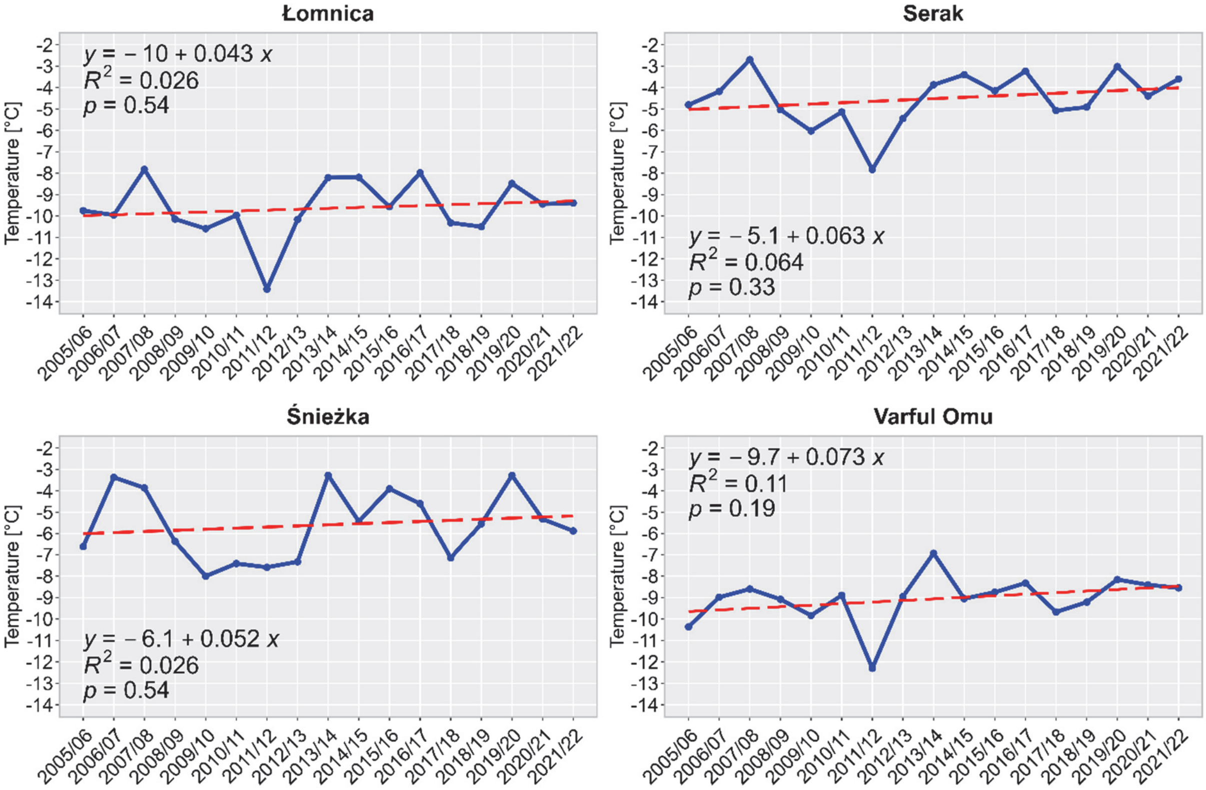

Fig. 3. The course of average air temperature in winter.

Frosty days were significantly more frequent than very frosty days, with an average of 95 days at Serak and 106 days at Śnieżka (*Fig. 4*). At the higher-altitude Carpathian stations, there were 139 frosty days at Varful Omu and 143 at Łomnica. The highest number of these days was recorded in 2022 at Łomnica (166 days) and 122 days at Serak. The highest number of frosty days at Varful Omu was in 2008 (165 days), while on Śnieżka, it was in 2021 (133 days). The lowest occurrence of these days was in 2014, with only 71 days at Serak and 85 days at Śnieżka. On average, the number of very frosty days during the study period ranged from 5 days at Serak to 35 days at Łomnica. The most extreme conditions in this regard were observed in 2005, with 48 very frosty days at Varful Omu and 57 at Łomnica. The research showed an increase in the number of frosty days at 3 out of 4 analyzed stations. The most significant changes in the number of frosty days were observed at Śnieżka, with an increase of 7.1 days/10 years. A decrease in the number of frosty days was observed at Varful Omu, with a decrease of 3.5 days/10 years. In all the analyzed stations, a decrease in the number of very frosty days was recorded. The most significant changes occurred at Varful Omu, with a decrease of 7.2 days/10 years, and at Łomnica, with a decrease of 6 days/ 10 years. However, these observed changes were not statistically significant.

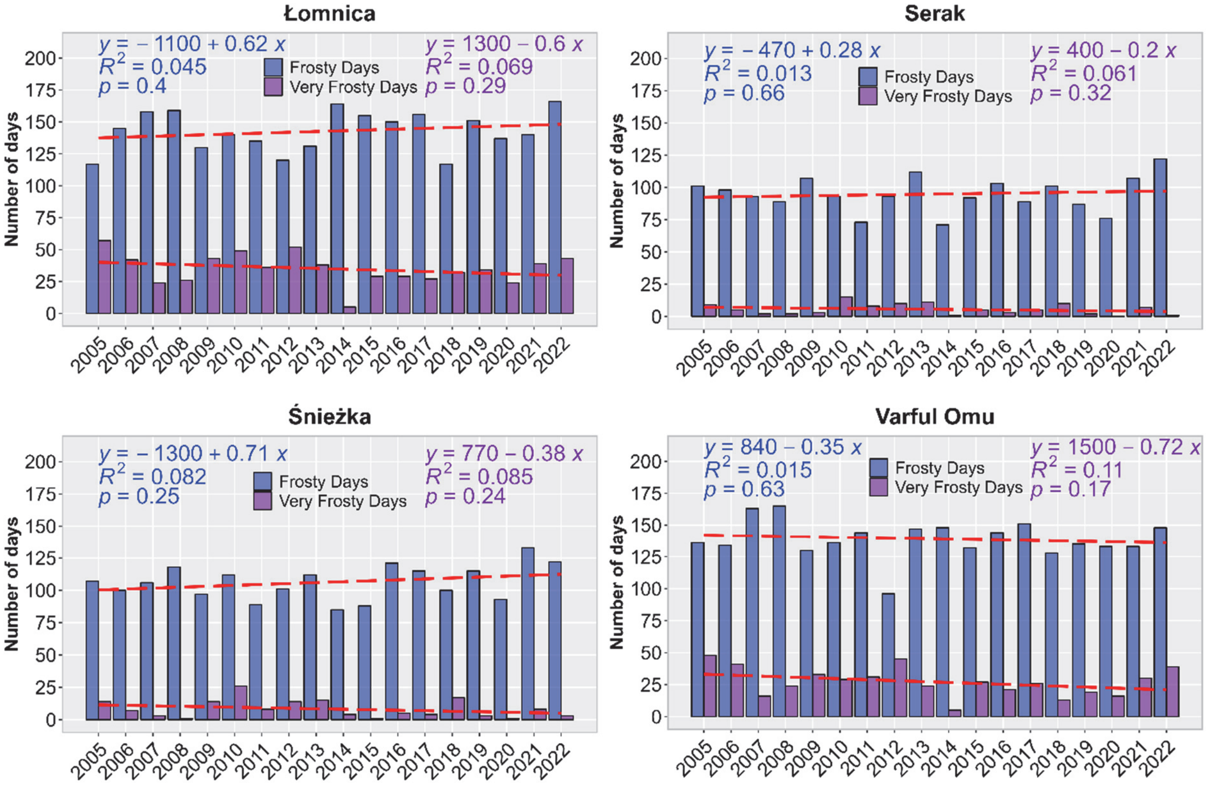

Fig. 4. The course of the number of frosty and very frosty days.

In terms of precipitation, the analyzed stations had similar values, except for the Łomnica station in the Carpathians. Over the study period, the average annual precipitation totaled 1052 mm at Serak, 1058 mm at Varful Omu, and 1102 mm at Śnieżka. A significantly higher amount of precipitation was recorded at Łomnica, with 1965 mm (*Table 4*). The lowest annual precipitation total was observed in 2011 at Varful Omu, with 752 mm, and in 2014 at Serak, with 825 mm. The highest annual precipitation total was recorded in 2017 at Varful Omu, with 1400 mm, and at Łomnica, with 2397 mm. The longest duration of snow cover was observed at Varful Omu, lasting 214 days, and at Łomnica, lasting 251 days. The shortest duration of snow cover was on average 158 days at Serak. The shortest snow cover occurred during the 2014/15 winter season at Serak (133 days), while the longest was in the 2013/14 season (278 days) at Łomnica. There was a considerable variation in the maximum snow cover thickness over the study period. On average, the maximum snow cover thickness ranged from 118 cm at Serak to 272 cm at Łomnica. The thinnest maximum snow cover during the study period was in the 2013/14 season at Serak (42 cm), while the thickest was in the 2008/09 season at Łomnica (407 cm).

Table 4. Accumulated atmospheric precipitation [mm] (A), Number of days with snow cover (B), Number of the days with maximum snow cover thickness [cm] (C). The color blue indicates the lowest value of each parameter for the stations during the studied multi-year period, while red represents the highest value.

Year/Season	Łomnica			Serak			Śnieżka			Varful Omu		
	A	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
2005 | 2005/06	1575	245	258	1037	174	**225**	1213	188	152	1029	228	190
2006 | 2006/07	2027	**224**	403	1181	142	93	1177	162	237	791	221	182
2007 | 2007/08	2325	277	328	1098	**186**	82	1241	**205**	118	863	231	**240**
2008 | 2008/09	1791	273	**407**	1094	170	178	1006	188	99	1061	221	174
2009 | 2009/10	2308	248	222	1035	167	108	1180	183	79	1134	222	142
2010 | 2010/11	2039	262	**94**	1191	150	96	**1301**	178	99	1302	219	136
2011 | 2011/12	**1399**	243	260	868	154	164	836	155	**50**	**752**	200	110
2012 | 2012/13	1674	237	264	1007	158	120	1172	178	189	987	**191**	176
2013 | 2013/14	1726	**278**	205	1066	138	**42**	1277	178	152	1064	208	124
2014 | 2014/15	1934	230	213	945	**133**	89	**825**	155	85	1002	197	172
2015 | 2015/16	1845	237	208	**856**	154	94	956	**153**	112	876	215	236
2016 | 2016/17	1948	263	302	1124	174	66	1006	162	148	1226	**237**	110
2017 | 2017/18	**2397**	246	246	1028	155	98	1178	199	103	**1400**	228	219
2018 | 2018/19	1855	236	284	912	163	159	846	170	122	1188	210	146
2019 | 2019/20	2142	244	278	1191	135	92	1274	186	199	1056	195	**72**
2020 | 2020/21	2141	267	322	**1256**	164	104	1095	177	**247**	1130	230	196
2021 | 2021/22	2079	256	292	1092	178	101	1203	169	144	1251	214	223
2022	2157			1049			1043	183		942		
Mean	**1965**	**251**	**272**	**1057**	**158**	**118**	**1102**	**176**	**138**	**1058**	**214**	**170**

Among the other meteorological elements, wind speed stands out as an important factor influencing human thermal perception. Its average value was 21 km/h at Serak, 22 km/h at Łomnica, 28 km/h at Varful Omu, and a substantial 42 km/h at Śnieżka (*Table 5*). The highest average annual wind speed was recorded in 2008, reaching 54 km/h at Śnieżka. Horizontal visibility exhibited minor variations between the mentioned stations, except for the Łomnica station, where the average annual horizontal visibility was 33 km. In the other stations, horizontal visibility ranged from 19 to 20 km. A significant difference is observed in the number of foggy days. The average annual number of foggy days ranged from 266 days at Łomnica to 305 days at Śnieżka. In the most anomalous year at Varful Omu, fog was present for almost 11 months, with 333 foggy days in 2009.

Fog occurred least frequently in 2006 at Łomnica, with 239 foggy days on record. On average, the number of days with thunderstorm ranged from 24 days at Serak to 47 days at Varful Omu. Thunderstorms were most frequent in 2010 at Varful Omu (60 days) and least frequent at Serak in 2022 (13 days).

Table 5. Average wind speed [km/h] (A), Average horizontal visibility [km] (B), Number of days with thunderstorm (C), Number of days with fog (D). The color blue indicates the lowest value of each parameter for the stations during the studied multi-year period, while red represents the highest value.

	Łomnica				**Serak**				**Śnieżka**				**Varful Omu**			
Year	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**
2005	25	37	**17**	257	23	24	16	**231**	46	18	22	298	32	17	55	311
2006	23	36	22	**239**	23	19	16	254	51	18	29	**282**	34	**15**	50	314
2007	24	37	32	260	**24**	19	28	260	52	16	**40**	302	**38**	19	48	296
2008	**28**	35	24	270	23	19	22	269	**54**	16	22	315	32	18	45	308
2009	21	**27**	21	275	22	17	30	281	38	15	38	305	32	16	55	**333**
2010	23	29	23	278	21	**14**	26	283	37	**13**	26	311	32	17	**60**	322
2011	21	33	31	244	20	21	33	259	40	20	32	291	28	21	37	289
2012	23	33	30	262	22	20	**36**	272	41	19	31	310	28	24	43	**265**
2013	**19**	31	26	260	20	16	17	290	**36**	15	23	321	27	17	44	305
2014	19	31	22	286	20	18	34	**291**	37	18	34	**327**	27	21	43	307
2015	21	32	25	255	21	19	18	253	41	20	**17**	305	26	20	**31**	287
2016	21	30	34	**288**	19	18	21	283	37	19	22	314	26	18	49	326
2017	23	34	32	261	20	20	28	274	43	20	31	325	26	19	48	309
2018	19	34	**43**	269	22	22	27	261	38	**24**	26	292	24	19	48	302
2019	22	34	35	283	21	22	26	271	42	21	23	306	26	18	59	303
2020	21	38	28	260	21	**25**	21	256	41	23	26	285	**24**	**22**	41	289
2021	21	35	30	275	19	23	14	266	38	20	26	311	26	19	36	303
2022	22	**38**	24	277	**19**	25	**13**	270	41	22	22	293	25	20	50	305
Mean	**22**	**33**	**28**	**266**	**21**	**20**	**24**	**268**	**42**	**19**	**27**	**305**	**28**	**19**	**47**	**304**

3.2. Bioclimatic conditions

The values of the wind chill index (*WCI*) exhibited relatively consistent trends over the study period (*Fig. 5*). All the years in the four stations were classified as cold conditions. The highest average annual *WC*I value was 1226 W/m^2 at Śnieżka, while the lowest was 1000 W/m^2 at Serak. The mildest conditions were observed in 2014 at Serak (949 W/m^2). On the other hand, the most severe conditions were recorded in 2006 at Varful Omu, with an average *WCI* value of 1308 W/m^2. All the analyzed stations showed a decrease in *WCI* values during the study period, and these changes were statistically significant in all cases. The observed changes amounted to 27 W/m^2/10 years at both Śnieżka and Serak, and 48 W/m^2/10 years at Łomnica. The most significant changes were observed at Varful Omu, with a decrease of 51 W/m^2/10 years.

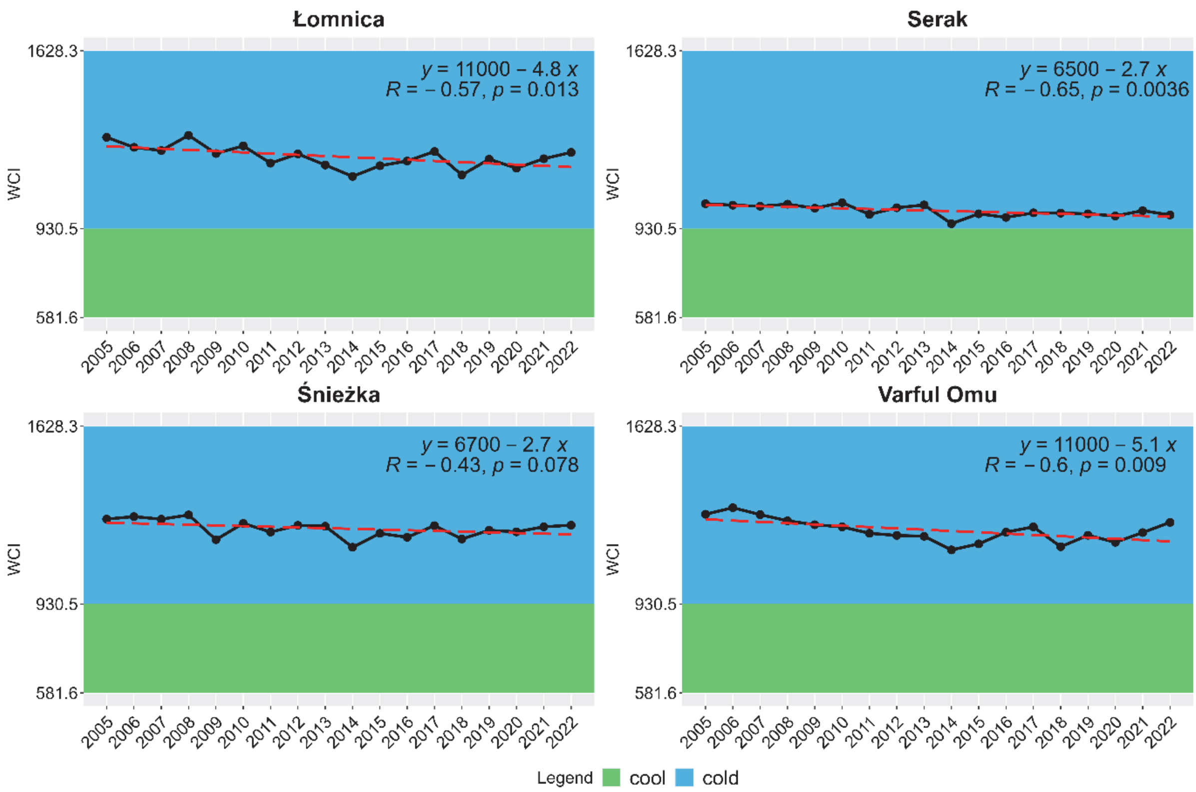

Fig. 5. The course of the wind chill index over the study period.

Significantly higher wind chill index (WCI) values were recorded in the Carpathians during the winter season (*Fig. 6*). These conditions were predominantly cold, with a few seasons classified as frosty. The frosty winters included the 2005/06, 2006/07, and 2011/12 seasons at Varful Omu, as well as the 2011/12 season at Łomnica and Śnieżka. In an average winter season, the *WCI* values ranged from 1333 W/m^2 at Serak to 1569 W/m^2 at Varful Omu. The most severe conditions were observed in the 2011/12 season at Śnieżka (1726 W/m^2) and Varful Omu (1743 W/m^2). In the 2016/17 season at Serak, the mildest conditions were recorded, with a *WCI* value of 1277 W/m^2. The analysis showed a clear decrease in *WCI* values over the study period, ranging from 14 W/m^2/10 years at Łomnica to 55 W/m^2/10 years at Varful Omu. However, these observed changes were not statistically significant.

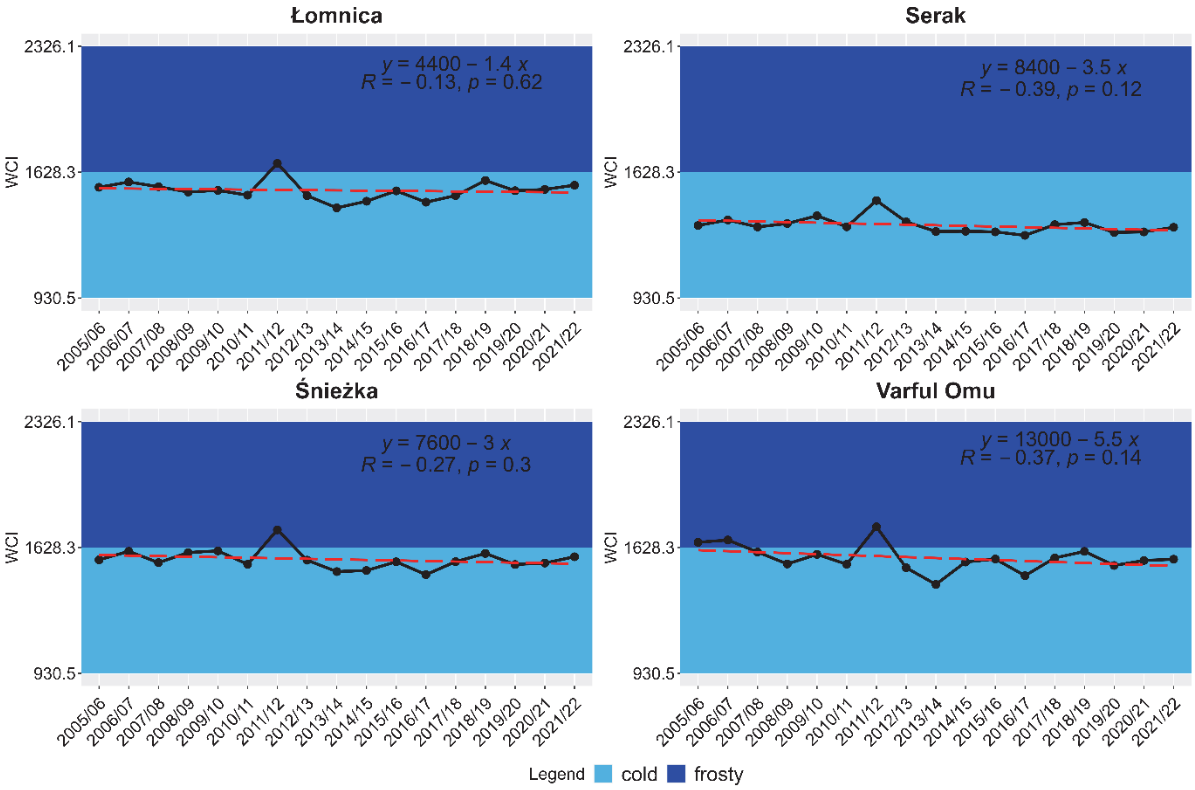

Fig. 6. The course of the wind chill index in winter.

The climate severity index values by Osokin during the winter season were classified as very severe, extremely severe, and predominantly exceptionally severe (*Fig. 7*). The first two severity classes were exclusively recorded at the Serak station, while the other stations exhibited predominantly exceptionally sharp conditions. The average value of the climate severity index during the winter season ranged from 5.4 at Serak to 11.4 at Varful Omu. At Łomnica and Śnieżka, the values were 9.5 and 9.6, respectively. The mildest winter was recorded in the 2016/17 season at Serak (4.9), while the most severe winter occurred in the 2018/19 season at Varful Omu (16.1). The research indicated a decrease in the climate severity index values at three of the analyzed stations, except for Łomnica. These changes ranged from 0.1/10 years at Łomnica to

1.4/10 years at Varful Omu. However, these changes were not statistically significant except for the Serak station.

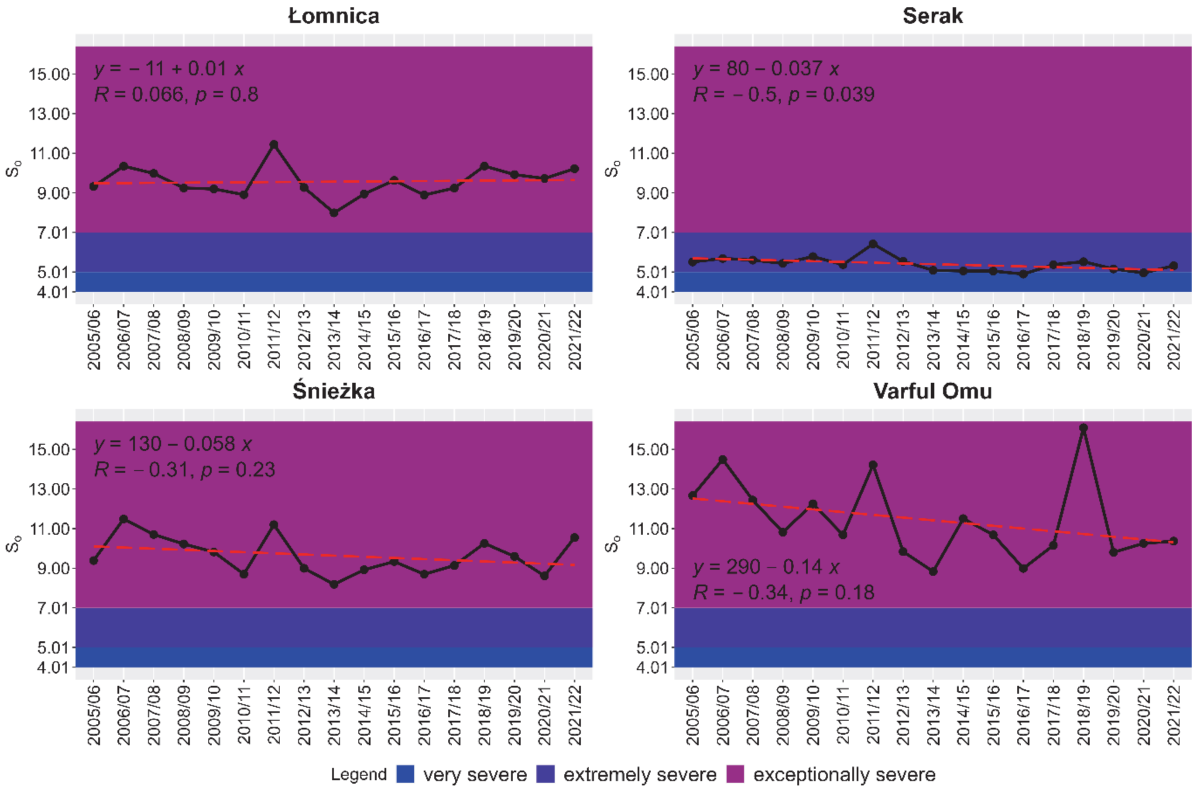

Fig. 7. The course of the Osokin climate severity index in winter.

4. Summary and discussion

The average annual air temperature varied from -2.5 °C at the Carpathian Łomnica station to 3.6 °C in the Sudetes at the Serak station. Meanwhile, on the highest peak in the Sudetes, Śnieżka, the average annual air temperature was 1.7 °C. It is worth noting that *Urban* and *Tomczyński* (2017) reported slightly different results in their study on changes in the average air temperature at Śnieżka from 1881 to 2012. In their study period, the average air temperature was 0.5 °C, with the highest values occurring in 2006 and 2011 (2.3 °C). However, in the current study, it was shown that 2014 was the warmest year at Śnieżka (2.7 °C). Particular attention should be paid to the Łomnica and Serak stations, where the coldest and warmest years in the study period were recorded. This occurred in 2005 at Łomnica, where -3.3 °C was recorded, and in 2013 at Serak, with a value of 2.6 °C. All mountain stations exhibited a significant increase in the average annual air temperature. The most pronounced changes were observed in the Carpathians at Varful Omu

(0.59 °C/10 years) and at Łomnica (0.49 °C/10 years). Previous studies also pointed to a significant increase in air temperature on high-altitude stations. *Micu* and *Micu* (2006) observed a temperature increase of 2.4 °C at the Varful Omu summit in the period from 1961 to 2003. Similarly, changes at Śnieżka amounted to 0.1 °C/10 years from 1881 to 2012 (*Urban* and *Tomczyński*, 2017).

During the winter season, the average air temperature ranged from -9.6 °C at Łomnica to -9.1 °C at Varful Omu, with -4.5 °C recorded at Serak. Similar results were obtained by *Micu* and *Micu* (2006), who, for the period from 1961 to 2003 at Varful Omu, reported a seasonal average air temperature of -9.2 °C. The coldest winter was observed in the 2011/12 season at Łomnica (-13.4 °C), while the warmest occurred in the 2007/08 season at Serak (-2.7 °C). The winter period was characterized by a significant increase in the average air temperature, ranging from 0.43 °C/10 years at Łomnica and 0.52 °C/10 years at Śnieżka to 0,73 °C/10 years at Varful Omu. A lower increase in the average air temperature at Śnieżka during the period from 1881 to 2012 was noted by *Głowicki* (2008), who reported an increase of 0.09 °C/10 years. Meanwhile, *Tomczyk* and *Miś* (2023) identified an increase of 0.25 °C/10 years from 1966 to 2021.

The increase in the average air temperature significantly influenced the frequency of winter days. The average number of frosty days ranged from 95 at Serak to 143 at Łomnica. Meanwhile, the number of very frosty days varied from 5 at Serak to 35 at Łomnica. In most cases, there was an increase in the number of frosty days and a decrease in very frosty days, except for Varful Omu, where a significant decrease in the number of frosty days was observed during the study period. On average, Śnieżka recorded 106 frosty days and 9 very frosty days. *Głowicki* (2008) observed slightly higher frequencies of winter days at Śnieżka for the period from 1951 to 2007. He recorded 129 frosty days and 12 very frosty days, which showed a decreasing trend during the study period.

The lowest average annual precipitation in the study period was recorded at the Sudeten station Serak (1057 mm), while the highest was observed at the Carpathian station Łomnica (1965 mm). The snow cover lasted the shortest time at the peak of Serak (158 days), while it persisted the longest at Łomnica (251 days). Similar results were obtained by *Szyga-Pluta* and *Mendel* (2023) in their study on meteorological conditions at Szrenica in the years 2018–2020. The authors showed that during the study period, the snow cover at the Sudeten measurement station lasted on average for 160 days per year. Among all the stations studied, the thinnest snow cover was typically observed in the Eastern Sudetes at Serak (118 cm), while the thickest cover was recorded at Łomnica (272 cm). The lowest horizontal visibility was observed at Śnieżka and Varful Omu (19 km), while the highest was recorded at Łomnica (33 km). Fog was least frequently present at Łomnica (266 days per year), while it was most frequently observed at Śnieżka (305 days per year). On the other hand, thunderstorms were least frequently observed at Serak, occurring on average for 24 days per year.

They were most frequently recorded at the Carpathian station Varful Omu, with an average of 47 days per year.

The bioclimate of the studied high mountain peaks, as represented by the wind chill index (*WCI*), was characterized by cold conditions. The mildest conditions were observed in the Sudetes at the Serak peak (949 W/m^2). On the other hand, the harshest conditions were observed at Śnieżka (1226 W/m^2). The lowest average annual *WCI* value was recorded in 2014 (949 W/m^2) at Serak, while the highest was in 2006 at Varful Omu (1308 W/m^2). Winter conditions were significantly harsher, confirming the occurrence of cold and frosty winters based on the wind chill index. Frosty winters were observed infrequently at Varful Omu, Łomnica, and Śnieżka. The most severe average winter conditions were observed at Varful Omu (1569 W/m^2), while the mildest were recorded at Serak (1333 W/m^2). Both for the entire year and for the winter period, a decrease in *WCI* values was observed, with the most significant changes noted at Varful Omu (51 W/m^2/10 years for annual values and 55 W/m^2/10 years for winter values). *Błażejczyk et al*. (2020), analyzing bioclimatic conditions based on the universal thermal climate index, *UTCI* in the Northern Carpathians, found that the station at Łomnica had the most severe conditions in the studied area. The average *UTCI* value in the period from 1986 to 2015 was -15.7 °C, while the minimum daily value of this index was as low as -73.5 °C. Next, an analysis of the Osokin climate severity index was conducted for the winter period. The high mountain stations under consideration exhibited conditions ranging from very severe to exceptionally severe, with winters primarily classified as exceptionally severe. The average value of the index during the winter period ranged from 5.4 at Serak to 11.4 at Varful Omu. The most severe winter was recorded in the 2018/19 season at Varful Omu, with a climate severity index value of 16,1. On the other hand, the mildest winter was observed in the 2016/17 season at Serak, with a severity index value of 4.9. In most of the studied stations, a decrease in the severity index value was demonstrated, except for Łomnica. Changes ranged from 0.1/10 years at Łomnica to 1.4/10 years at Varful Omu.

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