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RESEARCH ARTICLE

Changes of snow cover in Poland

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Abstract The present paper examines variability of characteristics of snow cover (snow cover depth, number of days with snow cover and dates of beginning and end of snow cover) in Poland. The study makes use of a set of 43 long time series of observation records from the stations in Poland, from 1952 to 2013. To describe temporal changes in snow cover characteristics, the intervals of 1952–1990 and of 1991–2013 are compared and trends in analysed data are sought (e.g., using the Mann–Kendall test). Observed behaviour of time series of snow-related variables is complex and not easy to interpret, for instance because of the location of the research area in the zone of transitional moderate climate, where strong variability of climate events is one of the main attributes. A statistical link between the North Atlantic Oscillation (NAO) index and the snow cover depth, as well as the number of snow cover days is found.

Keywords Snow cover depth · Snowy season · Variability · NAO index · Poland

Introduction

Unequivocal warming of the global climate system is now evident from observations of increases in air temperatures at various spatial scales, from local to national, regional, continental, hemispheric, and global (Kundzewicz and Huang 2010; Stanisławska et al. 2013; IPCC 2013). Almost the entire globe has experienced surface warming. Many of the observed changes have been unprecedented over the time scales of decades to millennia. The globally averaged combined land and ocean surface temperature data show a warming of 0.85 (0.65–1.06) °C, over the period 1880–2012, when multiple independently produced datasets exist (IPCC 2013). Each of the sixteen years of the 21st century, 2001–2016, belongs to a set of seventeen globally warmest years on record. Global temperature changes are accompanied, expectedly, by changes in other environmental elements, e.g., the sea level or the state of the cryosphere.

The air temperature is only one of several climate elements and factors influencing snow cover. Other factors include: atmospheric circulation, precipitation phase and amount, wind speed, solar radiation, sunshine, etc. Snow cover plays a key role in environmental and socio-economic systems. It is regarded as a crucial component of the global climatic system in relation to the role in modifying the transfer of energy and water vapour between the surface of the Earth and the atmosphere (Brown and Goodison 1996). From the climatological point of view, snow cover functions as a thermal insulation between the atmosphere and the ground, thus lowering cold extremes of temperature of the ground surface. Its occurrence is of essential importance for water resources (via snow water contents). By acting as a seasonal reservoir of water, snow likewise strongly alters the hydrological cycle. Earlier snow melting in winter or spring causes ground to dry earlier, increasing the likelihood of drought in summer (Jaagus 1997). Snowmelt plays an important role in hydrological (and river) regime. The hydrological regime is closely related to seasonal changes in climate. In Poland, rainfall amount and

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evaporation are controlling factors of the hydrological regime in a warmer part of the year, while precipitation (snowfall and rainfall) and air temperature are the essential factors in a colder part of the year. Hence, the dynamics of the cryosphere in the snowmelt-fed river catchments are of crucial importance for water resources management. Snow cover may also influence many human activities, e.g., agriculture, energy production or transport. Thus, snow cover decides on hibernating conditions of winter crops, protecting them from frost damage during the winter months. Hydro-power and energy supply are largely dependent on, and sensitive to, changes in snow amount and duration. Heavy snowfall (and, as a result, deep snow cover) tends to cause traffic hazards and communication problems. Finally, snow cover is important in sports and recreation (skiing, sledging, walking), aesthetics, and tradition.

It seems to be of much interest to examine long time series of national observation records, wherever available, to look for changes. Snow cover in Poland, similarly to other countries located in central European lowlands, is dominated by strong inter-winter and intra-winter variability. Year-to-year variability of snow cover reflects well the overall winter climatic variability. The variability throughout the season may be represented by cold periods alternating with the mild ones and by the short- or long-lasting snow cover (Bednorz 2013; Falarz 2004). Other research studies also report large variability between individual seasons, and the lack of distinct, statistically significant trends in snow cover depth (Brown and Petkova 2007; Czarnecka 2012, etc.). Several authors, such as Falarz (2004), Nowosad and Bartoszek (2007) and Czarnecka (2012) spotted a slight decreasing trend of snow cover characteristics (number of days with snow cover, depth of snow cover, occurrence frequency) in Poland during the second half of the 20th century, but no change was distinguished for a longer period. Some authors noted a tendency of gathering of snow-poor winters (e.g., Jaagus 1997; Niedźwiecki 1998) and reported about winters with particularly abundant snow cover (e.g., 1970, 1979, 2010) and outstandingly snowless (e.g., 1949, 1930, 2008), cf. Hejduk and Hejduk (2014). In general, the Northern Hemisphere spring snow cover has decreased in extent (IPCC 2013).

There have been several recent publications indicating a North Atlantic Oscillation (NAO) track in snow cover records. However, these studies analyze the connections of the NAO with different specific characteristics of the snow cover, e.g., the number of days with snow cover (e.g., Bednorz 2002), the depth of snow cover or the date of disappearance of the snow (Hori and Yasunari 2003). The study areas of these research works are different, like a part of Poland (e.g., Bednorz 2002), the whole of Poland (Czarnecka 2011) or a macro-region (e.g., western Eurasian continent in Hori and Yasunari 2003).

In general, the strong coupling of the NAO and snow extent during winter (especially in January and February) was confined to the area of Western Europe (Hori and Yasunari 2003). This connection becomes less significant towards the East (Gutzler and Rosen 1992; Clark et al. 1999; Bednorz 2004). The strong negative correlation for the number of days with snow cover in Poland was found (Bednorz 2002). The strongest connection of the NAO index vs depth of snow cover in Poland exists in January and in February (Czarnecka 2012). The NAO index can also explain the variability of dates of disappearance of the snow cover (Czarnecka 2011). During warmer winters, in the positive NAO phase, a large variability of the melt supply and earlier culminations of flows were noted by Wrzesiński (2010). This indicates decreasing number of days with snow cover.

The present paper examines the set of long time-series of snow cover characteristics in Poland based on daily values of snow cover depth at 43 meteorological stations in 1952–2013. The snow cover characteristics includes: snow cover depth, number (derived) of days with snow cover during winter (also in adjacent seasons: autumn and spring), and the dates of beginning and end of snow cover.

Data and methodology

Although instrumental temperature measurements in Polish lands, like in other European countries, started around the end of the 18th century, due to historical reasons (armed conflicts, long lasting lack of independent state, and major changes of national boundaries before 1945), records of good-quality daily meteorological data in Poland are shorter than in many European countries with more stable and less convoluted history. Polish Meteorological and Hydrological Service (the Institute of Meteorology and Water Management-National Research Institute, Polish acronym: IMGW-PIB) provided a time series of depth of snow cover records observed at meteorological stations in Poland. The basic criteria for selection of stations were: (1) the length of the available time series, and (2) the spatial distribution of stations with the goal of covering the whole territory of Poland and its climate regions, in a possibly uniform way.

In this study, daily depth of snow cover from 43 stations in Poland was analysed. The studied data started on 1 October 1951 (38 meteorological stations) or later (5 stations) and continued until 31 December 2013. The shorter series of observation data concern stations in: Rzeszów (data start in 1952), Nowy Sącz and Lesko (from 1954), Terespol (from 1955) and Leszno (the shortest time series, starting in 1958). The meteorological stations used in the present study are listed in Table 1 and mapped in Fig. 1.

Table 1 List of meteorological stations used in this work

Station	Latitude	Longitude	Elevation [m. a.s.l.]	Station	Latitude	Longitude	Elevation [m. a.s.l.]
Białystok	53°06′	23°10′	148	Olsztyn	53°46′	20°25′	133
Bielsko-Biała-Aleksandrowice	49°48′	19°00′	398	Opole	50°40′	17°58′	176
Częstochowa	50°49′	19°06′	295	Płock-Trzepowo	52°35′	19°44′	106
Elbląg-Milejewo	54°10′	19°26′	38	Poznań	52°25′	16°50′	86
Gorzów Wielkopolski	52°45′	15°17′	72	Racibórz-Studzienna	50°05′	18°13′	190
Hel	54°36′	18°49′	1	Rzeszów-Jasionka	50°06′	22°03′	200
Jelenia Góra	50°54′	15°48′	342	Sandomierz	50°42′	21°43′	217
Kalisz	51°44′	18°05′	140	Siedlce	52°11′	22°16′	146
Kasprowy Wierch	49°14′	19°59′	1991	Słubice	52°21′	14°36′	21
Katowice	50°29′	19°05′	317	Suwałki	54°08′	22°57′	184
Kielce-Suków	50°51′	20°37′	268	Szczecin-Dąbie	53°24′	14°37′	1
Kłodzko	50°26′	16°39′	316	Śnieżka	50°44′	15°44′	1603
Koło	52°12′	18°40′	116	Świnoujście	53°55′	14°14′	6
Koszalin	54°12′	16°09′	33	Tarnów	50°02′	20°59′	209
Kraków-Balice	50°05′	19°48′	237	Terespol	52°04′	23°37′	133
Legnica	51°13′	16°10′	122	Toruń	53°03′	18°35′	69
Lesko	49°28′	22°20′	386	Ustka	54°35′	16°52′	6
Leszno-Strzyżewice	51°50′	16°32′	91	Wieluń	51°13′	18°35′	195
Lublin-Radawiec	51°13′	22°24′	238	Wrocław	51°06′	16°53′	120
Łeba	54°45′	17°32′	2	Zakopane	49°18′	19°57′	857
Łódź-Lublinek	51°44′	18°24′	187	Zielona Góra	51°56′	15°30′	180
Nowy Sącz	49°37′	20°42′	292				

Fig. 1 Map of locations of meteorological stations used in this work

Based on time series of daily depth of snow cover records the following characteristics of snow cover were estimated:

- mean value of snow cover depth for every month of the cold half-year (from October to April) in cm;
- mean value of snow cover depth for winter (December–January–February) in cm;
- maximum value of snow cover depth for winter (December–January–February) in cm;
- number of days with snow cover during every winter (DJF) and mean number of days with snow cover during DJF;
- number of days with snow cover during snow season (from the beginning of October to the end of May);
- first day with snow cover during every winter and mean date of appearance of snow cover in winter season;
- last day with snow cover during winter and mean date of disappearance of snow cover in winter season;
- the Pearson correlation coefficient between the NAO index and analysed snow cover characteristics (snow cover depth and the number of days with snow cover).

In this paper, the link of the NAO index value with snow cover depth, as well as with the number of days with snow cover is analysed based on mean value of the NAO index for DJF and corresponding values of snow cover depth and the number of days with snow cover in DJF. This research

uses the North Atlantic Oscillation Index defined first by Barnston and Livezey (1987), worked up by Hurrell (1995). The NAO consists of a north–south dipole of anomalies, with one center located over Greenland and the other center of opposite sign spanning the central latitudes of the North Atlantic between 35° and 40°N. Data of the monthly NAO index for the 65-year period of 1950–2015 originate from the Climate Prediction Center (available at http://www.cpc.noaa.gov).

To describe temporal changes in snow cover characteristics, for every station:

- the intervals of 1952–1990 and of 1991–2013 were compared;
- the Mann–Kendall statistic was used;
- the rate of change per year for the whole analysed period was calculated.

To detect existing changes/trends in time series of snow cover data, the Hydrospect 2.0 software was used (Radziejewski and Kundzewicz 2000). Statistical significance of trend for every station at various levels was determined. The Hydrospect 2.0 software package allows changes in long time-series of hydrological records to be detected. Among the statistical tests available in the package the Mann–Kendall test was used in the research reported in this paper. Additionally, simple linear regression was used, that allows the user to find the slope of the linear trend and the significance level, if the records are independent and normally distributed (else, normalization is offered under the normal-scores regression test).

Apart from trend detection in the complete data records covering 1952–2013, differences between values of indices in two compared intervals, 1952–1990 and 1991–2013, were illustrated. There is a disproportion in the length between analysed periods (38 years vs 23 years). Moreover, after preliminary analysis, it turned out that characteristic of observed data changed considerably after 1990. Therefore, for the purposes of the present paper, the authors decided on such a division of time series.

To describe spatial variability of snow cover characteristics, IDRISI GIS platform was used. For spatial interpolation of the snow-related characteristics, the Kriging method was used. Authors are aware that ordinary Kriging may underestimate high values and overestimate low values in case when the purpose of interpolation is to delineate areas that exceed a threshold level of the predicted surface values, but it seemed to be an optimal predictor in this paper.

Strength of the relationship between the value of the NAO index and the depth of snow cover, and the number of days with snow cover was expressed by the R^2 value (the square of the Pearson correlation coefficient) of polynomial and linear regression, respectively.

Results

Snow cover depth

Mean snow cover during DJF

The mean depth of snow cover in winter (DJF) in 1952–2013 in Poland varies from 2.2 to 11.8 cm (except for mountain areas, where the depth of snow cover is considerably higher). The lowest mean depth of snow cover is characteristic for the western part of lowland Poland, while the highest-for the north-eastern part (Suwałki District)–Fig. 2.

Comparing the intervals 1952–1990 and 1991–2013, one can draw a conclusion that the former one was more snowy (in terms of mean depth of snow cover) in 38 out of 43 analysed stations (for spatial variability see Fig. 3a, b).

Figure 4 illustrates the time series of observed changes in mean depth of snow cover [cm] for the Toruń station for DJF, as an example. No significant trend on the 95% level was detected for most of the country, using statistic of Mann–Kendall. In general, after 1980, a cluster of years with small cover occurred (including a whole 20-year interval, 1988–2007, with mean winter snow cover depth below 5 cm). However, more snowy winters (with higher depth of mean snow cover) have also appeared more recently.

Spatial variability of temporal changes in mean depth of snow cover in winter (DJF) in 1952–2013 is presented in Fig. 5. It is presented as a slope of linear regression (rate of change per unit time–year), measured in mm/year. There is no distinct spatial pattern in this parameter; the value of change per year is positive in some locations, while negative in others. There are many more locations with
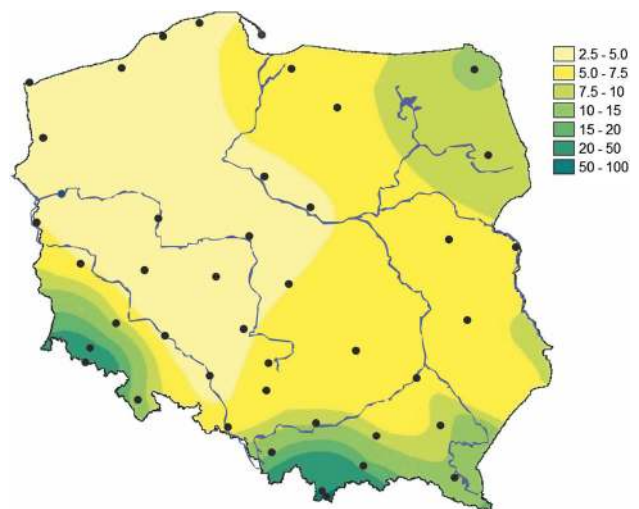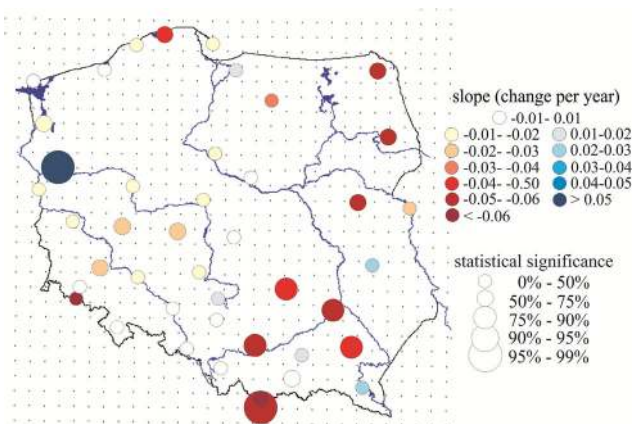

Fig. 2 The mean depth of snow cover [cm] in winter (DJF) in the period of 1952–2013 in Poland
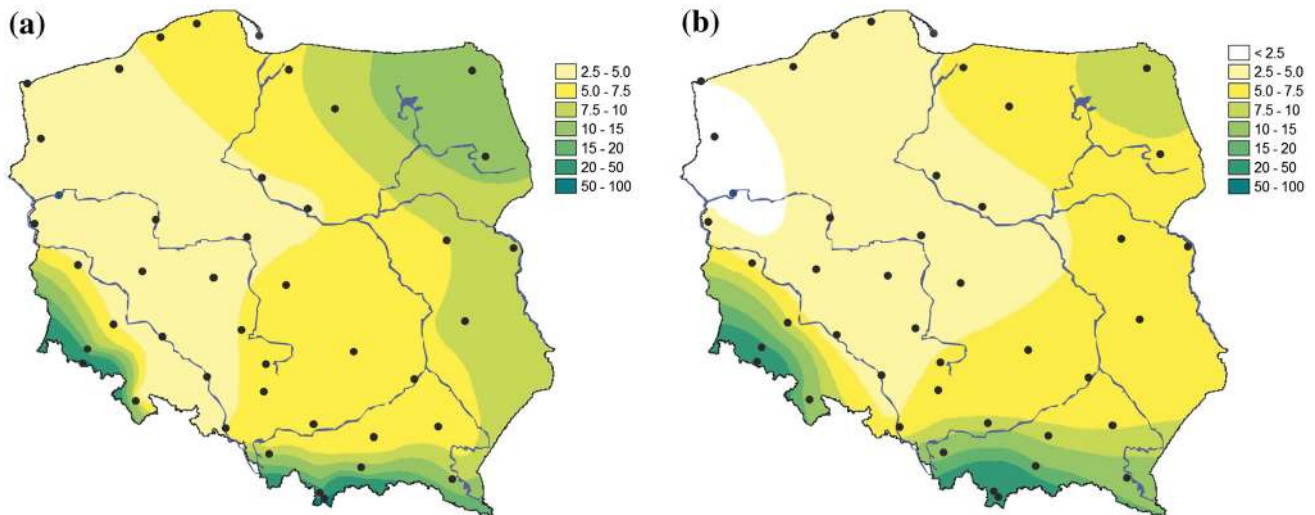
Fig. 3 The mean depth of snow cover [cm] in winter (DJF) in Poland in the intervals of (**a**) 1952–1990 and (**b**) 1991–2013
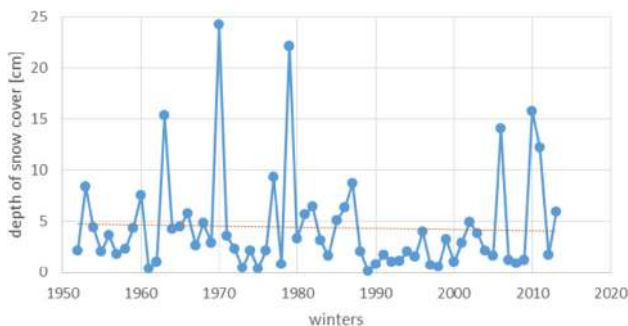
Fig. 4 Time series of mean depth of snow cover [cm] in DJF in Toruń (1952–2013). *Red line*–linear regression of time series

Fig. 5 Temporal changes in mean depth of snow cover in winter (DJF) in 1952–2013 expressed by the rate of change per year and the statistical significance. The values of change per year and statistical significance have been established with the help of the Hydrospect package, based on linear regression

negative values of slope than with positive values of slope. However, it seems that in the East, there are larger decreases of the mean depth of snow cover in the analysed

period. Nevertheless, great majority of these changes are not statistically significant at the level of 95% (Fig. 5).

NAO index vs mean depth of snow cover

The NAO index appears to be negatively correlated with the mean snow cover depth. So, for a positive value of the NAO index, there is a fairly high probability that the mean depth of snow cover would be below the multi-year mean. In contrast, for a negative value of the NAO index, there is a fairly high probability of snow cover depth exceeding the mean. This relationship gets weaker to the East of Poland. Figure 6 presents examples of different strength of relationship between the value of the NAO index and the depth of snow cover (Szczecin–an example of a stronger relation with $R^2 = 0.43$ and Rzeszów–an example of a weaker relation, $R^2 = 0.25$). At the end of this section, Fig. 7 illustrates strength of the relationship between the value of the NAO index and the mean depth of snow cover expressed by the R^2 value of non-linear (quadratic) regression for the entire area of Poland. In this figure, one can clearly note that the connection of the mean depth of snow cover with the NAO index decreases towards the East. Significance level of correlation coefficient for all the stations (excluding mountain ones) is on the level of 99%. For the mountain stations (Kasprowy Wierch, Zakopane, Śnieżka) a relation between the NAO index and mean depth of snow cover does not exist.

Maximum snow cover depth

The maximum depth of snow cover in winter (DJF) in 1952–2013 in Poland varies from 34 cm in Poznań and Słubice to 85 cm in Kraków (while in mountain areas
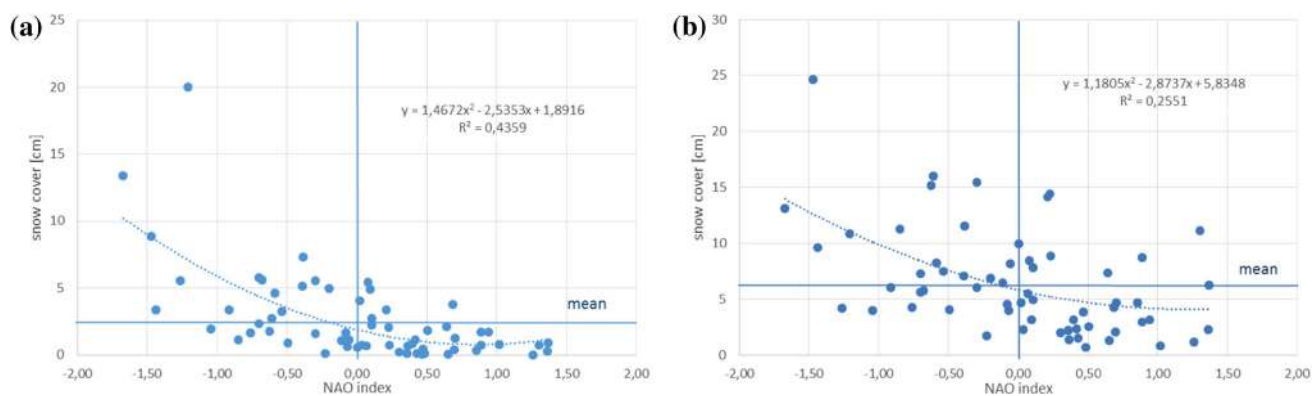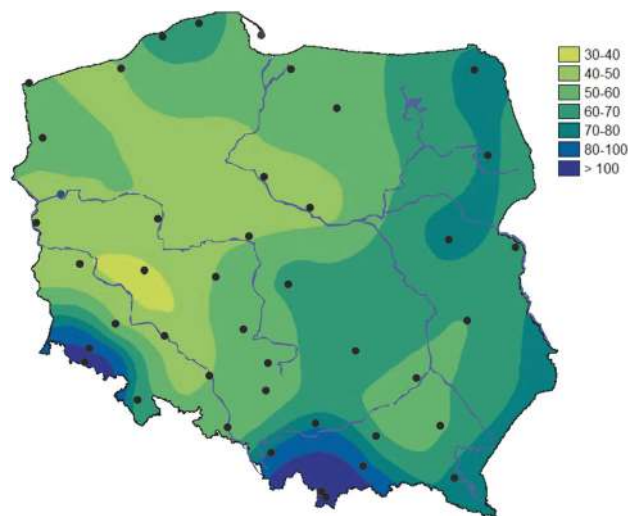
Fig. 6 NAO index vs depth of snow cover in DJF in (a) Szczecin (North–West Poland) and (b) Rzeszów (South–East Poland)
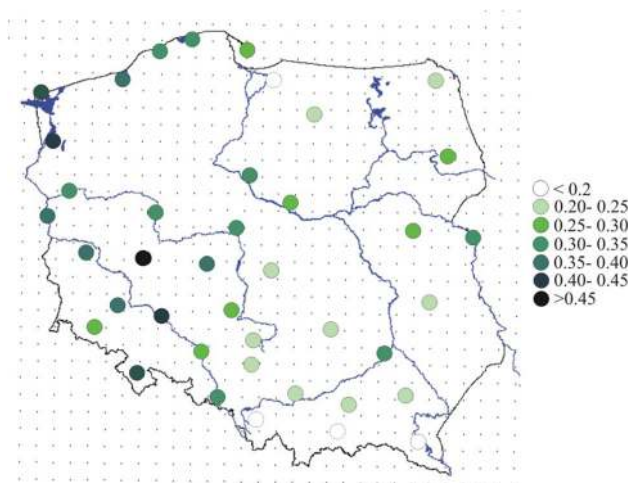
Fig. 7 Strength of the relationship between the value of the NAO index and the mean depth of snow cover in Poland in the period of 1952–2013 expressed by the R^2 value of non-linear regression


Fig. 8 Spatial distribution of the maximum depth of snow cover [cm] in winter (DJF) in 1952–2013 in Poland

maximum depth of snow cover exceeds 300 cm). In 1952–2013, the pattern of spatial variability of the maximum depth of snow cover in DJF in Poland is similar to the one of the mean depth, i.e., the maximum depth of snow cover increases from the West to the East (North–East) cf. Fig. 8.

The maximum depth of snow cover in winter (DJF) recorded in the period of 1952–2013 is in most cases equal to the maximum value recorded in the period of 1952–1990. The values recorded later, in the period of 1990–2013, are definitely lower (Fig. 9). In the period of 1952–1990, the maximum value of snow cover depth was recorded for 39 stations, while for the period of 1991–2013 only for four stations. The years 1963 and 1979 are absolute record holders. In these years, maximum of snow cover depth occurred for 13 and 12 stations, respectively.
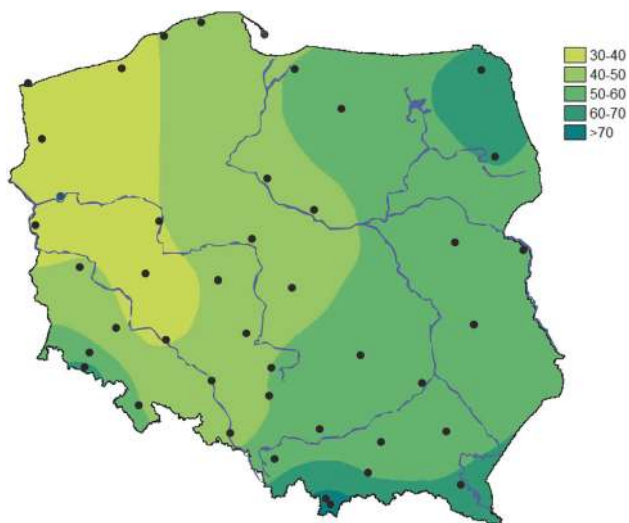
Number of days with snow cover

The mean (over all winters in the interval 1952–2013) number of days with snow cover increases from the West to the East (North-East) and varies from 29.6 days in Szczecin to 65.8 in Suwałki (Fig. 10) with the mean value of 47.2 days. Even higher values are recorded in the mountains where snow cover remains over the whole winter, as a rule.

If the entire snowy period including the non-winter months (OCT, NOV, MAR, APR) is taken into consideration, the average number of days with the snow cover in Poland amounts to 60.6 days (mountain stations not included). It means that before and after winter, the snow cover persists for two additional weeks, and lower numbers of extra days are observed in the western and north–western parts of Poland while higher numbers are observed in the areas of upland in southern Poland and in North–
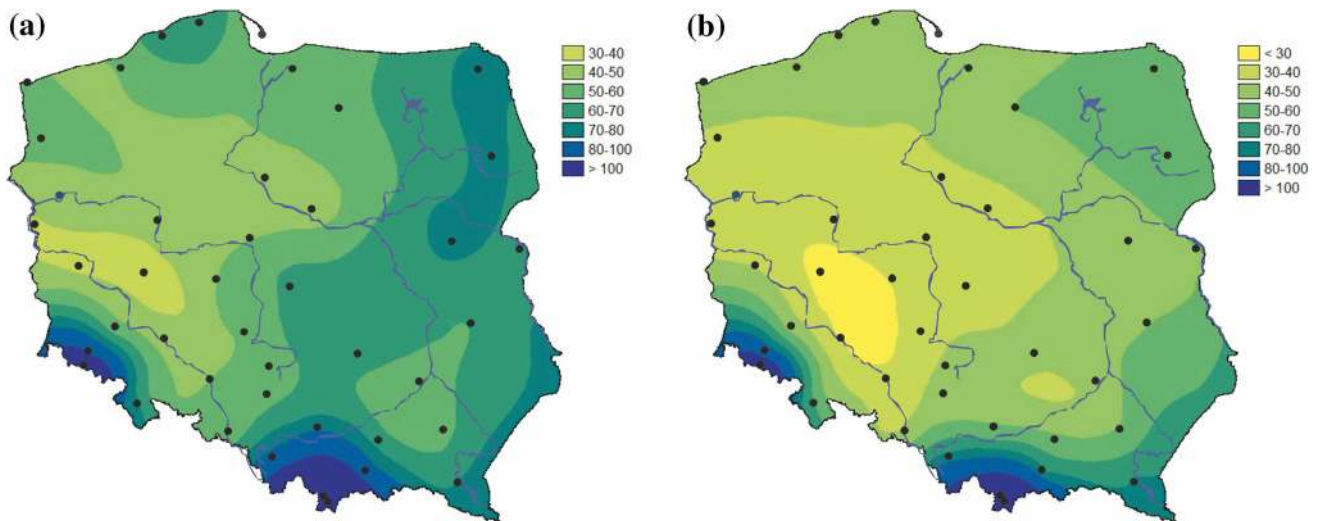
Fig. 9 The maximum depth of snow cover [cm] in winter (DJF) in Poland in the intervals of (**a**) 1952–1990 and (**b**) 1991–2013

Fig. 10 Mean number of days with snow cover in DJF for 1952–2013

East. In the mountains, the number of days with snow cover is much higher, almost doubled as compared to DJF.

The mean number of days with snow cover in winter (DJF) decreases in time (Fig. 11), but no statistically significant trend has been observed in the number of days with snow cover in DJF using Mann–Kendall statistic. However, in most cases, linear regression goes down (cf. an example of Zielona Góra-Fig. 12). A quasi-periodicity (approx. 10 years) of maxima can be spotted, with maximum in DJF of 1970, but with strong area-dependence. The winter (DJF) of 1970 was the most snowy one in terms of the number of days with snow cover for 32 out of 43 stations. Even if weak decreases in the number of days with snow cover in DJF for 1952–2013 were noted for entire Poland, they are not significant on the 95% level for most of the

country. The lower changes are noted in the southern part of Poland (Fig. 13).

NAO vs mean number of days with snow cover

Observational evidence suggests that the NAO index is negatively correlated with the number of days with snow cover in Poland. The link is even stronger than for snow depth.

Thus, for a positive value of the NAO index, there is quite a high probability that the number of days with snow cover would be below the multi-year mean. Consequently, for a negative value of the NAO index, there is a fairly high probability that the number of days with snow cover would be higher than the mean. Figure 14 presents examples of different strength of relationship between the NAO and the number of days with snow cover (Szczecin–an example of a strong relation with $R^2 = 0.47$ and Rzeszów–an example of a weak relation, with $R^2 = 0.25$).

The spatial variability of the relationship between the NAO index and the number of days with snow cover in 1952–2013 for the entire area of Poland, expressed by the R^2 value of linear regression, is presented in Fig. 15. In general, this relationship is weaker in the southern upland part of Poland, while for the lowland areas it is stronger. Still, significance level of correlation coefficient for all the stations (excluding mountain ones) is on the level of 99%.
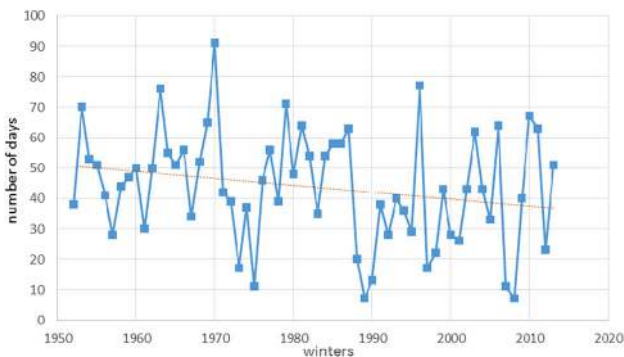
Start of the snowy season

In this section, strictly first day with appearance of snow cover during snow season is analysed.
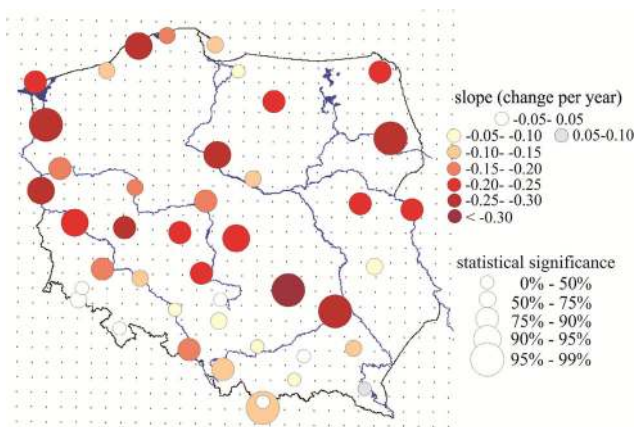
Throughout Poland, the mean day of snow cover appearance in the winter season in the analysed period of
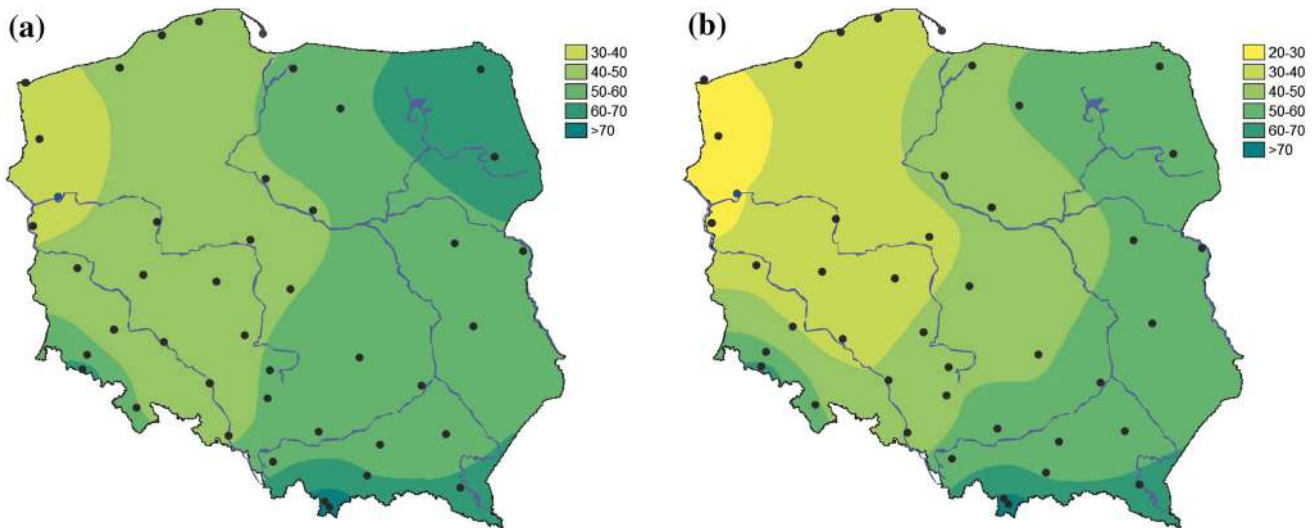
Fig. 11 Mean number of days with snow cover in winter (DJF) in Poland in the intervals of (**a**) 1952–1990 and (**b**) 1991–2013

Fig. 12 Number of days with snow cover in DJF in Zielona Góra (1952–2013). *Red line*–linear regression of time series


Fig. 13 Temporal changes in number of days with snow cover in winter (DJF) in 1952–2013 expressed by the rate of change per year and the statistical significance. The values of change per year and statistical significance have been established with the help of the Hydrospect package, based on linear regression

1952–2013 is 23 November. However, if the mountain stations, where the snow cover appears considerably earlier (in October), were not taken into consideration, the beginning of the snowy season would be 26 November. Excluding mountain areas, the snowy season, on average, starts between 14 November in Lesko and 10 December in Hel. In general, earlier appearance of snow cover is characteristic for the eastern part of Poland (in mid-November), in the western and north-western (coastal) parts snow cover appears later (first decade of December)–Fig. 16. When comparing the date of first appearance of snow cover for the intervals of 1952–1990 and 1991–2013, it seems that more recently snowy season started later (Fig. 17). However, no distinct tendency has been observed in the date of the first day of snow cover across Poland.

In mountain areas, snow cover has been recorded several times on 1 October, which is the first day of data of snow cover analysis in this research. Except for mountain areas, the earliest start of the snowy season took place on 3 October 1973 in Nowy Sącz, while the latest start of the snowy season was on 24 February 1988 in Szczecin.

Figure 18 illustrates time series of recorded date of the first day of snow cover on the example of Elbląg. No distinct tendency has been observed in the date of the first day of snow cover across Poland, except for Lesko, where the start of the snowy season takes place gradually earlier (on the level of confidence 95% using Mann–Kendall test). In general, the beginning of the snowy season depends on the region of the country. The appearance of snow cover is strongly place- and time-dependent and inter-annual variability is very strong.
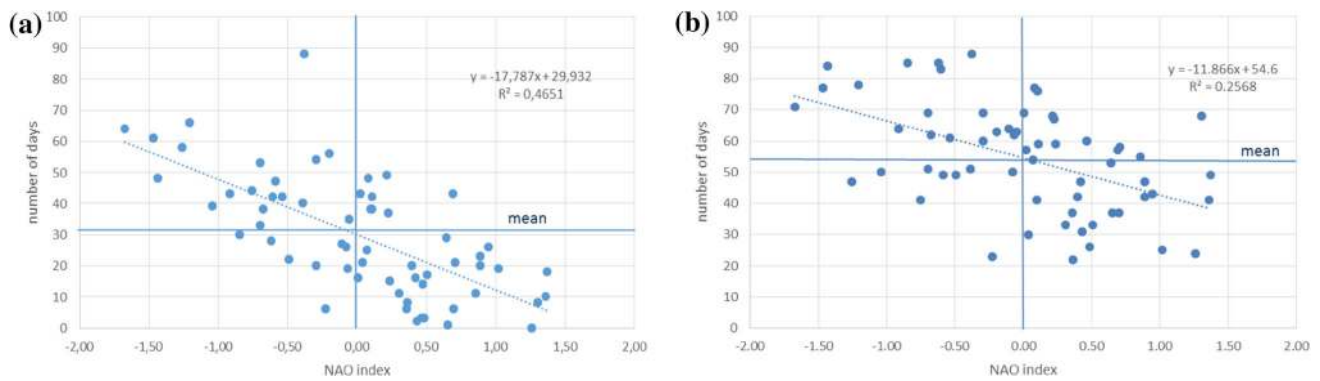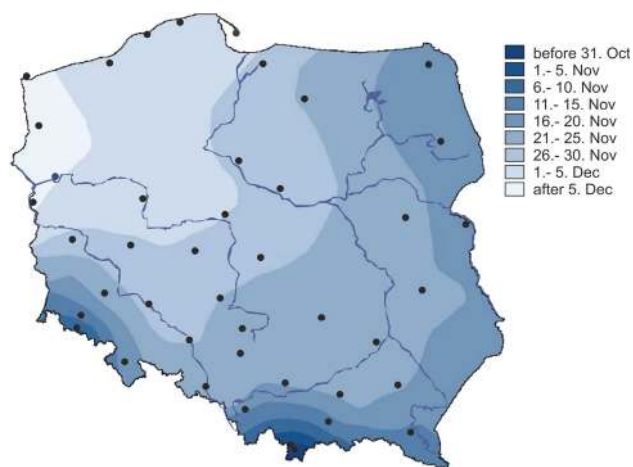
Fig. 14 NAO index vs number of days with snow cover in DJF in (**a**) Szczecin (North–West Poland) and (**b**) Rzeszów (South–East Poland)
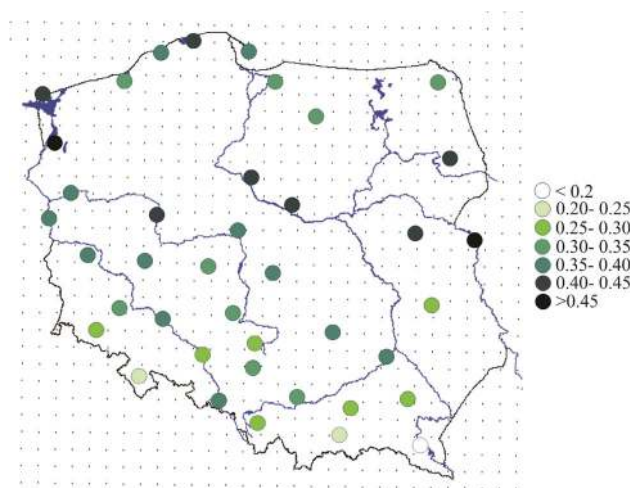
Fig. 15 Strength of the relationship between the NAO index and the number of days with snow cover in Poland in the period of 1953–2013, expressed by the R^2 value of linear regression

Fig. 16 The first day of snow cover in Poland; mean for all years in 1952–2013

End of the snowy season

In this section the absolutely last day with snow cover in every winter is analysed.

In the analyzed period of 1952–2013, except mountain areas, the snowy season ends, on average, between 11 March in Szczecin and Słubice, and 8 April in Bielsko Biała. In general, snow cover persists longest in the eastern and the southern part of Poland, while in the north–western parts it disappears early–see Fig. 19. The mean day of snow cover disappearance in Poland is 28 March, or 26 March, if mountain areas are not included.

The comparison of the dates of disappearance of snow cover for the periods of 1952–1990 and 1991–2013 is presented in Fig. 20. For the period of 1991–2013, snow cover stays shorter. The last day of snow cover is recorded several days earlier in some regions (especially in the North–East part of the country), however, no distinct tendency has been noted across Poland.

In mountain and foothill areas, snow cover may not disappear until 30 April. In the lowland part of Poland, the snow did not disappear until the end of April in Zielona Góra in 1985 and in Łódź in 1962. The earliest disappearance of snow cover took place on 22 November 1989 in Szczecin. This means that in some years there was no snow cover in Szczecin during the whole winter. In 1989, snow cover disappeared on 22 November and was absent throughout the winter. In contrast, in 1987/1988, there was no snow cover over nearly whole winter. The first snow cover day occurred towards the end of climatic winter–on 24 February 1988.

Figure 21 illustrates the time series of recorded last day of snow cover on the example of Białystok. No distinct tendency has been observed in the date of last days of snow cover across Poland. Similarly, to the first day of the snow cover in the winter season, the last day is strongly place- and time-dependent and inter-annual variability is very strong.

(a)

(b)
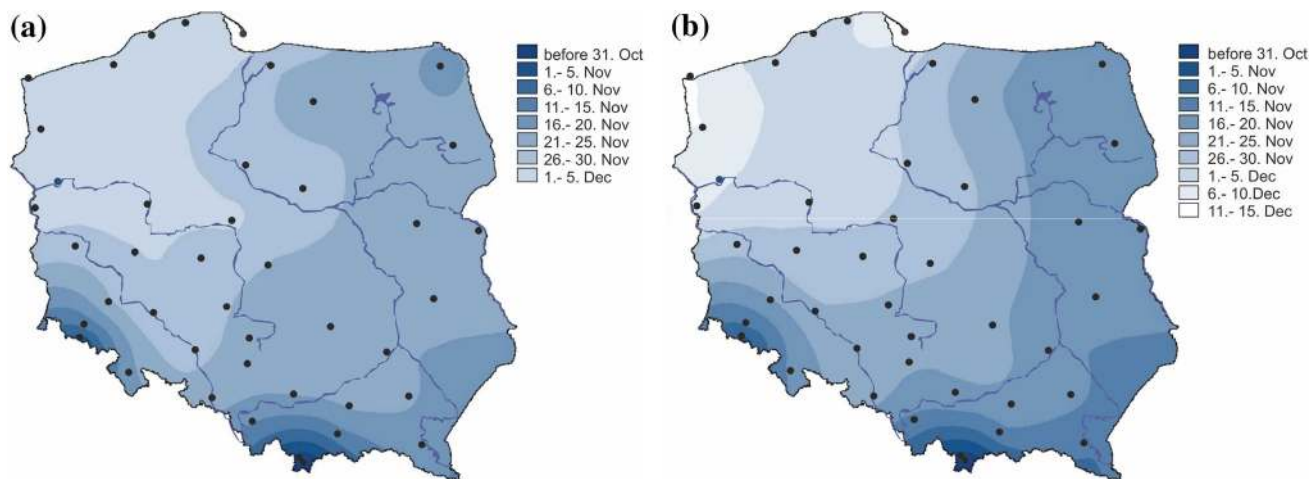
Fig. 17 The first day of snow cover in Poland in the intervals of (**a**) 1952–1990 and (**b**) 1991–2013
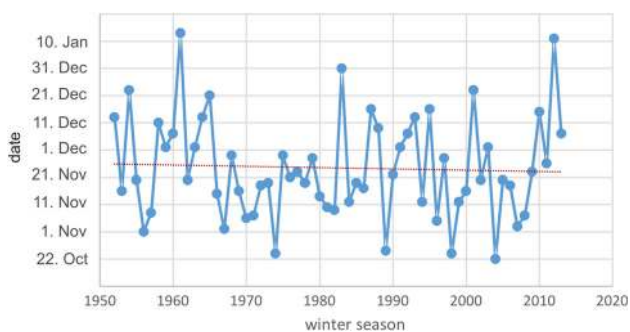
Fig. 18 Time series of recorded first day of snow cover in Elbląg. *Red line*–linear regression of time series
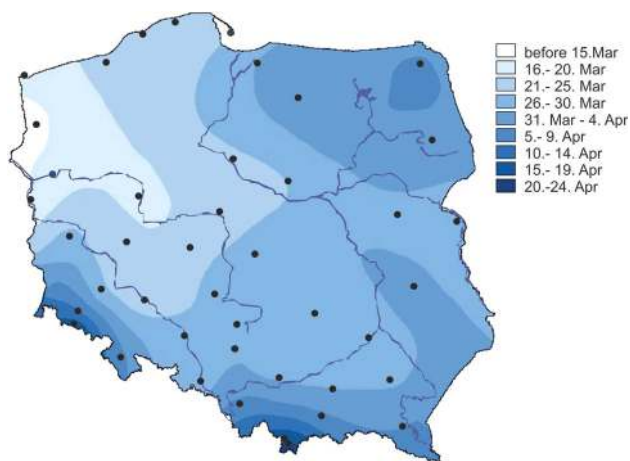
Fig. 19 The last day of snow cover in Poland; mean for all years in 1952–2013

Concluding remarks

The present paper examines the variability of characteristics of snow cover (snow cover depth, number of days with snow cover and dates of beginning and end of snow cover)

in Poland. Observed behaviour of time series of snow is complex and not easy to interpret. Even if shrinking snow cover is typically expected in the warming climate of the moderate climate zone, typically the change in Poland is dominated by strong inter-winter variability, rendering trend detection difficult. Our findings coincide with other research studies, which also report large variability between individual seasons e.g., Falarz (2004), Nowosad and Bartoszek (2007), Czarnecka (2012) and Hejduk and Hejduk (2014).

During typical, mean winter (DJF) in Poland (1952–2013) depth of snow cover varies from 2.2 to 11.8 cm (except for mountain areas, where it is considerably larger) and is rising to the North–East. The mean number of days with snow cover increases from the West to the East (North–East) and varies from 29.6 to 65.8 days per winter. Higher values are recorded in mountain stations. On average, the snow cover lasts from 26 November to 26 March.

It seems that the increase in temperature should delay first snow cover appearance and accelerate and increase snowmelt. However, for Poland, dates of appearance and disappearance of snow cover show slight changes–some delay in appearance and advance in disappearance. Still, no statistically significant trend has been detected. Czarnecka (2011) reached similar conclusions. Similarly, no distinct, statistically significant, trend has been observed in the mean snow cover depth in DJF. However, comparing the intervals 1952–1990 and 1991–2013, the former one was more snowy (in terms of mean depth of snow cover). Other research studies also report the lack of distinct, statistically significant trends in snow cover depth in Poland, e.g., Falarz (2004), Czarnecka (2012), etc. No distinct statistically significant trend has been observed in the number of days with snow cover in DJF as well. However, in most
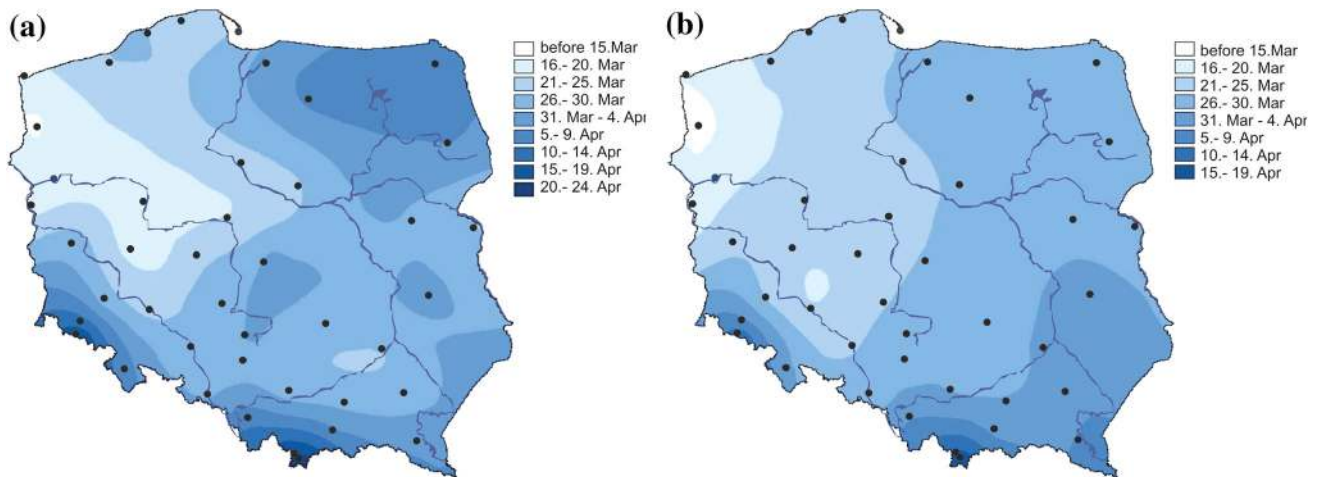
Fig. 20 The last day of snow cover in Poland in the intervals of (**a**) 1952–1990 and (**b**) 1991–2013
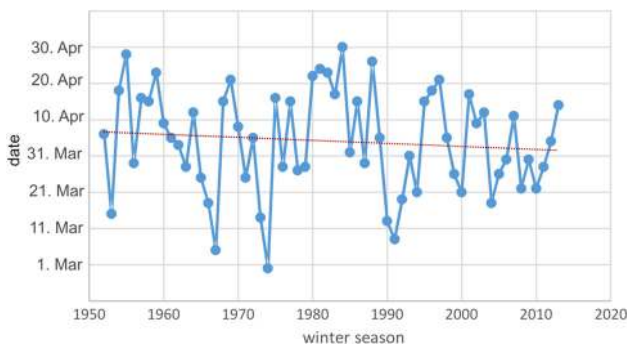
Fig. 21 Time series of recorded last day of snow cover in Białystok. *Red line*–linear regression of time series

cases, linear regression for time series of number of days with snow cover has a negative slope. The obtained results corroborate findings in recent papers of other researchers. Several authors, such as Falarz (2004), Nowosad and Bartoszek (2007) and Czarnecka (2012) spotted a slight decreasing trend (statistically insignificant) in the number of days with snow cover in Poland during the second half of the 20th century.

The pattern of air circulation in the North Atlantic region (described by the NAO index) has influence on characteristics of snow cover in Poland in winter. The positive phase of the NAO can be associated with the occurrence of less snowy winters, whereas the negative phase increases the probability of the occurrence of more snowy winters. A statistical link between the value of NAO index and the snow cover depth, as well as the number of snow cover days was found. The connection of snow cover depth and the NAO index decreases to the East, while connection of the number of days with the snow cover and the NAO index is almost equal for the lowland areas of Poland and much weaker in the upland areas on the South. For comparison, a strong negative correlation between the

NAO index and the number of days with snow cover in Poland was found by Bednorz (2002). Next, the strongest connection of the NAO index with the depth of snow cover in Poland was reported in Bednorz (2004), while Czarnecka (2012) reports it for January and February only.

Due to substantial importance of snow cover for thermal insulation, water availability and river regime, a continued analysis of snow cover characteristics seems to be still necessary for solving several practical problems. There are benefits and threats in many fields of the national economy, such as agriculture/farming, water management, transport and tourism related to snow cover.

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