




## Article

# Changes in Air Temperature and Snow Cover in Winter in Poland

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**Abstract:** The primary objective of the paper was to characterize the climatic conditions in the winter season in Poland in the years 1966/67–2019/20. The study was based on daily values of minimum (Tmin) and maximum air temperature (Tmax), and daily values of snow cover depth. The study showed an increase in both Tmin and Tmax in winter. The most intensive changes were recorded in north-eastern and northern regions. The coldest winters were recorded in the first half of the analyzed multiannual period, exceptionally cold being winters 1969/70 and 1984/85. The warmest winters occurred in the second half of the analyzed period and among seasons with the highest mean Tmax, particularly winters 2019/20 and 1989/90 stood out. In the study period, a decrease in snow cover depth statistically significant in the majority of stations in Poland was determined, as well as its variability both within the winter season and multiannual.

**Keywords:** air temperature; snow cover depth; winter; climate change; Poland



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## 1. Introduction

The currently observed climate warming raises no doubts, and the first decade of the 21st century is recognized as the warmest in the history of instrumental measurements [1]. It is estimated that human activity caused global warming approximately 1.0 °C above the level from before the industrial age, with a probable range from 0.8 °C to 1.2 °C [2]. Further increase in air temperature is forecasted for the following decades. According to the IPCC report [3] and other research, temperature will grow faster in winter than in the remaining seasons, particularly in far future (2071–2100), according to scenario RCP8.5 by more than 1 °C [4,5].

Warming more intense than the global average is observed in many terrestrial regions in different seasons, which is followed by extreme records in recent years. For example the boreal winter season 2019/2020 was warmest in the history of measurements, with mean temperature higher by 1.4 °C in comparison to the warmest winter so far in 2015/2016. In Europe rapid changes are observed and an increase in temperature has been the most evident in the north of the continent [6]. In central and north Europe, an increase in extreme temperature values is considerably higher than the corresponding average winter warming, and approximately 2.5 times higher than average global warming [7].

Changes in temperature in Poland correspond with changes in thermal conditions throughout central Europe [8]. In Poland, the strongest increase in temperature is observed in spring and summer [9–11] and the observed warming, is strongly manifested in a decrease in the frequency of occurrence of cold days and cold waves [12–16]. According to Koenigk et al. [17], winter temperatures are correlated the strongest with the variability of marine ice around Greenland. Ziernicka-Wojtaszek and Zuśka [18] estimate that in the future, one in five winters in Poland will show positive mean areal air temperature in all months, and the most important negative effect of occurrence of warm winters is reduction of the duration and thickness of snow cover.

Snow cover is most sensitive to changes in temperature and precipitation and therefore it is considered a good indicator of climate change. European snow cover is primarily determined by air temperature. The effect of precipitation on the snowpack is less obvious, primarily because the snowfall/rainfall ratio is strongly controlled by air temperature [19]. The relationship between snow cover and other climatic elements strongly depends on geographic location, latitude, and elevation [20,21]. An increase in temperature has decreased snow accumulation, and reduced snow cover duration at mid-latitudes and mid- and low elevations, and not in the coldest regions, e.g., [21–25].

The temperature-snow cover relationship activates one of the strongest climate change feedback as snow, due to its high albedo, strongly modifies surface-atmosphere energy fluxes [26]. An increase in temperature results in the diminishment of snow cover and on the other hand, decrease in the range of snow cover is considered as the primary cause of strong temperature increase in winter in eastern Europe [27,28]. Differences in the range of snow cover in Europe probably contribute to the occurrence of warm and cold days in winter [29]. A correlation exists between the tendency for decrease in the range of snow cover in Europe and the growing (decreasing) trend of the number of warm (cold) days throughout Europe.

Large scale studies concerning snow cover duration have predominantly recognized declining trends in the Northern Hemisphere, with the most intense reduction since the 1980s, e.g., [22,30,31]. Lowland areas of central and northern Europe are characterized by the reduction of cover duration [32,33], although a simultaneous tendency of an increase in snow cover depth has been recorded [33,34]. In Poland, however, only a slight decreasing trend of snow cover characteristics was detected in the second half of the 20th century [32,35–39]. High variability between individual seasons and an increasing frequency of mild and snowless winters occurring in a moderate climate zone was also emphasized, e.g., [40,41]. The occurring slight discrepancy between the current general ideas concerning snow cover tendency, namely the expectations of a strongly declining trend, and results of previous studies covering the second half of the 20th century, make the research of the contemporary changes in winter snow cover in Poland a relevant issue.

Further diminishing of seasonal snow cover is expected in Europe in accordance with climatic projections [42,43]. The projections suggest a reduction of maximum snow cover thickness by approximately –15% and approximately –20% for RCP4.5 and RCP8.5, respectively, by the period 2021–2050. The reductions will double by the period 2071–2100 irrespective of RCP, and may reach up to –40% according to RCP8.5 [44]. The variability of snow cover thickness in the second half of the 20th century increased from year to year, and it was spatially variable in Poland [35]. According to research by Piotrowski and Jędruszkiewicz [45], thermal conditions of winters and snow cover in Poland have been and in the foreseeable future (2021–2050) will be closely related to atmospheric circulation.

At European mid-latitudes, long-term changes in winter weather conditions are partly modulated by short-term fluctuations associated with the variability of atmospheric circulation [24,46]. The leading role of the predominant winter teleconnection pattern over the Euro-Atlantic region, i.e., North Atlantic Oscillation (NAO) as a driving factor has been emphasized in previous studies, i.e., [24,47–50]. Therefore, although the increasing tendency of air temperature and the declining tendency of snow cover is projected in Poland under the warming climate, a large inter-winter variability can still be expected, due to the overlapping impact of circulation conditions.

Central Europe has experienced several mild winters since the 1990s. Last winter 2019/2020, extremely warm and snowless, was one of the motivations to undertake this study. The primary objective of the paper was to characterize the climatic conditions in the winter season in Poland in the years 1966/67–2019/20. The implementation of the primary study objective involved: (1) analysis of the temporal and spatial variability of thermal conditions in winter, and (2) occurrence of snow cover, as well as (3) determination of the effect of atmospheric circulation on thermal and nival conditions in winter.

## 2. Data and Study Methods

The study was based on daily values of minimum (Tmin) and maximum air temperature (Tmax), and daily values of snow cover depth. The data were obtained from the Institute of Meteorology and Water Management-National Research Institute for 40 stations in Poland from the period 1966/67–2019/20, whereas 31 of the stations had a complete data set concerning snow cover for the discussed observation period (Figure 1). The winter season was defined as a sequence of three months from December to February.

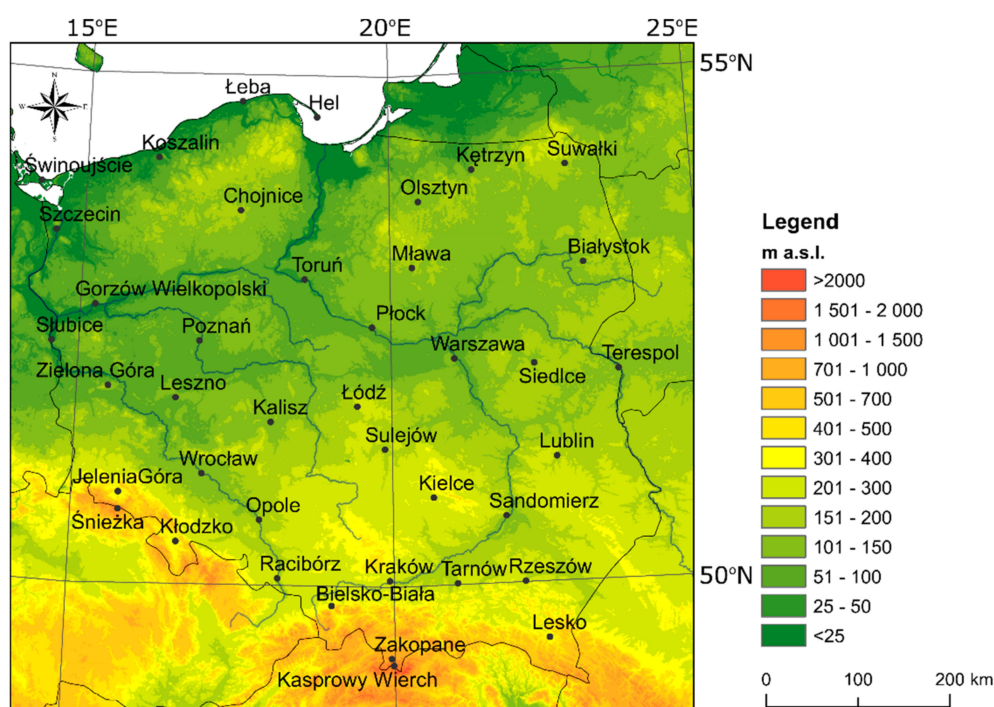


Figure 1. Location of stations.

First, the obtained data provided the basis for the calculation of mean Tmin and Tmax in particular winter months and seasons. Based on these data, seasons and months with the lowest mean Tmin and highest mean Tmax were determined, showing the range of fluctuations of thermal conditions in winter. Then, the direction of changes in mean Tmin and Tmax was analyzed, and the statistical significance of the observed changes was determined ( $p < 0.05$ ,  $p < 0.01$ ,  $p < 0.001$ ). The assessment of the trend of changes employed linear regression, and the significance of trends was verified by means of a t-Student test. Daily data provided the basis for the determination of days with the lowest Tmin and highest Tmax in the analyzed multiannual period. Tmin and Tmax anomalies were also calculated for the selected winter seasons. The anomalies were calculated as the difference between mean air temperature value in a particular season, and mean value in the season in the analyzed years.

Analogically, multiannual changes in characteristics of snow cover were analyzed, as well as their anomalies for selected extreme winters. This employed the basic properties of snow cover, i.e., number of days with snow cover during winter defined as the months of December, January, and February, and mean snow cover depth calculated only for days of its occurrence. Anomalies were calculated similarly as in the case of air temperatures.

The determination of circulation conditions employed two macroscale circulation types, i.e., North Atlantic Oscillation (NAO) and Scandinavian pattern (SCAND). As found in earlier studies, these types have the strongest effect on the climatic and weather conditions in central Europe, including Poland [51,52]. Monthly values of the NAO and SCAND indices were obtained from the data bases of Climate Prediction Centre NOAA.

The NAO is a bipolar circulation type resulting from the co-occurrence of the Azores High and Icelandic Low. The type is characterized by two phases, positive and negative. In the first case, lower than average air pressure is recorded in the center of the Icelandic Low, and higher in the Azores High. The co-occurrence of higher than average pressure in the Icelandic Low and lower in the Azores High constitutes the negative NAO phase [53,54]. In the positive phase, NAO brings mild winters in central Europe, and in the negative phase cold and snowy winters [55–57].

The SCAND pattern is characterized by the occurrence of a strong high pressure system over the Scandinavian Peninsula. Simultaneously, an area of lower than average pressure extends from western Europe to eastern Russia/western Mongolia. In the positive phase, pressure is higher than average, sometimes creating a blockade situation over Scandinavia and western Russia. The negative phase is related to lower than average pressure over northern Europe [58–61].

The aforementioned data provided the basis for the calculation of the Pearson correlation coefficient between mean winter NAO and SCAND index and mean Tmin and Tmax, as well as analysis of statistical significance at levels of  $p < 0.05$ ,  $p < 0.01$ , and  $p < 0.001$ . Then, statistical significance of the difference in temperature between Tmin and Tmax was calculated for the positive and negative NAO and SCAND phase. This stage covered years in which the index value was below the first and above the third quartile from the analyzed years. The determination of statistical significance employed test  $t$  for independent samples, and like above, three significance thresholds were applied. Moreover, the difference in temperature was calculated (respectively for Tmin and Tmax) between the negative and positive phase of the selected indices. Analogical procedures were applied for the winter number of days with snow cover, comparing the permanence of the snow cover in years characterized by the occurrence of a positive and negative phase of both considered circulation types.

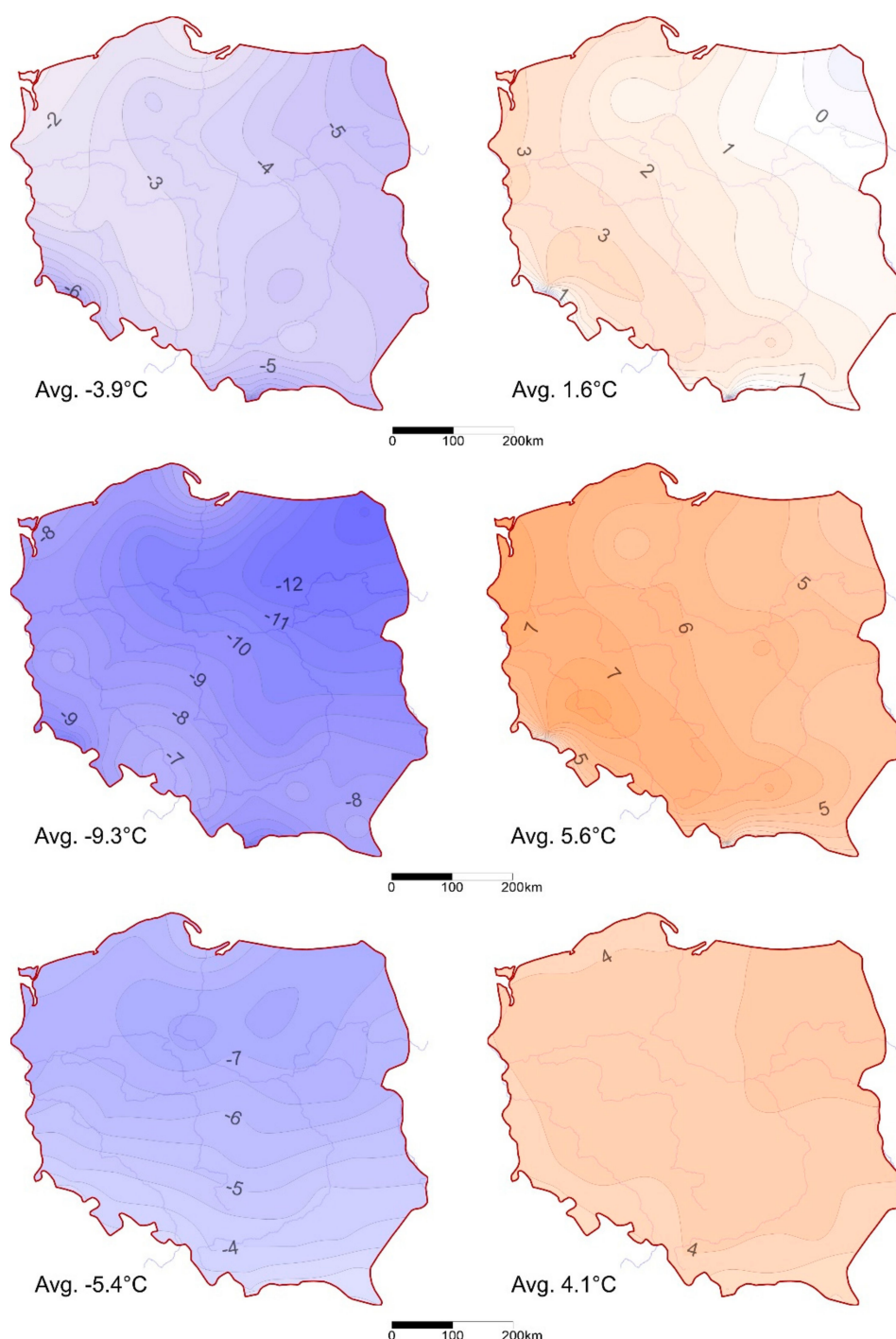
The mathematical and statistical processing of analysis results employed statistical procedures included in MS Excel. QGIS and Surfer software was used to visualize the obtained results.

### 3. Results

#### 3.1. Air Temperature

In winter in the years 1966/67–2019/20, mean Tmin and Tmax in Poland were  $-3.9\text{ }^{\circ}\text{C}$  and  $1.6\text{ }^{\circ}\text{C}$ , respectively, and increased from the north-east to the south-west and west of the country (Figure 2). Such a spatial distribution was disturbed in mountain areas, where the factor changing thermal conditions is land elevation above sea level. The lowest mean Tmin and Tmax were recorded in stations located at the highest elevations, i.e., on Kasprowy Wierch ( $-10.1\text{ }^{\circ}\text{C}$  and  $-4.7\text{ }^{\circ}\text{C}$ , respectively) and Śnieżka ( $-8.3\text{ }^{\circ}\text{C}$  and  $-3.4\text{ }^{\circ}\text{C}$ , respectively). Outside of mountain areas, the lowest mean Tmin and Tmax were recorded in the north-east of the country with a minimum in Suwałki ( $-5.8\text{ }^{\circ}\text{C}$  and  $-0.8\text{ }^{\circ}\text{C}$ , respectively), and the highest values were observed in the west and north of the country, i.e., mean Tmin in Hel ( $-1.1\text{ }^{\circ}\text{C}$ ), and Tmax in Słubice ( $3.7\text{ }^{\circ}\text{C}$ ). In the analyzed multi-annual period, throughout the area, an increase in both Tmin and Tmax was recorded. The observed changes over the study area were statistically significant (Table 1; Figure 3). In both cases, the greatest changes were observed in north-eastern and northern Poland. The greatest increase in Tmin and Tmax was recorded in Suwałki. It was  $0.70\text{ }^{\circ}\text{C}/10\text{ years}$  and  $0.57\text{ }^{\circ}\text{C}/10\text{ years}$ , respectively. Moreover, changes in Tmin at a level of  $\geq 0.50\text{ }^{\circ}\text{C}/10\text{ years}$  were also recorded in Białystok, Chojnice, Kętrzyn, Koszalin, Mława, Olsztyn, Rzeszów, Siedlce, Szczecin, Terespol, and Warszawa. Changes in Tmax at a level of  $\geq 0.50\text{ }^{\circ}\text{C}/10\text{ years}$  were recorded in Kętrzyn, Suwałki, Szczecin, and Terespol. In the majority of stations (i.e., in 26 out of 40 stations), changes in Tmin were higher than changes in Tmax, and the greatest differences in the increase occurred in the east, and particularly in the south-east of the country.





**Figure 2.** Mean Tmin and Tmax in winter in the years 1966/67–2019/20 (**top row**), mean Tmin and Tmax in winter of (respectively) 1969/70 and 2019/20 (**middle row**), and Tmin and Tmax anomalies during those winters (**bottom row**). Left column—Tmin, right column—Tmax.

In the analyzed multiannual period, very high variability of thermal conditions in the winter season was observed in Poland. In the majority of stations (in 23 out of 40 stations), the coldest winter was recorded in the season 1969/70 with mean Tmin of  $-9.3^{\circ}\text{C}$  for the entire area (Table 1). An increase in mean Tmin occurred from the north-east to the south and west of the country, and along the coast (Figure 2). In particular stations, mean Tmin values varied from  $-13.1^{\circ}\text{C}$  in Suwałki to  $-6.1^{\circ}\text{C}$  in Hel. In the analyzed season, in stations located the highest, mean Tmin was  $-11.9^{\circ}\text{C}$  on Kasprowy Wierch and  $-11.3^{\circ}\text{C}$  on Śnieżka. During that winter, mean Tmin was lower than average in the multiannual

period from 1.9 °C on Kasprowy Wierch to 7.8 °C in Toruń. In the remaining stations (in 17 out of 40 stations), the coldest winter was recorded in season 1984/85.

**Table 1.** Characteristics of thermal conditions in winter in the years 1966/67–2019/20. Stations are arranged in spatial order from the north to the south.

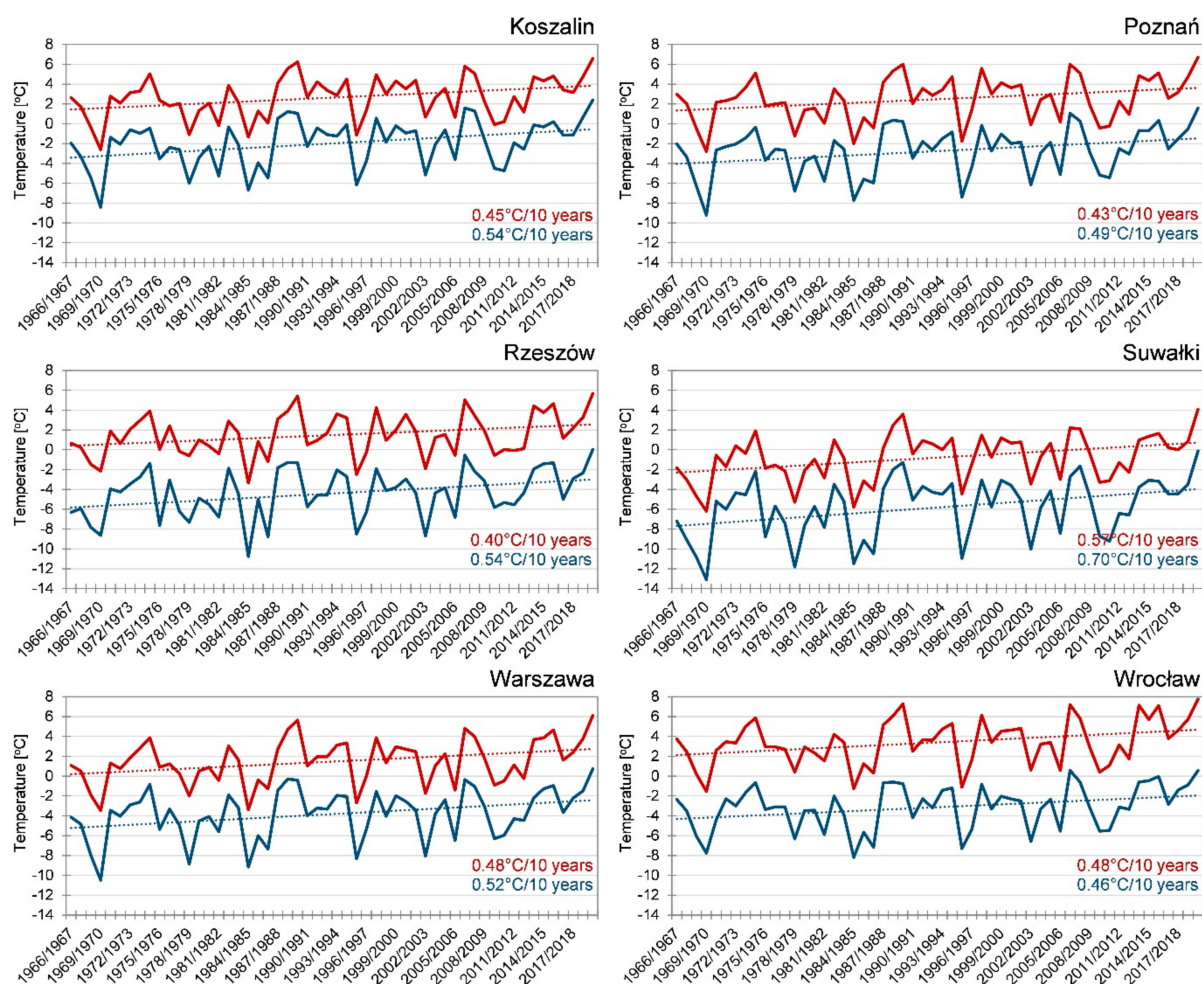
Station	Changes (°C/10 Years)		Coldest Season	Warmest Season	Station	Changes (°C/10 Years)		Coldest Season	Warmest Season
	Tmin	Tmax				Tmin	Tmax		
Łeba	<b>0.48</b>	<b>0.39</b>	1969/70	2019/20	Leszno	<b>0.41</b>	<b>0.43</b>	1969/70	2019/20
Hel	<u><b>0.44</b></u>	<b>0.38</b>	1969/70	2019/20	Kalisz	<b>0.47</b>	<b>0.40</b>	1969/70	2019/20
Koszalin	<u><b>0.54</b></u>	<b>0.45</b>	1969/70	2019/20	Łódź	<b>0.42</b>	<b>0.44</b>	1969/70	2019/20
Suwałki	<b>0.70 *</b>	<u><b>0.57</b></u>	1969/70	2019/20	Sulejów	<b>0.46</b>	<b>0.41</b>	1984/85	2019/20
Kętrzyn	<b>0.55</b>	<b>0.50</b>	1969/70	2019/20	Lublin	<b>0.47</b>	0.34	1984/85	2019/20
Świnoujście	<b>0.42</b>	<b>0.43</b>	1969/70	2019/20	Wrocław	<b>0.46</b>	<b>0.48</b>	1984/85	2019/20
Olsztyn	<b>0.56</b>	<b>0.46</b>	1969/70	2019/20	Jelenia Góra	0.26	<b>0.36</b>	1984/85	1989/90
Chojnice	<b>0.53</b>	<u><b>0.49</b></u>	1969/70	2019/20	Kielce	0.39	<b>0.39</b>	1984/85	2019/20
Szczecin	<b>0.51</b>	<u><b>0.50</b></u>	1969/70	2019/20	Śnieżka	0.22	0.26	1984/85	1989/90
Białystok	<b>0.59</b>	<b>0.47</b>	1969/70	2019/20	Sandomierz	<b>0.47</b>	<b>0.46</b>	1984/85	2019/20
Mława	<b>0.57</b>	<b>0.47</b>	1969/70	2019/20	Opole	0.26	0.40	1984/85	1989/90
Toruń	<b>0.46</b>	<b>0.47</b>	1969/70	2019/20	Kłodzko	0.25	0.28	1984/85	2006/07
Gorzów Wielkopolski	<b>0.48</b>	<b>0.46</b>	1969/70	2019/20	Rzeszów	<b>0.54</b>	<b>0.40</b>	1984/85	2019/20
Płock	<b>0.45</b>	0.38	1969/70	2019/20	Kraków	0.35	<b>0.44</b>	1984/85	2019/20
Poznań	<b>0.49</b>	<b>0.43</b>	1969/70	2019/20	Racibórz	0.29	0.24	1969/70	2006/07
Ślubice	<b>0.49</b>	<b>0.41</b>	1969/70	2019/20	Tarnów	<b>0.38</b>	<b>0.45</b>	1984/85	2006/07
Siedlce	<b>0.54</b>	<b>0.44</b>	1969/70	2019/20	Bielsko-Biała	<b>0.38</b>	0.35	1984/85	2013/14
Warszawa	<b>0.52</b>	<b>0.48</b>	1969/70	2019/20	Lesko	<b>0.38</b>	0.16	1984/85	2013/14
Terespol	<u><b>0.61</b></u>	<b>0.50</b>	1984/85	2019/20	Zakopane	<b>0.35</b>	<b>0.34</b>	1984/85	1989/90
Zielona Góra	<b>0.38</b>	<b>0.39</b>	1969/70	2019/20	Kasprowy Wierch	0.19	0.23	1984/85	2019/20

**bold**— $p < 0.05$ , **bold and underlined**— $p < 0.01$ , **bold and \***— $p < 0.001$ .

The warmest winter in the analyzed multiannual period was recorded in season 2019/20. It broke a record in 31 out of 40 stations (Table 1). Mean Tmax for the season was 5.6 °C for the entire area. Except for mountain areas, the lowest mean Tmax was recorded in the north-east and east of the country, and highest in the south-west and west (Figure 2). In particular stations, mean Tmax values varied from 4.1 °C in Suwałki to 7.8 °C in Wrocław. Mean Tmax below 0 °C was only recorded in high mountain stations. It was −1.3 °C on Kasprowy Wierch and −0.3 °C on Śnieżka. Mean Tmax in the analyzed season was higher than average from the multiannual period from 3 °C in Lesko and Zakopane to 4.9 °C in Suwałki.

Different thermal conditions developed in particular months of the winter season. In a large majority of stations, the lowest values of mean monthly Tmin were recorded in the first half of the analyzed period. The highest mean monthly Tmax was observed in seasons in the last two decades, and season 1989/90. In December, the lowest mean monthly Tmin in the majority of stations (in 33 out of 40 stations) occurred in winter 1969/70, and varied from −13.8 °C in Suwałki to −5.7 °C in Hel. The highest mean monthly Tmax for that month over the study area (in 34 out of 40 stations) was recorded in season 2015/16, with values from 4.7 °C in Suwałki to 9.8 °C in Wrocław. In mountain stations, thermal

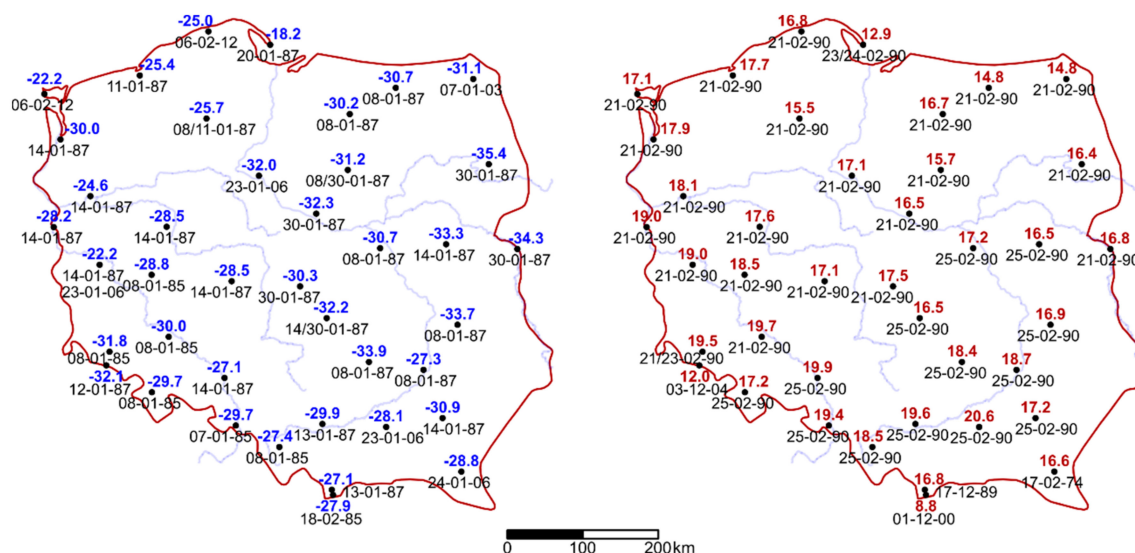
conditions developed at a level of  $-0.9^{\circ}\text{C}$  on Kasprowy Wierch and  $2.8^{\circ}\text{C}$  on Śnieżka. In January, in as many as 39 stations, the lowest mean monthly Tmin was recorded in season 1986/87, varying from  $-20.4^{\circ}\text{C}$  in Białystok to  $-9^{\circ}\text{C}$  in Świnoujście. Below  $-20^{\circ}\text{C}$  was also recorded in other stations of eastern Poland, i.e., in Suwałki and Terespol. Except for mountain stations, the highest mean monthly Tmax was recorded in season 2006/07. Its value varied from  $3.5^{\circ}\text{C}$  in Suwałki to  $8.1^{\circ}\text{C}$  in Słubice. In the aforementioned mountain stations, thermal conditions fluctuated around  $-2.6^{\circ}\text{C}$  on Kasprowy Wierch and  $-2^{\circ}\text{C}$  on Śnieżka. In the last month of the winter season, i.e., in February, the lowest monthly Tmin in the majority of stations (in 30 out of 40 stations) was recorded in winter 1985/86. It varied from  $-16.5^{\circ}\text{C}$  in Suwałki to  $-8^{\circ}\text{C}$  in Hel. Moreover, in nine stations located in south-eastern Poland, the lowest mean monthly Tmin was recorded in winter 1984/85. The highest mean monthly Tmax primarily occurred in season 1989/90, and varied from  $6.7^{\circ}\text{C}$  in Suwałki to  $11.5^{\circ}\text{C}$  in Słubice. Lower values were observed in mountain stations, i.e.,  $-1.1^{\circ}\text{C}$  on Kasprowy Wierch and  $0.9^{\circ}\text{C}$  on Śnieżka.



**Figure 3.** Course of mean Tmin (blue line) and Tmax (red line) in winter in the years 1966/67–2019/20 with rate of changes.

In the analyzed years, the lowest daily Tmin occurred mainly in January, and the highest daily Tmax in the second half of February or at the beginning of December. The lowest daily Tmin over the major area (particularly in the eastern and central regions of the country) was  $\leq -30^{\circ}\text{C}$  (Figure 4). In particular stations, the absolute minimum Tmin varied from  $-35.4^{\circ}\text{C}$  in Białystok to  $-18.2^{\circ}\text{C}$  in Hel. In the majority of stations, the values were recorded in season 1986/87 (particularly on 14.01 and 08.01) and 1984/85 (particularly on 8.01). The highest daily Tmax reached  $>20^{\circ}\text{C}$  in Tarnów ( $20.6^{\circ}\text{C}$ ; 25.02.1990). In a

large majority of stations, the highest values were recorded in winter season 1989/90. As evidenced above, in many stations that season was the warmest in the analyzed 54-year period. The above data suggest that the range of air temperature fluctuations in the winter season in Poland was 56 °C, and in particular stations it varied from 31.1 °C in Hel to 52.3 °C in Kielce. A decrease in the range of fluctuations occurred from the east to the west and north of the country.



**Figure 4.** Lowest daily Tmin (**left map**) and highest daily Tmax (**right map**) in winter in the years 1966/67–2019/20.

### 3.2. Snow Cover

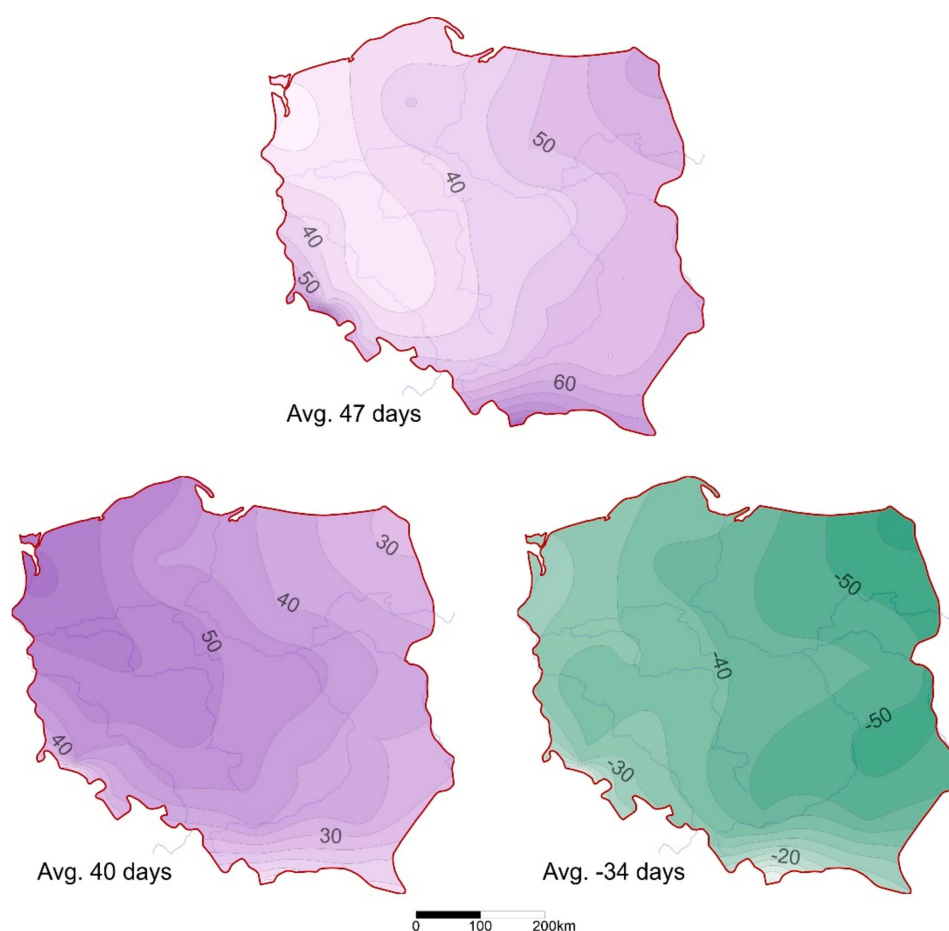
In Poland, the number of days with snow cover recorded during three winter months in the years 1966/67–2019/20 varied from 25 days in the north-west (Szczecin) to 62 days in the north-east (Suwałki) and 88–90 days in the mountains (Figure 5). In the Tatra Mountains (Kasprowy Wierch), scarce days with no snow cover were only recorded in the beginning of December. In the Sudetes (Śnieżka), days with no snow cover were more numerous, and occurred in December and in the beginning of January. In lowland areas, the western part of the country remained considerably less snowy (less than 40 days with snow cover) than the eastern part, where an average number of days with snow cover exceeded 50. The permanence of snow cover largely depends on temperature, particularly the transition through 0 °C. Therefore, maps of snow cover largely reflect the distribution of mean temperature of winter months.

A similar spatial distribution is characteristic of mean snow cover depth, and the lowest (below 6 cm) mean values for three winter months were observed in the western part of Poland (Figure 6). In lowlands, snow cover reached the highest average long-term depth in the eastern frontiers (>10 cm), and more than 14 cm in Suwałki. These values are hardly impressive in comparison to mean snow cover thickness in the mountains, where an average of 72 cm (Śnieżka) and 93 cm is recorded (Kasprowy Wierch).

Like thermal conditions, the snowiness of winters are characterized by high variability and are subject to strong fluctuations from season to season (Figure 7). In the analyzed multiannual period, thermally extreme winters also proved extremely snowy, and in almost all stations (with the exception of Bielsko Biala), season 1969/70 was characterized by the highest number of days with snow cover. In this season, snow cover persisted throughout the winter in Poland resulting in positive anomalies of snow cover duration from 30 days in the east to more than 60 days in the west of Poland (Figure 5). Season 1969/70 also stood out in terms of snow cover depth. This parameter showed the highest deviations in the north-east, where snow cover was more than 25 cm thicker than on average (Figure 6).



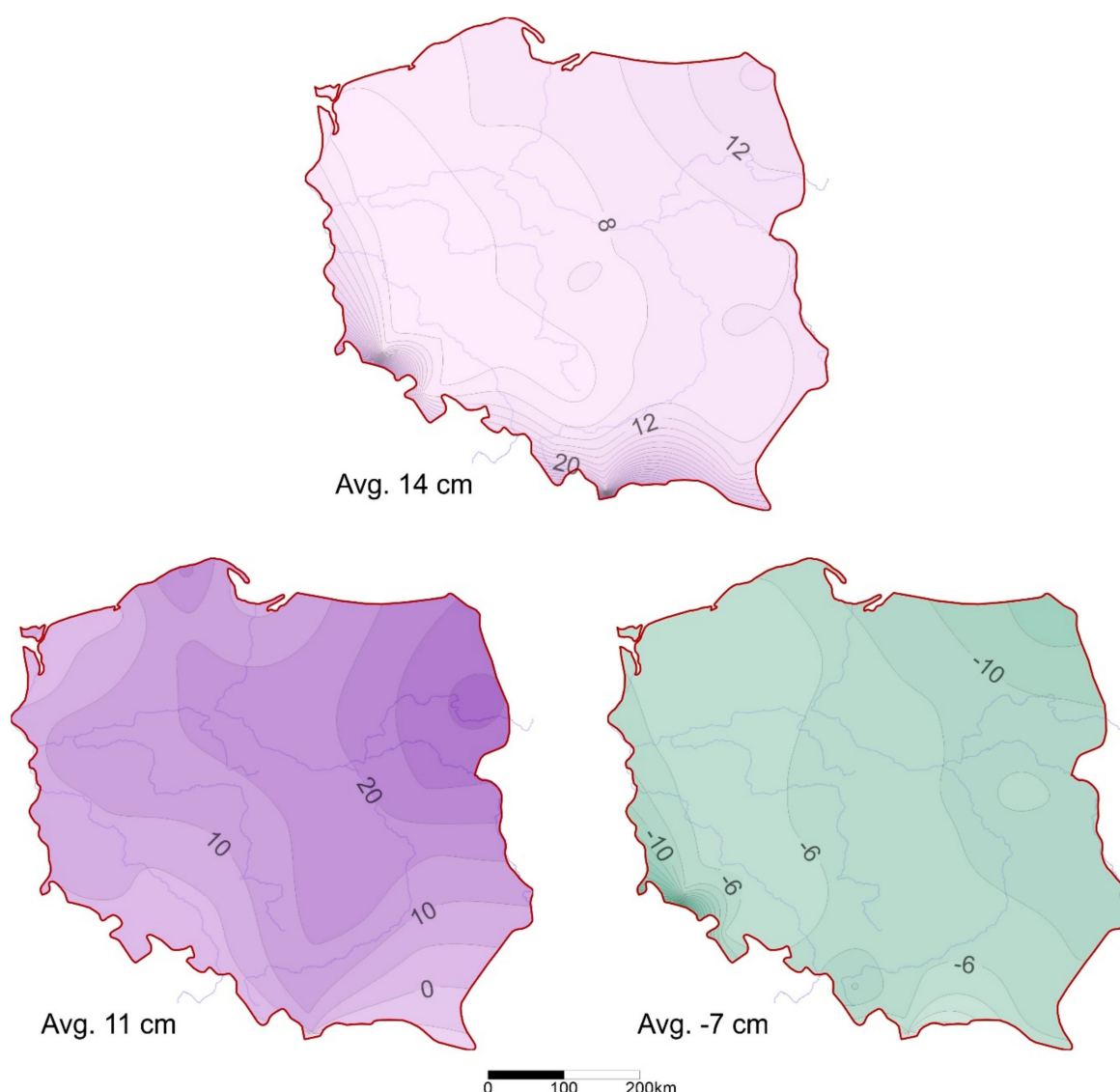
In the south of Poland (Kasprowy Wierch, Lesko, Śnieżka), in winter months of season 1969/70, considerably lower snow cover depth was recorded.



**Figure 5.** Mean winter number of days with snow cover averaged for winters 1966/1967–2019/2020 (**top**). Anomalies of number of days in extreme winters 1969/1970 (**bottom left**) and 2019/2020 (**bottom right**).

During the warmest winter, namely the last winter of the study period, i.e., 2019/20, at 14 stations, primarily in the west and center of Poland, snow cover did not occur at all, and in the east and in the mountains, snow cover persisting shorter than usual was considerably thinner than usual (Figure 6).

An increase in temperature in winter months in the moderately climate zone is related to the transition of temperature through the value of 0 °C, considerably affecting the formation and permanence of snow cover. Due to a considerable increase in temperature in winters recorded in the analyzed period 1966/1967–2019/2020, in the majority of stations (19 out of 31), a statistically significant decrease in the number of days with snow cover was determined, progressing at a rate from 3.5 to 4.9 days/10 years (Table 2). In areas with the most abundant snow cover and lowest temperature, i.e., in the cold and snowy east of Poland and in the mountains and submontane areas, the trends were negative, but statistically non-significant. The trend proved positive only on Śnieżka (Sudetes), and was approximate to zero. Only in three stations: Suwałki and Siedlce in the north-east and Łeba in the north, a statistically significant decrease in the depth of snow cover was recorded. Over the remaining area, the trend was negative (with the exception of Kasprowy Wierch), but statistically non-significant.

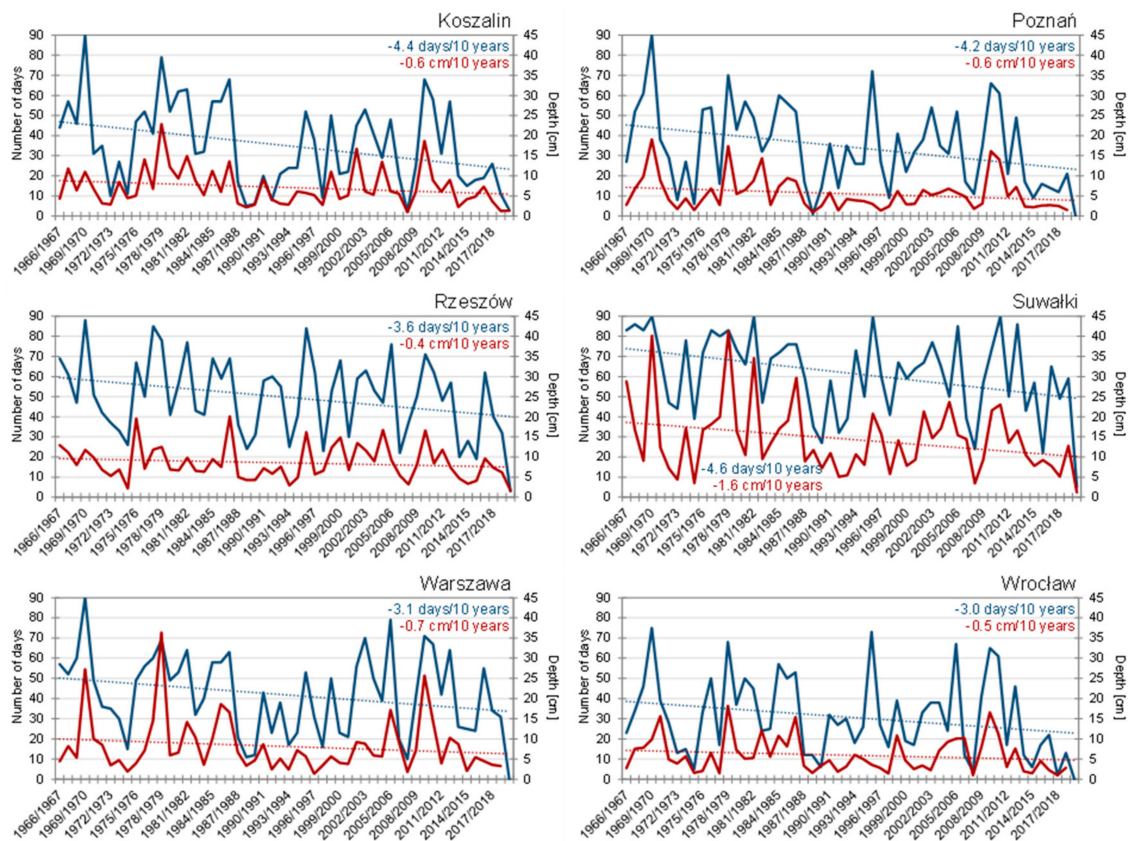


**Figure 6.** Mean snow cover depth averaged for winters 1966/1967–2019/2020 (**top**). Anomalies in mean snow cover depth in extreme winters 1969/1970 (**bottom left**) and 2019/2020 (**bottom right**).

### 3.3. Effect of Circulation Conditions

In the analyzed years, mean value of the NAO index in winter varied from  $-1.7$  in season 2009/10 to  $1.7$  in season 2014/15. In the case of SCAND, its values varied from  $-1.1$  in season 1988/89 to  $1.6$  in season 1971/72. The analyzed multiannual period showed an increase in the values of NAO index and a decrease in SCAND index. The recorded changes were statistically significant only in the case of NAO. During the coldest winter (1969/70), NAO index value was  $-0.38$ , and SCAND index  $0.53$ . During the warmest winter (2019/20), the values of the analyzed indices were  $1.27$  and  $-0.80$ , respectively.

The research in the analyzed area (except for the station on Kasprowy Wierch and in Lesko in the case of  $T_{min}$  and SCAND, and in Lesko in the case of  $T_{max}$  and SCAND) showed statistically significant correlations between thermal conditions in winter in Poland and selected teleconnection patterns, namely, NAO and SCAND. The effect of these circulation types showed spatial variability, and decreased from the north to the south of the country. In the case of NAO, the correlation coefficient  $r$  was positive, and ranged at a similar level both for  $T_{min}$  (mean  $0.62$ ) and  $T_{max}$  (mean  $0.63$ ). In the case of SCAND, correlation coefficient  $r$  was negative, and stronger for  $T_{min}$  (mean  $-0.44$ ).



**Figure 7.** Course of the number of days with snow cover (**blue**) and mean thickness of snow cover (**red**) in winter in the years 1966/67–2019/20 with rate of changes.

**Table 2.** Variability of snow cover duration and mean depth for winter months in seasons 1966/67–2019/20. Stations are arranged in spatial order from the north to the south.

Station	Change in Duration [days/10 years]	Change in Depth [cm/10 years]	Most Snowy Season	Least Snowy Season	Station	Change in Duration [days/10 years]	Change in Depth [cm/10 years]	Most Snowy Season	Least Snowy Season
Łeba	−3.9	−1.4	1969/1970	2019/2020	Kalisz	−4.9	−0.7	1969/1970	2019/2020
Hel	−4.0	−0.6	1969/1970 1981/1982	2019/2020	Łódź	−4.6	−0.7	1969/1970	2019/2020
Koszalin	−4.4	−0.6	1969/1970	2007/2008	Lublin	−3.5	−0.4	1969/1970 1981/1982	2019/2020
Suwałki	−4.6	−1.6	4 seasons *	2019/2020	Wrocław	−3.0	−0.5	1969/1970	2019/2020
Świnoujście	−4.3	−0.4	1969/1970	2019/2020	Jelenia Góra	−1.8	−0.3	1969/1970	2006/2007
Chojnice	−4.6	−1.0	1969/1970	2019/2020	Kielce	−4.2	−0.5	1969/1970	2019/2020
Szczecin	−4.2	−0.5	1969/1970	1988/1989 2019/2020	Śnieżka	0.0	−0.7	37 seasons *	1967/1968
Białystok	−4.2	−1.4	1969/1970	2019/2020	Opole	−2.8	−0.2	1969/1970	2019/2020
Mława	−3.2	−0.2	1969/1970	2019/2020	Kłodzko	−1.7	−0.2	1969/1970	2013/2014

Table 2. Cont.

Station	Change in Duration [days/10 years]	Change in Depth [cm/10 years]	Most Snowy Season	Least Snowy Season	Station	Change in Duration [days/10 years]	Change in Depth [cm/10 years]	Most Snowy Season	Least Snowy Season
Toruń	<b>−4.1</b>	−0.3		2019/2020	Rzeszów	<b>−3.6</b>	−0.4	1969/1970	2019/2020
Gorzów Wielkopolski	<b>−4.1</b>	−0.5	1969/1970	2019/2020	Kraków	<b>−3.5</b>		1969/1970, 1995/1006	2019/2020
Poznań	−4.2	−0.6	1969/1970	2019/2020	Bielsko-Biała	<b>−3.5</b>	−0.1	2005/2006	2013/2014
Siedlce	−3.1	<b>−1.5</b>	1969/1970	2019/2020	Lesko	−1.3		1966/1967	2006/2007
Warszawa	−3.1	−0.7	1969/1970	2019/2020	Zakopane	−1.6	−0.8	10 seasons *	2015/2016
Terespol	−2.9	−0.8	1969/1970	2019/2020	Kasprowy Wierch	−0.1	0.1	49 seasons *	2000/2001
Zielona Góra	<b>−4.0</b>	−0.4	1969/1970	2019/2020					

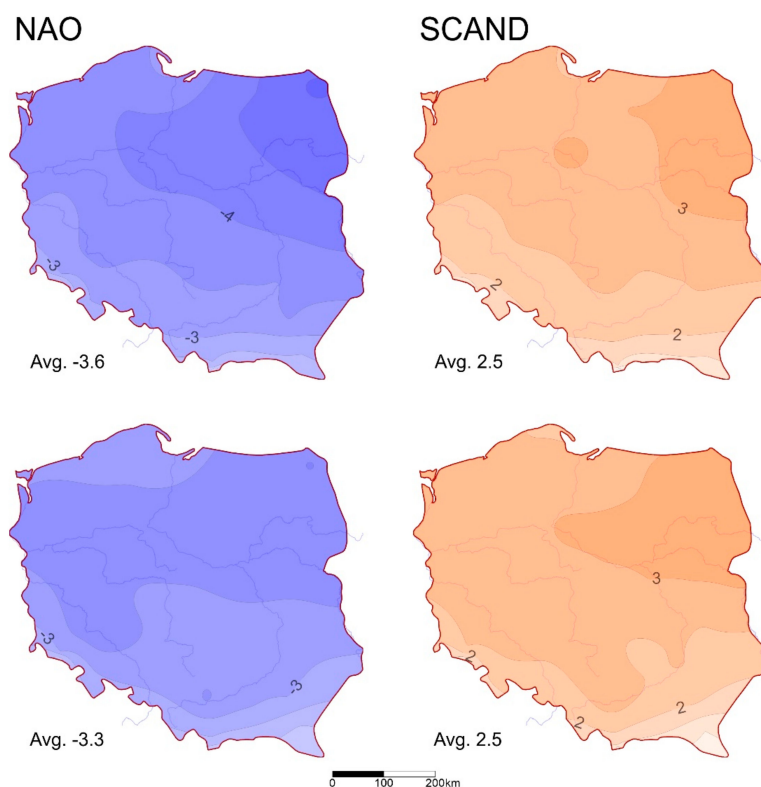
**bold**— $p < 0.05$ ; **bold and underlined**— $p < 0.01$ ; \* more than one season (including 1969/1970).

In the negative NAO phase,  $T_{min}$  and  $T_{max}$  were lower than in the positive phase (Figure 8). The greatest differences were recorded in north-eastern Poland, and decreased southwards. In particular stations, the differences varied from 1.2 °C for  $T_{min}$  and 1.6 °C for  $T_{max}$  on Kasprowy Wierch to 5 °C for  $T_{min}$  and 4 °C for  $T_{max}$  w Suwałki. Differences in  $T_{min}$  and  $T_{max}$  in the positive and negative NAO phase were statistically significant, in more than 92% of stations at a level of 0.001.

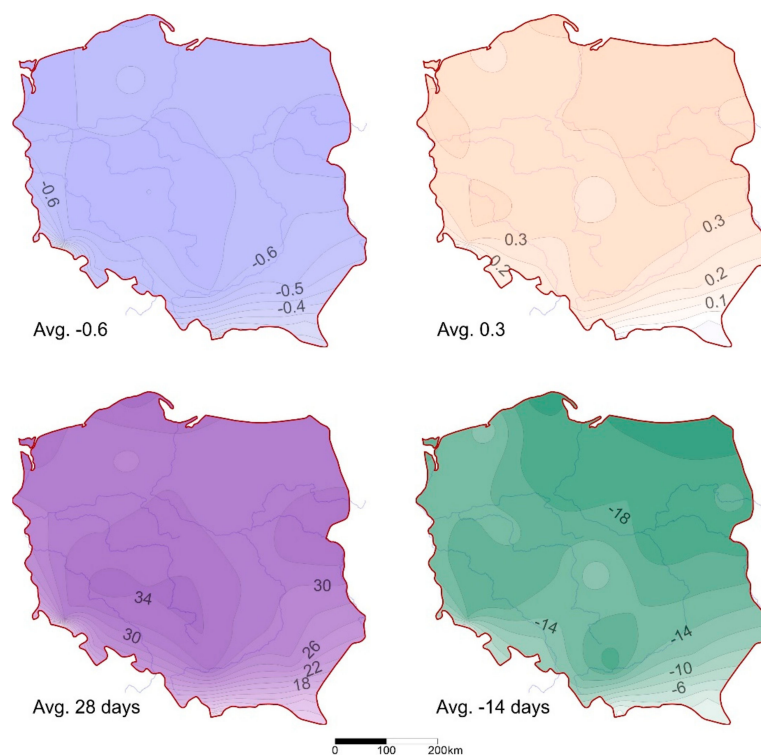
Similarly in the case of SCAND, different thermal conditions were recorded in the negative and positive phase of the pattern. In the negative phase, higher  $T_{min}$  and  $T_{max}$  was recorded than in the positive phase (Figure 8). Like in the case of NAO, the differences decreased from the north-east towards the south of the country, and varied from 0.2 °C on Kasprowy Wierch to 3.3 °C in Białystok for  $T_{min}$  and from 0.9 °C on Kasprowy Wierch to 3.1 °C in Białystok, Kętrzyn, Mława, Terespol, and Toruń for  $T_{max}$ . Apart from four stations (Kasprowy Wierch, Lesko, Śnieżka, Zakopane), in the case of  $T_{min}$  and three stations (Kasprowy Wierch, Lesko, Śnieżka) for  $T_{max}$ , differences in air temperature between SCAND phases were statistically significant. A higher level of statistical significance was determined for  $T_{max}$ .

A strong dependency on the pressure field over the Euro-Atlantic sector and on the direction of advection of air masses is characteristic for snow cover duration. The correlation of the number of days with snow cover during three winter months and indices of two teleconnection patterns over the majority of the territory of Poland is statistically significant (Figure 9). The correlation with NAO index is negative, and equals  $< -0.6$ , with the exception of mountain and submontane stations (Śnieżka, Kasprowy Wierch, and Zakopane), where the correlation coefficient  $r$  was approximate to zero and statistically non-significant. Such a dependency translates into the occurrence of statistically significant at a level of 0.001 (with the exception of mountain stations) differences in the duration of snow cover in the positive and negative NAO phase. In the negative phase which—as evidenced—favors temperature decrease, over 30 more days with snow cover are recorded than in the positive phase, both in the east of Poland and in the less snowy west. The effect of NAO considerably weakens in submontane regions, where the difference in snow cover duration in the positive and negative phase does not exceed 15 days.





**Figure 8.** Difference in Tmin (**top maps**) and Tmax (**bottom maps**) between the negative and positive phase of teleconnection patterns.



**Figure 9.** Correlation between the number of days with snow cover and North Atlantic Oscillation (NAO)/Scandinavian pattern (SCAND) winter indices (**upper row**), and difference in snow cover duration between the negative and positive phase of NAO/SCAND (**lower row**).

The SCAND pattern has a weaker effect on the snowiness of winters in Poland, and the correlation coefficient  $r$  of the SCAND index with the number of days with snow cover in lowland areas is 0.3–0.35 (Figure 9). The coefficient  $r$  is lower and statistically non-significant in mountain and submontane stations, where it decreased to values approximate to zero. In the positive SCAND phase, a higher number of days with snow cover is therefore observed, particularly in the north-east, where snow is recorded 21 days longer than in the negative phase. In western and central Poland, snow persists more than two weeks longer in the positive SCAND phase. Differences in the duration of snow cover are statistically significant in more than 56% of stations at a level of 0.05. Like in the case of NAO, the smallest difference in the duration of snow cover between the positive and negative SCAND phase is recorded in the south, where it only persists for several days.

#### 4. Discussion and Summary

The study showed an increase in both  $T_{min}$  and  $T_{max}$  in winter. It was statistically significant over a majority of the country. The greatest changes were recorded in north-eastern and northern regions. The obtained results confirm earlier studies conducted throughout the country [11] as well as in selected regions [52,62,63]. In the majority of stations, the recorded changes in  $T_{min}$  were more considerable than changes in  $T_{max}$ , particularly in the east of the country. A more intensive increase in  $T_{min}$  in comparison to  $T_{max}$  has also been pointed to by other authors, e.g., [11,64–67]. Forecasted changes in  $T_{min}$  are generally more coherent in all models than for  $T_{max}$  [65]. The authors explain it with the fact that changes in  $T_{min}$  are weakly correlated with changes in cloudiness. A consequence of the progressing increase in air temperature is a decrease in the frequency of cold waves [16,68] with a simultaneous increase in the frequency of warm waves in winter [15]. Another effect of the observed warming is a delay of the beginning and earlier end of thermal winter, and consequently a reduction of its duration [69,70].

The coldest winters were recorded in the first half of the analyzed multiannual period. Exceptionally cold winters deserve particular attention, i.e., 1969/70 and 1984/85. As found earlier [71], it was also a period with frequently occurring cold waves. One of the most intensive cold waves occurred in 1987 [71,72], i.e., outside of the two coldest seasons. During that wave, in many stations of central Europe, the lowest  $T_{max}$  of cold waves to date was recorded [68]. The warmest winters occurred in the second half of the analyzed period. Among seasons with the highest mean  $T_{max}$ , particularly winters 2019/20 and 1989/90 stood out. Analysis of the long-term research from Poznań [63] and Toruń [62] reaffirms that season 2019/20 was the warmest at least since the second half of the 19th century. During the second of the aforementioned seasons, in the majority of stations, absolute maximums of  $T_{max}$  were recorded not only in Poland, but also in other regions of central Europe [15]. The most important negative effect of occurrence of warm winters is a reduction of the duration and thickness of snow cover [18].

The increasing temperature of winter months in Poland is associated with significant changes in the occurrence of snow cover. In addition to its seasonal and multiannual variability, significant decreasing trends in snow cover duration have been found in the majority of stations in Poland, which confirm earlier results [35,37,38,73]. However, the trends in snow cover duration computed for the contemporary period (until 2019/2020) are stronger than the for the older periods (until 1998 [35] and until 2013 [38]), when a negative trend of snow cover duration was statistically significant at only a few stations [38] or even not significant at all with exception of mountain stations [35]. A further progression of the negative change in snow cover occurrence in Poland is projected for both the near (2021–2050) and far (2071–2100) future [39]. Trends in the snow cover duration in Poland are congruous to tendencies recognized over the entire Northern Hemisphere, where the duration of the snow season has declined by five days per decade since the early 1970s [31]. It should be emphasized that since the 1980s the rate of changes increased in Poland, as well as in many other regions of Europe, while the greatest changes have been observed in the Arctic [74].

Less significant negative trends were obtained for the changes in the depth of snow cover depth in Poland, which was reaffirmed in the previous studies [35,37,38]. While snow cover duration is strongly related to temperature, the amount of snow translating to the depth of the snow layer is reliant to the amount of precipitation coming in the form of snowfall. This explains the different rate of changes in snow cover depth and duration, which is particularly apparent in higher latitudes, as documented for Northern Eurasia [22]. Fontrodona Bach et al. [25] found decreases in maximum and mean snow depth over Europe, except in the coldest climates, however, mean snow depth generally decreases stronger than maximum seasonal snow depth.

In general, a decrease in snow cover depth was determined at lower, and an increase at higher altitudes in southern Poland. The same relationship was found in Norway [75]. In the case of stations at high altitudes, lack or only slight changes in snow depth in mid-winter were recorded in the Swiss Alps, and negative tendencies were more evident in the case of stations at medium and low altitudes [76–78]. The same pattern was determined in the Romanian Carpathians [79] and Russia [80]. Some signals of a decrease in annual maximum snow depth in high altitudes were recorded in Swiss Alps [81].

The study showed a strong correlation of winter temperature and snow conditions with atmospheric circulation. This confirms earlier studies pointing to the main role of atmospheric circulation in shaping weather and climatic conditions at moderate latitudes [82,83]. Over a major study area, statistically significant correlations were determined between air temperature in winter and selected teleconnection patterns. The strength of the correlations decreased from the north to the south of the country. Among the selected circulation types, the North Atlantic Oscillation affected the thermal conditions the strongest. Among four circulation types affecting the weather and climate of central Europe [84], NAO and SCAND have the strongest effect in Poland [51,52,85]. In the negative NAO phase and positive SCAND phase, lower temperature was recorded in comparison to the positive and negative phase, respectively, and differences in air temperature over the major area were statistically significant. The occurrence of the negative NAO phase or positive SCAND phase is also related to longer duration of ice cover on lakes [57,86]. Deviations from the mean value in the case of NAO reach >30 days, and in the case of SCAND >20 days. The correlations of different conditions of warm Europe/cold Arctic, increasingly stronger since 1998, are also important. It was found earlier [87] that a decrease in temperature in winter in Europe is related to the negative NAO phase and positive SCAND phase, and higher temperature in the period is determined by opposite phases of these circulation types.

The study showed that, just like for temperature, NAO has a stronger effect on the snowiness of winters in Poland than SCAND. The effect of both circulation patterns shows spatial variability in Poland, confirming results obtained in other European regions for the Swiss Alps [78] or for Germany [88]. In the Romanian Carpathians, negative and weak correlations between the number of days with snow cover, particularly in the period from December to March, and seasonal values of the NAO index were determined [79]. High accumulation of snow during the occurrence of NAO was also found in Bulgaria [89]. In Poland the positive NAO phase is related to less snowy winters, and the negative phase to an increase in the probability of occurrence of a more snowy winter, and the difference in the number of days with snow cover in the positive and negative phase exceeds 30 days in the majority of stations, with the correlation coefficient amounting to  $<-0.6$ . A strong negative correlation between NAO and the number of days with snow cover in Poland was determined earlier, e.g., [38,48,50]. Snow cover in Poland is additionally correlated with NAO in October before the winter season [50]. This study showed that the SCAND pattern has a weaker effect on the snowiness of winters in Poland than NAO. Due to lower temperature, the positive SCAND phase causes a higher number of days with snow cover in Poland in comparison to the negative phase and the difference in the number of days in positive and negative phase amounts to a dozen or so, hardly exceeding 20 days in the northeast. However, it is different in other regions of Europe and years with low snow accumulation in Bulgaria [89] are related to the positive SCAND phase, because it caused

warming in autumn, a delay of the beginning of the snow cover season, and a decrease in winter precipitation.

In Poland, both  $T_{min}$  and  $T_{max}$  increased in the winter period, although changes in  $T_{min}$  were more considerable. Significant temperature changes are associated with declining snow cover, and extremely warm winters occurring most frequently in recent years proved to be also least snowy. This complies with global warming trends, which is most pronounced in the Northern Hemisphere terrestrial regions. However, winter weather conditions are also strongly influenced by the macroscale circulation, which is responsible for a great in-seasonal and multiannual variability of thermal conditions and snowiness and may partly disrupt the monotony of the contemporary warming trend.

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