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Snow cover variability in Lithuania over the last 50 years and its relationship with large-scale atmospheric circulation

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In this study, the snow cover dynamics in Lithuania from 1961 to 2010 is analyzed. The spatial distribution of snow cover parameters, as well as intra-seasonal variability and long-term changes are evaluated. Snow survey results in the open field and the forest are compared. The Hess-Brezowski circulation form classification is used to link heavy snow cover accumulation or ablation events in Lithuania with the synoptic situations. The long-term variability of the number of days with snow cover and its connection with large-scale atmospheric circulation patterns (AO and NAO) is also investigated. The decrease in the number of days with snow cover during the study period is determined throughout the whole territory of Lithuania. Meanwhile, changes in the maximum snow depth are not so unambiguous. The study results also show that large-scale atmospheric patterns strongly influence the snow cover regime.

Introduction

Snow cover is the most changeable land-surface condition in boreal environments (including polar- and mid-latitudes). The snow cover's physical characteristics depend on the winter weather conditions. On the other hand, snow is not only a product of winter, but it is also one of the major climate-forming forces (Serreze and Barry 2005). Moreover, the snow albedo is a very important characteristic because it determines changes in the atmospheric boundary layer. Therefore, the characterization of snow cover became a very important issue in climate change trends in the 20th century (BACC Author Team 2008, Vaughan *et al*. 2013).

Snow is a common feature in the Baltic Sea Region every winter (BACC Author Team 2008). In Lithuania, diverse research into snow cover developed at the beginning of the 21st century (Bukantis *et al*. 2001, Galvonaitė *et al*. 2007). Rimkus and Stankunavichius (2002) investigated the trends of the snow's characteristics. Researchers also analyzed the relations between snow conditions and atmospheric circulation (Gečaitė and Rimkus 2010) or the North Atlantic Oscillation (NAO) (Bartkevičienė 2003, Stankunavičius 2004). Scientists from neighboring countries also investigated the snow cover's relationship with atmospheric circulations (Jaagus 2006, Falarz 2007, Draveniece 2009, Klavins and Rodinov 2010). Nevertheless, snow cover variability analysis still has gaps in Lithuania and elsewhere.

Nowadays, snow analysis and research has a very wide spectrum of interests. Our research focuses on four aspects of snow cover vari-

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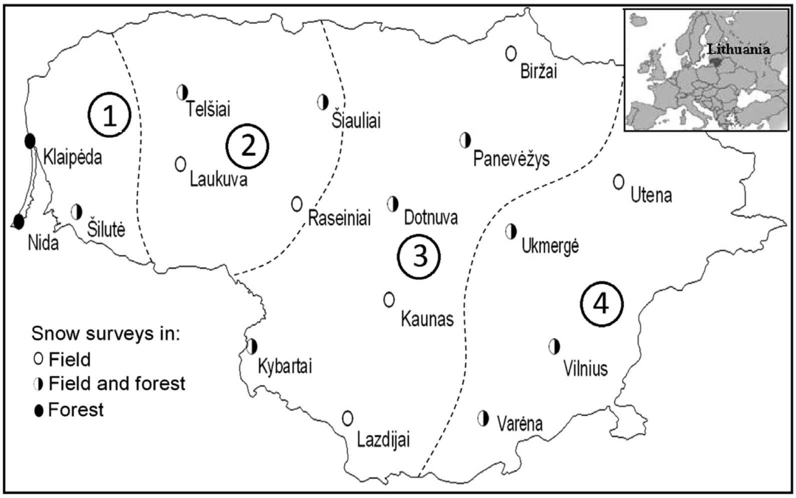

Fig. 1. The location of meteorological stations the data of which were used in the study and the type of snow survey information in meteorological stations. Geographical regions of Lithuania are: 1 = Coastal Lowland; 2 = Žemaičiai Highland; 3 = Middle Lithuanian Lowland; 4 = Baltic Highlands.

ability in Lithuania: (1) Spatial distribution and the intra-seasonal dynamics of snow cover, (2) atmospheric circulation conditions during intensive accumulation and ablation processes, (3) long-term changes to the snow cover's characteristics, and (4) the impact of large-scale atmospheric circulation on the snow cover.

There is a special interest in the spatial distribution and intra-seasonal dynamics of snow cover in the northern hemisphere (Brown 2000, Peng *et al*. 2013) and on a regional scale (Bednorz 2004, Kitaev *et al*. 2005, Bulygina *et al*. 2009). Also, long-term changes in the snow cover's characteristics (Bulygina *et al*. 2011, Peng *et al*. 2013) and the relationship between the snow cover and large-scale atmospheric circulation (Cohen *et al*. 2007, Falarz 2007, Popova 2007, Bednorz 2011, Falarz 2013) are frequently studied. The snow cover regime and its variability are very much dependent on NAO and Arctic Oscillation (AO) phases (Saito and Cohen 2003, Bartolini *et al*. 2010, Allen and Zender 2011, Kim *et al*. 2013), anomalies (Kitaev *et al*. 2002, Seager *et al*. 2010), and regional differences (Bednorz 2002, Falarz 2007, Gečaitė and Rimkus 2010, Klavins and Rodinov 2010).

Moreover, researchers investigated physical snow pack characteristics in different landscapes (Pomeroy *et al*. 2002, Winkler *et al*. 2005, Jost *et al*. 2007, Varhola *et al*. 2010). The efficiency of metamorphic processes in open fields and forests (Andreadis *et al*. 2009, Veatch *et al*. 2009, Varhola *et al*. 2010), the variation of snow cover in different types of forests (Jost *et al*. 2007, Kitaev 2013) and the impacts of forest interception on the snow-pack characteristics (Hedstrom and Pomeroy 1998, Winkler 2001, Talbot *et al*. 2006) are also being analyzed.

The climate is changing, and therefore a refreshment of snow cover trends and discovering new characteristics is necessary. The main aim of this paper is to analyze the inter-annual and intra-annual dynamics of the snow cover's characteristics in terms of climate change in Lithuania. We related the snow cover parameters to the NAO and AO indices and analyzed the atmospheric circulation impact on snow accumulation and ablation processes. We also identified the snow cover's characteristics in different landscape patterns.

Material and methods

Number of days with snow cover and snow depth

For an analysis of the snow cover's characteristics in Lithuania, we used the data from 17 meteorological stations (MS) (Fig. 1). The research covered the period from 1961 to 2010, except for Dotnuva MS, for which the period was 1963–2010. We filled single gaps (less than 1% of all raw data was missing) in the station data sets with the values of the snow cover's characteristics calculated using the ratio method.

The Lithuanian meteorological stations carry out daily snow depth measurements, and also determine the percentage of the surrounding area (visible from the meteorological station) covered with snow. A day with snow cover is defined as a day when snow covers more than 50% of the surrounding area. We calculated the average maximum depth of the snow for the period 1961–2010 according to daily measurements. The annual maximum snow depth was evaluated as the maximum daily value of the cold season. In this study, we also evaluated the total number of days with snow cover, as well as the number of days when the snow depth exceeded 10 cm or 20 cm.

Snow surveys can give additional information on the snow cover's characteristics. A snow survey is an evaluation of the mean values of snow depth, snow density and snow water equivalent in a typical landscape along permanent, 1–2-km-long transects. This means that the observational points do not vary much. If possible, the MSs make measurements in open fields and in forests. They carry out snow surveys on the last day of each ten-day period when the snow covers more than half of the area and its depth exceeds 5 cm. The stations measure the snow depth in open fields every 20 m and in forests every 10 m, at 100 measurement points in total. They measure the mean snow density and snow water equivalent in open fields every 200 m and in forests every 100 m, at ten measurement points in total.

We analyzed the snow survey records from MSs for the period 1961–2010; 15 out of the 17 stations carried out snow surveys in open fields, and 11 out of the 17 stations carried out surveys in forests. Nine stations made measurements in both open fields and forests (Fig. 1). We used data from these nine stations for comparison of the snow depth, density and snow water equivalent dynamic in open fields and forests during the cold season. We calculated the average snow depth, density and snow water equivalent for each ten-day period from December to March. Although snow cover can build up earlier, such cases are quite rare and the number of measurements was not sufficient to make a generalization. The annual number of the analyzed snow-survey records from each meteorological station depends on the snow conditions, and they vary from 1 (in very warm winters) to 15 (in very cold and snowy winters). The total number of the analyzed snow-survey records exceeded 4500. We also used a *t*-test for the purpose of evaluating the significance of the differences in mean values between open fields and forests. Test values with a probability $p < 0.05$ were considered to be statistically significant.

Classification of atmospheric circulation forms

We used the macro-circulation form classification by P. Hess and H. Brezowski (Werner and Gerstengarbe 2010) for linking heavy snow-cover accumulation or ablation events in Lithuania with the prevailing synoptic situation schemes. This classification (1952) is one of the most widely used (Bartholy *et al.* 2007) based on large-scale atmospheric circulation patterns over the North Atlantic and European regions (Fig. 2).

The classification designed for central European synoptic patterns and circulation forms did not always correspond to the same situation over Lithuania. Therefore, the circulation forms were reviewed for Lithuania's territory using a 500-hPa geopotential height (Fig. 2a) and sea-level pressure (Fig. 2b) schemes (North Atlantic sector). This classification distinguished three circulation forms, six weather types and 29 weather condition subtypes (Table 1). The weather subtype U was marked only under unclassified conditions. The smallest units — weather condition subtypes — describe specific synoptic situation patterns every day. Macro-circulation forms could be zonal, mixed or meridional (Bartholy *et al.* 2007, Werner and Gerstengarbe 2010). A zonal circulation (weather type A) occurs when a clear west–east direction air mass flow forms between a subtropical high-pressure zone over the North Atlantic and a low-pressure zone forms over the sub-polar regions. A mixed circulation (weather types B, C) is typical for both zonal and meridional air mass flows. Stationary and processes blocking high-pressure (between 50°N and 60°N) form a meridional circulation (weather types D, E, F). All north–south direction ridges are classified in this macro-circulation form (Rimkus *et al.* 2011).

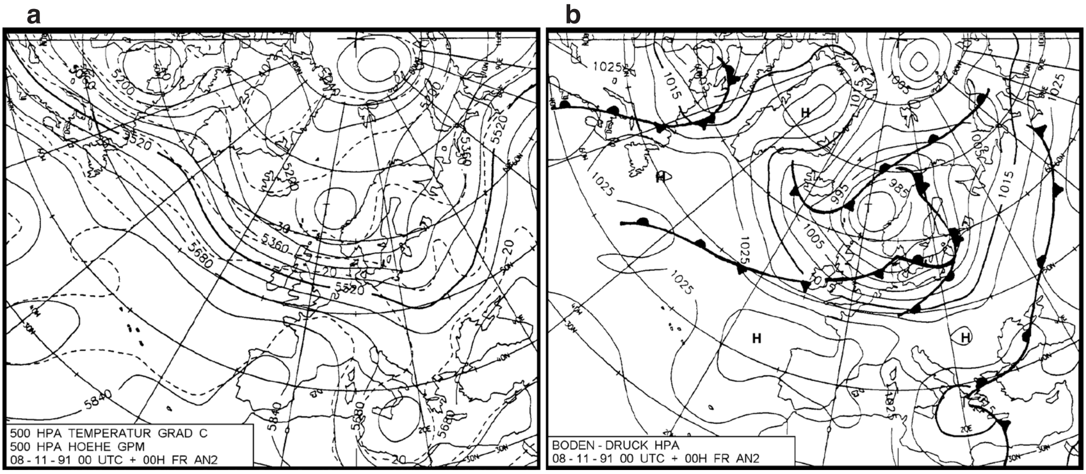

Fig. 2. The example of weather condition WZ used in the P. Hess and H. Brezowski macro-circulation classification: (**a**) 500 hPa geopotential height, and (**b**) sea-level pressure (Werner and Gerstengarbe 2010).

In this study, we analyzed the period from 1961 to 2009. All the cases when the mean snow depth in Lithuania increased or decreased by 3 cm or more per day were classified into the corresponding weather type (Table 1). In Lithuania, heavy snowfalls are usually associated with frontal system patterns — moist weather advection from the west (sometimes from the south), while thaws are associated with the advection of warmer air from the west and southwest, mostly in late winter (Galvonaitė *et al*. 2007). In total, there were 119 cases of strong snow accumulation and 110 cases of strong snow ablation during the investigation period.

Long-term changes

We analyzed the dynamics of the annual maximum snow depth, the annual number of days with snow cover, as well as the number of days when the snow depth exceeded 10 cm or 20 cm in Lithuania during the period 1961–2010. We calculated the magnitude of changes of the snow cover's characteristics by using a Theil-Sen estimator (Helsel and Hirsh 1992). This method of slope calculation is more robust than the least square method due to its low sensitivity to outliers. We applied the Mann-Kendall tests to determine the statistical significance ($p < 0.05$) of the

Table 1. Classification of weather types and conditions according to the P. Hess and H. Brezowski macro-circulation classification for Lithuania (after Werner and Gerstengarbe 2010).

Circulation form	Weather type	Weather conditions
Zonal	A: Western	WA, WS, WZ
Mixed	B: Southwestern	SWA, SWZ, TRW, WW
	B: Northwestern	HNZ, NWA;
	B: High pressure centre	BM, HM, SA, SEA
	C: Low pressure centre	NWZ
Meridional	D: Northern	HB, HNA, NA, NZ
	E: Northeastern	HFNA, HFNZ, NEA, NEZ, TRM
	E: Eastern	HFA, HFZ
	F: Southeastern	SEZ, TB
	F: Southern	SZ, TM

observed trends. The Mann-Kendall test is a tests widely used in environmental science because it is simple, robust and can cope with missing values and values below the detection limit. We used MULTMK/PARTMK software for calculations (Libiseller 2002).

Large-scale atmospheric circulation

Large-scale atmospheric patterns are one of the main factors determining winter snow conditions. Lithuania is in the zone of influence of the North Atlantic (NAO) and Arctic (AO) oscillations. In this study, we determined the relationships between the snow cover indices in the territory of Lithuania and the atmospheric circulation indices from 1961 to 2010. The strength of the linear relationship was evaluated using the Pearson correlation (r_P). Correlation coefficients with a probability $p < 0.05$ were considered to be statistically significant. The standardized NAO values (according to P. Jones) were taken from the University of East Anglia Climate Research Unit Database and the AO values were taken from the U.S. National Climatic Data Center Database. We divided the standardized AO and NAO values into three gradations (greater than 0.5, between –0.5 and 0.5, and less than –0.5), and evaluated the spatial differences of snow cover parameters in Lithuania during different phases of oscillation.

Results

Spatial distribution and the intra-seasonal dynamics of snow cover

Permanent snow cover in Lithuania usually forms during the second half of December and melts in mid-March. The average number of days with snow cover varies from 63–67 days in the southwestern part of Lithuania and the coastal region, to more than 100 days in the most eastern part (Fig. 3a). The greatest values of the coefficient of variation (CV of the annual number of days with snow cover exceeding 0.4) were found for the southwestern part of the country, while the lowest (varying from 0.24 to 0.27) were determined for the eastern part of Lithuania (Table 2).

The large variability in winter weather conditions in Lithuania leads to fluctuations in the snow depth, the duration of the snow accumulation period, as well as the thaw frequency. The maximum snow depth had a strong inter-annual variability. The high values of the variation coefficient indicate a large instability in this parameter. In some areas CV exceeded 0.7, while in eastern Lithuania the values were lower. In most cases the maximum snow depth was observed in January or February (32% and 28% of cases, respectively) and less frequently in March (24% of cases) and December (14% of cases).

The average maximum snow depth in Lithuania was very similarly distributed as the number of days with snow cover. The distance from the Baltic Sea and the absolute elevation mostly determined the distribution of the number of days with thick snow cover in Lithuanian territory (Fig. 3b). On average, there were 18–49 days when the snow depth exceeded 10 cm, and up to 25 days when it exceeded 20 cm. The greatest number of these days was in observed January and February.

The relatively warm sea in the winter has a major impact on the distribution of snow cover in Lithuania. The lowest values of the snow cover's characteristics were found in the Coastal Lowland (Fig. 3). This effect was particularly strong in the first half of the winter. Higher values in Laukuva MS were due to the altitude of the station (Table 2). Besides that, more precipitation fell on the southwestern slopes of the Žemaičiai Highland. Both factors — the altitude and the distance from the Baltic Sea — explain the high values of the snow cover's characteristics in the Baltic Highlands.

We analyzed the snow depth, density and snow water equivalent dynamics in open fields and forests in Lithuania according to date from nine MSs (Fig. 1). According to the snow survey data, the snow depth in the open fields and forests was almost the same (the difference in mean values did not exceed 1 cm) at the beginning of the snow accumulation period (December to first half of January) (Fig. 4a). Due to the impact of stronger winds in an open field, snow becomes denser and thinner than in a forested area, where

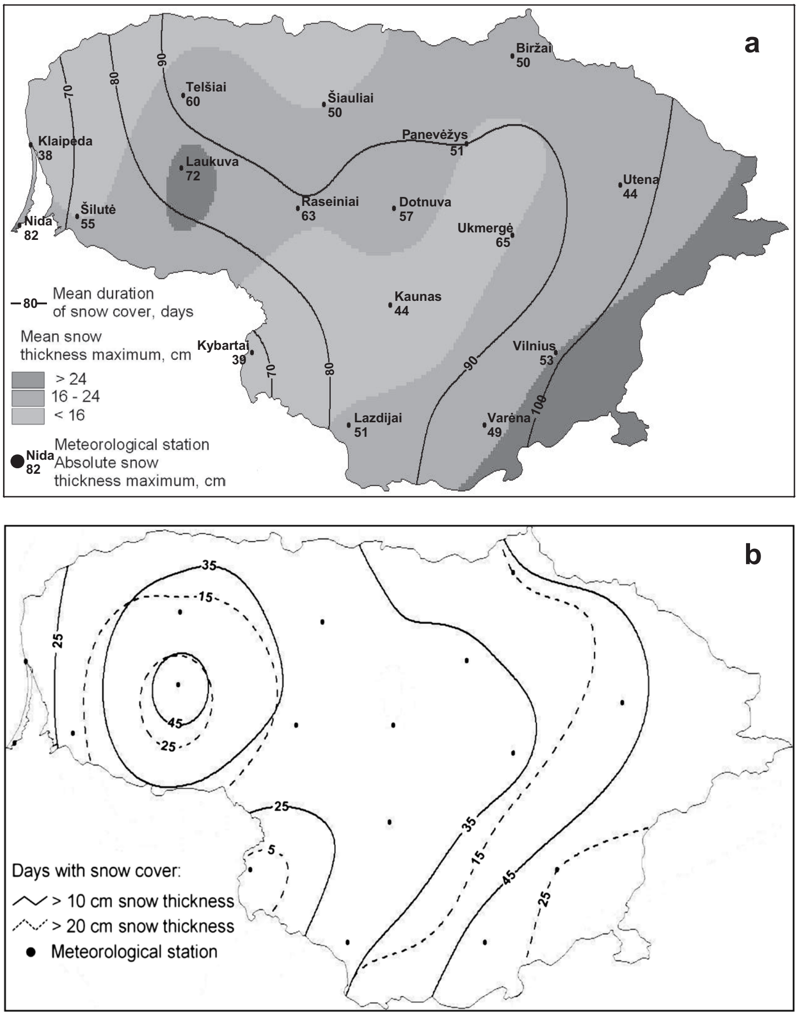

Fig. 3. (**a**) The mean number of days with snow cover and the mean maximum snow depth, and (**b**) the mean number of days with snow depth above 10 cm and 20 cm in Lithuania in 1961–2010.

the snow is intercepted by the forest canopy. The effect of the forest canopy gradually becomes less strong because the maximum interception ability of the canopy layer cannot be exceeded during intensified snow accumulation. The amount of total solar radiation beneath the forest canopy is lower, which reduces the radiative melting of snow and snow evaporation. Consequently, during the second part of the snow accumulation period, the snow cover in the forests was thicker (by 3–4 cm on average) than in the open fields, and this difference existed until the end of ablation (Fig. 4a). According to the *t*-test results, this difference was statistically significant ($p < 0.05$) from the second 10-day period of January onwards (Table 3). It should be noted that from the forests, the snow disappeared approximately ten days later than from the open fields.

Throughout the entire cold season, the snow density was growing (Fig. 4b). During the accumulation period, changes in the total snow density caused by variations in the internal structure of the snow were not significant due to the falling of new, low-density snow. The snow density varied from 0.18 to 0.23 g cm^{-3}. During the second half of the season, the amount of snowfall gradually decreased and snow ablation started. Snow melt was especially strong in March. During that time, the snow density reached its maximum (it usually exceeded 0.30 g cm^{-3}). During the whole season, the snow density in the open fields remained higher than

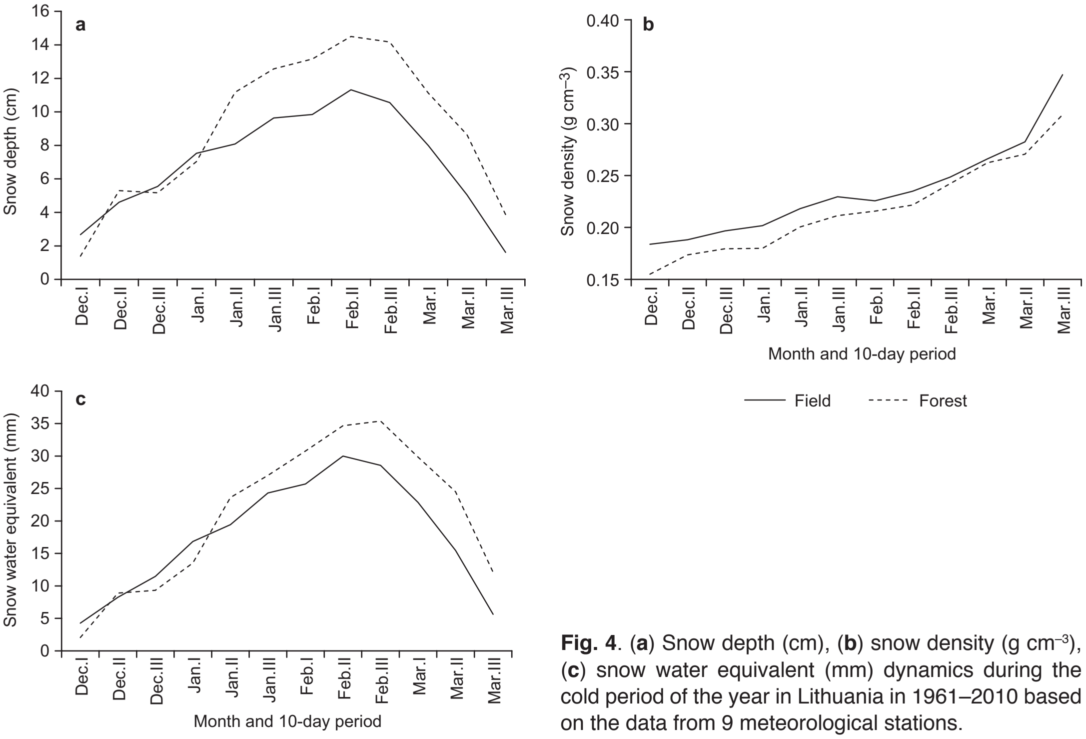

Fig. 4. (**a**) Snow depth (cm), (**b**) snow density (g cm^{-3}), (**c**) snow water equivalent (mm) dynamics during the cold period of the year in Lithuania in 1961–2010 based on the data from 9 meteorological stations.

Table 2. Statistical parameters of the main snow cover characteristics and its annual changes in 1961–2010. Statistical significant changes (Mann-Kendall test, $p < 0.05$) are set in boldface. CV is the coefficient of variation.

Location	Absolute height (m **a.s.l.**)	Number of days with snow cover			Number of days with snow cover above 10 cm			Maximum snow depth (cm)		
		Mean	CV	Change (*p*)	Mean	CV	Change (*p*)	Mean	CV	Change (*p*)
Coastal Lowland										
Klaipėda	6	63	0.46	–0.33 (0.255)	20	1.24	–0.03 (0.551)	13	0.65	0.02 (0.750)
Nida	2	67	0.48	–0.29 (0.398)	35	0.96	–0.07 (0.731)	24	0.77	0.17 (0.295)
Šilutė	3	71	0.40	–0.36 (0.216)	28	1.12	–0.11 (0.530)	16	0.69	–0.00 (1.000)
Žemaičiai Highland										
Laukuva	165	85	0.36	–0.31 (0.197)	48	0.75	–0.67 (0.051)	25	0.57	–0.04 (0.756)
Raseiniai	111	89	0.29	–0.34 (0.192)	33	1.02	–0.21 (0.314)	17	0.72	–0.09 (0.244)
Šiauliai	106	93	0.28	–0.48 (0.076)	33	0.95	–0.11 (0.633)	16	0.62	0.00 (0.854)
Telšiai	153	92	0.32	–0.20 (0.427)	39	0.86	–0.20 (0.525)	20	0.61	0.05 (0.621)
Middle Lithuanian Lowland										
Biržai	60	94	0.27	**–0.43** (0.046)	44	0.76	–0.50 (0.222)	18	0.57	–0.05 (0.519)
Kaunas	76	85	0.28	–0.24 (0.218)	28	1.00	–0.06 (0.605)	14	0.57	0.04 (0.669)
Kybartai	58	68	0.39	–0.50 (0.065)	18	1.30	0.00 (0.899)	11	0.73	0.07 (0.299)
Dotnuva	69	86	0.32	**–0.54** (0.024)	35	0.87	–0.47 (0.156)	18	0.64	–0.18 (0.110)
Panevėžys	57	90	0.28	–0.33 (0.099)	33	0.89	–0.25 (0.393)	16	0.58	0.03 (0.700)
Ukmergė	72	82	0.30	**–0.47** (0.032)	33	0.93	–0.28 (0.202)	16	0.63	–0.14 (0.244)
Baltic Highlands										
Lazdijai	133	83	0.30	–0.20 (0.417)	32	0.95	–0.35 (0.167)	17	0.71	–0.09 (0.331)
Utena	105	97	0.25	**–0.50** (0.009)	43	0.74	**–0.71** (0.040)	19	0.54	–0.11 (0.261)
Varėna	109	95	0.24	**–0.58** (0.005)	49	0.66	–0.52 (0.160)	22	0.55	0.00 (0.978)
Vilnius	162	99	0.26	**–0.48** (0.026)	49	0.68	**–0.80** (0.047)	24	0.54	–0.13 (0.257)

Table 3. The assessment of statistical differences [t-test result (p value)] in snow depth, snow density and snow water equivalent between the open field and the forest in different ten-day periods in December–March of 1961–2010 based on the data from 9 meteorological stations (df = 16). Statistical significant t-test values ($p < 0.05$) are set in boldface.

	Month:ten-day period											
	Dec.I	Dec.II	Dec.III	Jan.I	Jan.II	Jan.III	Feb.I	Feb.II	Feb.III	Mar.I	Mar.II	Mar.III
Snow depth	**3.21** (0.006)	1.20 (0.250)	0.63 (0.539)	0.56 (0.586)	**3.35** (0.005)	**2.52** (0.025)	**3.23** (0.006)	**2.60** (0.021)	**2.87** (0.012)	**2.96** (0.010)	**3.88** (0.002)	**3.98** (0.001)
Snow density	**2.76** (0.014)	**2.33** (0.033)	2.09 (0.053)	**2.95** (0.009)	**3.08** (0.007)	**2.39** (0.029)	1.75 (0.099)	**2.63** (0.018)	1.25 (0.230)	0.53 (0.603)	1.20 (0.248)	**2.62** (0.019)
Snow water equivalent	**3.58** (0.003)	0.52 (0.612)	1.69 (0.110)	1.79 (0.093)	1.91 (0.074)	1.12 (0.278)	2.01 (0.061)	1.52 (0.149)	1.99 (0.064)	2.02 (0.061)	**2.91** (0.010)	**3.27** (0.005)

in the forests (by 0.01–0.04 g cm^{-3}). This difference was especially large after a snowfall. The wind speed was one of the most important factors determining the snow density of a newly-formed snow cover. The snow density in the open fields after a snowfall was higher than in the forests because of higher wind speeds. According to the t-test results, the difference was mostly statistically significant until the end of January (Table 3). This density difference gradually decreased and almost disappeared at the beginning of the intensive melting period (Fig. 4b). Since the snow melted faster in the open fields, the density of the snow also increased more quickly.

The changes in the snow water-equivalent during the cold season of the year were very similar to the changes in the snow depth (Fig. 4c). We found a small difference (not exceeding 4 mm) in the snow water equivalent between the forests and the open fields at the beginning of the snow accumulation period. Later, due to the above-mentioned reasons, this difference increased (up to 9 mm in the middle of March), but the it was slightly lower than in the case of the snow depth due to the greater snow density in the open fields. A statistically significant difference was determined for the last two 10-day periods of March (p values were equal to 0.01 and 0.005, respectively) (Table 3).

The results of this study show that the effect of the forests was mainly due to the impact on radiative balance and the wind regime, as well as due to the snow interception by the forest canopies. Therefore, in forested areas the duration of snow cover was longer and the snow density was lower than in the open fields.

Atmospheric circulation conditions during intensive accumulation and ablation processes

Our analysis shows that atmospheric circulation conditions for intensive accumulation and ablation processes were quite different (Table 4). The probability of strong accumulation arises when a low-pressure system centre (type C) is over Lithuania and when the northern component (types B, D or E) prevails in the atmospheric circulation (Table 4). The occurrence of intensive snow accumulation tripled during type C (22%), as compared with that in the overall situation (7%) during the cold seasons from 1961 to 2009 in Lithuania. The zonal circulation (type A) is also responsible for sharp accumulation processes, though its recurrence was lower than the overall situation (25%) during the cold seasons. The main reason for this is that zonal circulation was the most frequent weather type in winter. The air mass temperature and moisture conditions determined to a large extent the precipitation intensity and phase (liquid or solid). The process (accumulation or ablation) also depends on the air mass flows and the development of frontal systems.

The western atmospheric circulation was the reason for half of the cases with strong ablation (Table 4). The most frequent weather condition WZ (type A) clearly illustrates intensive ablation processes in Lithuania, and its recurrence was even up to 34%. WZ is a form of zonal circulation (Fig. 2a), when a highly-developed frontal zone extends from the British Isles across southern Scandinavia and the Baltic Region towards eastern Europe (Werner and Gerstengarbe 2010), and the Lithuanian territory belongs to the southern periphery of this cyclone (Fig. 2b). Ablation processes were also very active during weather type situations called "high pressure centers" (23%) and "southwestern" (15%).

Long-term changes to the snow cover's characteristics

A large number of days with snow cover during the first three decades of the 1961–2010 period determined the negative changes to this indicator during this period in Lithuania. In many areas, the decrease in the annual number of days with snow cover exceeded 20 during this 50-year period. In 6 out of the 17 analyzed locations, the changes were statistically significant ($p < 0.05$) according to the Mann-Kendall test (Table 2). Meanwhile, statistically insignificant changes in the maximum snow depth were not so unambiguous. Negative tendencies dominated in the eastern part of the country, while in the west the maximum snow depth increased slightly.

We found a decrease in the number of days when the snow depth exceeded 10 cm (Table 2), but according to the Mann-Kendall test these changes were statistically significant ($p < 0.05$) at two stations only (Table 2). If the average number of days when the snow depth > 10 cm was higher than 40 in Lithuania at the beginning of the analyzed period, then at the end of the period this number decreased to 27. Negative changes in the number of days when the snow depth exceeded 20 cm were weaker (Fig. 5). This can be explained by the fact that in spite of the decline in the total number of days with snow cover, a high probability of heavy snowfalls remained. It is very likely that a relatively short-term, yet quite thick snow cover would form.

Table 4. Frequencies (%) of different weather type occurrences over Lithuania during the strong accumulation (> 3 cm) and strong ablation (> 3 cm) events in 1961–2009.

Weather types	All days (November–April)	Strong snow accumulation	Strong snow ablation
A: Western	25	20	50
B: Southwestern	14	8	14
Northwestern	3	6	2
High pressure centre	20	7	23
C: Low pressure centre	7	22	0
D: Northern	9	14	2
E: Northeastern	11	17	4
Eastern	4	2	2
F: Southeastern	3	2	1
Southern	3	2	2
U*	1	0	0
All	100	100	100

* Subtype U was used for unclassified conditions.

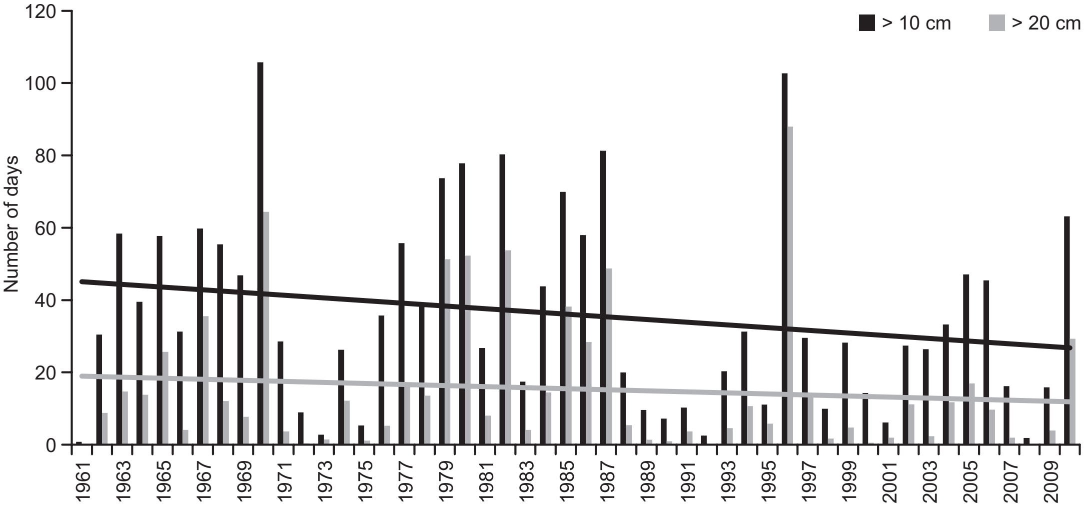

Fig. 5. Dynamics of the mean number of days with snow cover above 10 cm and 20 cm in 1961–2010 according to the data from 17 meteorological stations. Both trends are statistically insignificant.

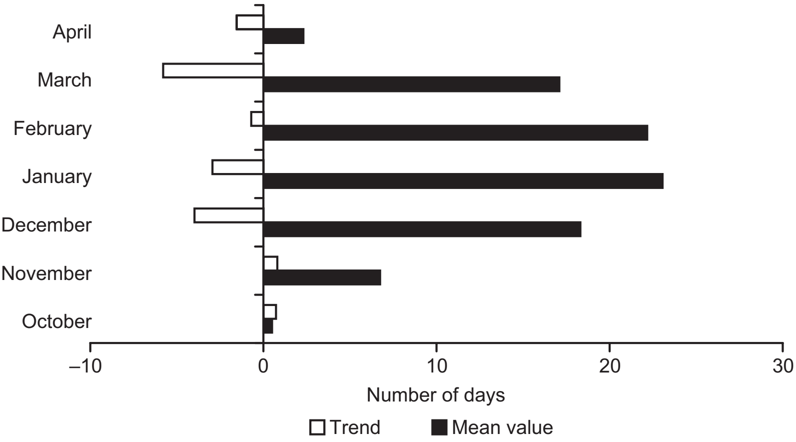

Fig. 6. The mean number of days with snow cover in Lithuania and its changes per 50 years (1961–2010) according to the data from 17 meteorological stations.

During different months of the cold period, the number of days with snow cover increased slightly in October and November and strongly decreased during the period from December to April (Fig. 6). However, statistically significant changes occurred only in April (p = 0.021). During the first half of the period under investigation, snow often covered most of the country during a large part of March and sometimes in April, while during the last two decades of the investigation period such cases were rare due to the earlier melting of the snow cover. In October and November, a short-term snow cover usually did not form annually, but over the past two decades such cases have occurred more frequently.

The impact of large-scale atmospheric circulation on the snow cover regime

The strength and location of large-scale pressure centers (NAO, AO) have a significant impact on the weather in Europe, especially during the winter. The analysis of large-scale atmospheric pattern relationships with snow cover parameters in Lithuania showed that the number of days with snow cover correlates strongly and negatively with the values of the AO index (r_{P} vary from –0.70 till –0.58) (Table 5). Moderate and strong correlations between AO and the number of days with snow cover were found for January and February (r_{P} varied from –0.70 to

–0.56), while for December a weak correlation was found for some locations only. In December, during a strong negative phase of AO when the meridian circulation prevails, the air mass temperatures can fluctuate a lot. Furthermore, local conditions (distance from the sea, absolute height, slope orientation) have a strong influence on the formation of snow cover at the start of the winter. The analysis of the correlation between AO and the maximum snow depth showed that this relationship was weaker than that between AO and the number of days with snow cover (Table 5). Moderate and week negative correlations (r_P varied from –0.45 to –0.33) between AO and the maximum snow depth were determined only for some parts of the country (Table 5). The maximum snow depth was often recorded after short and intense snowfalls, but this variable does not properly describe the conditions of the entire cold season.

We estimated that in 83% of all cases, the relation between the number of days with snow cover and the Arctic Oscillation was negative. In cases of maximum snow depth, this number was lower — 69%. A strong westerly flow (positive AO) from the Atlantic Ocean brings warmer and wetter air. Higher air temperatures and more frequent rainfall events were recorded during these phases.

We also found a moderate and strong negative relationship between the NAO and the number of days with snow cover throughout Lithuania in 1961–2010. This relation was strongest in the southern part of the Žemaičiai Highland and in the eastern part of the country (r_P varied from –0.66 to –0.58). Furthermore, this relationship was stronger in January and February than in December and March. In 69% of these cases, we recorded an opposite anomaly sign of these parameters during the analyzed period (slightly less than in case with AO). Particularly high positive NAO values were recorded between 1988 and 1995, when there were winters with an especially small amount of snow in Lithuania. The analysis of the correlation between the maximum snow depth and the NAO showed weak and moderate relationships in large parts of Lithuania (Table 5). In the Žemaičiai Highland, the average snow depth values were higher than in the surrounding areas due to the influence of the slope orientation to the prevailing air-flows and the impact of the absolute height. Even during strongly positive phases of the NAO, there was a greater probability of an intense snowfall. During the period under investigation, the number of cases in Lithuania when the NAO and maximum snow depth anomalies showed an opposite phases reached 63%.

We found that when the standardized AO and NAO index values were low ($z < –0.5$), there were smaller territorial differences in the number of days with snow cover (the mean range was 44 days for AO and 46 days for NAO). When the index values were high ($z > 0.5$), the mean range increased to 61 and 62 days.

Discussions and conclusions

The results showed a decrease in the number of

Table 5. The correlation coefficients between snow cover characteristics in Lithuania and Arctic Oscillation (AO) as well as North Atlantic Oscillation (NAO) indexes during cold season of the year (October–April). Statistically significant coefficients ($p < 0.05$) are set in boldface.

Location	Number of days with snow cover		Maximum snow depth (cm)	
	AO	NAO	AO	NAO
Coastal Lowland				
Klaipėda	**–0.58**	**–0.49**	–0.17	**–0.37**
Nida	**–0.58**	**–0.51**	**–0.44**	**–0.31**
Šilutė	**–0.62**	**–0.51**	**–0.39**	**–0.35**
Žemaičiai Highland				
Laukuva	**–0.65**	**–0.61**	–0.17	–0.27
Raseiniai	**–0.66**	**–0.60**	–0.24	**–0.47**
Šiauliai	**–0.69**	**–0.58**	–0.11	**–0.46**
Telšiai	**–0.64**	**–0.58**	**–0.45**	**–0.31**
Middle Lithuanian Lowland				
Biržai	**–0.70**	**–0.57**	–0.22	**–0.48**
Dotnuva	**–0.67**	**–0.54**	–0.03	**–0.39**
Kaunas	**–0.64**	**–0.54**	**–0.35**	**–0.37**
Kybartai	**–0.65**	**–0.55**	**–0.33**	**–0.34**
Panevėžys	**–0.69**	**–0.60**	–0.16	**–0.33**
Ukmergė	**–0.65**	**–0.54**	–0.27	**–0.46**
Baltic Highlands				
Lazdijai	**–0.57**	**–0.55**	**–0.42**	**–0.54**
Utena	**–0.68**	**–0.60**	**–0.34**	**–0.34**
Varėna	**–0.70**	**–0.64**	**–0.47**	**–0.42**
Vilnius	**–0.68**	**–0.66**	**–0.31**	**–0.51**

days with snow cover and maximum snow depth in Lithuania. The recent tendencies correspond to previous findings in Lithuania (Bukantis *et al.* 2001, Rimkus and Stankunavichius 2002) and in the Baltic Sea Region (Bednorz 2004, Falarz 2004, Draveniece *et al.* 2006, Jaagus 2006, BACC Author Team 2008). The mean duration of snow cover decreased by 17 days during the 1961–2010 period, whereas the maximum snow depth decreased by 3.5 cm (Gečaitė and Rimkus 2010). This coincides with the trends in temperature change in Lithuania. A rapid rise in the air temperature occurred from January to April, while changes in June and October in some parts of Lithuanian were slightly negative (Mickevič and Rimkus, 2013). We determined strong and very strong correlations between the number of days with snow cover in December and February and the mean air temperature (r_P varied from 0.75 to 0.90). We found the strongest correlation in the coastal area. In this area, the average winter temperature is close to 0 °C, so even slight changes in the temperature strongly affect the snow conditions.

The fluctuations in the number of days with the snow cover were very similar to those in the air temperature during the cold season in Lithuania (Galvonaitė *et al.* 2007, Gečaitė and Rimkus 2010). The ice-free Baltic Sea influences mostly the western and southwestern regions of Lithuania. This region is also affected more by the warm and humid air masses coming from the North Atlantic, which then gradually transform over the territory of Lithuania. The lower air temperatures during the cold season of the year in the eastern part of Lithuania lead to an earlier build-up of the snow cover and its prolonged duration.

We recorded the lowest mean maximum snow depth values in the coastal region and southwestern part of Lithuania. To sum up, the distance from the warm Baltic Sea and the absolute height of the location were the two most important factors determining the features of the spatial distribution of the snow cover in Lithuania.

It should be mentioned that very high mean values and rapid fluctuations in the snow depth were recorded at Nida MS, which is located in a narrow strip of land between the Baltic Sea and the Curonian Lagoon. The meso-scale circulation features of this location are the cause; in spite of the influence of the warm sea, heavy snowfalls often occur and the snow depth fluctuates significantly. As a consequence, the daily absolute maximum snow depth (82 cm; 14 March 1980) in Lithuania was recorded in Nida during the period from 1961 to 2010.

The results of the comparisons between the open-field and forest snow cover are important to spatial planning, water resource management, fishery, forestry, ecology and wildlife conservation activities. Such information could be useful for snow-cover modelling (Koivusalo and Kokkonen 2002, Andreadis *et al.* 2009, Varhola *et al.* 2010). Most previous research focused on intra-annual changes in the snow depth (Pomeroy *et al.* 2002, Kitaev 2013), the overall impact of forested areas on snow cover (Jost *et al.* 2009, Veatch *et al.* 2009, Varhola *et al.* 2010), and the influences of the forests' structure and age on the accumulation and ablation processes (Winkler 2001, Winkler *et al.* 2005, Talbot *et al.* 2006). Our research focused on the comparison of intra-seasonal changes in the snow depth and density in the forests and open fields.

It is obvious that greater snow depths are observed in the forests than in the open fields over most of the cold period of the year in Lithuania. The research and meta-analysis carried out by Varhola *et al.* (2010) showed that in most cases forest canopies reduce the amount of snow that accumulates on the ground. Most of the previous studies focused on regions with a stable growth of the snow depth throughout the entire accumulation period (Winkler 2001, Veatch *et al.* 2009, Kitaev 2013). Usually, ablation processes affect the snow accumulation processes several times per season in Lithuania due to the warm weather advection from the west or the south (Rimkus *et al.* 2011). In such variable conditions, the forests act as snow depth regulators, where the magnitude of changes is smaller than in the open fields.

The intensity of snow accumulation and ablation depends on the atmospheric circulation over the Baltic Sea (Jaagus 2006, Klavins and Rodinov 2010, Bednorz 2011, Falarz 2013). Strong accumulation processes over Lithuania are often associated with deep cyclone centers. Normally, a series of cyclones (low pressure systems below

Scandinavia) move from the Norwegian Sea across the Baltic Countries in a southeastern direction (Bukantis *et al*. 2001, Falarz 2007). Weather events with a "northern" component are also responsible for heavy snow accumulation — cold air from the north moves beneath the existing warmer air over the territory, thus accelerating convection processes. Moreover, air masses travelling from the north are usually associated with snowfall (Draveniece 2009, Rimkus *et al*. 2011). In winter, if the temperature is slightly below 0 °C, a strong zonal cyclonic circulation with highly developed frontal systems and cloud brings snowfall responsible for rapid snow accumulation processes in the southern Baltic Region. Contrary, during the early and late winter seasons, if the temperature is above 0 °C, a strong zonal cyclonic circulation with highly developed frontal systems and cloud brings liquid precipitation (rain or drizzle), which is responsible for rapid snow ablation processes in this region (Bukantis *et al*. 2001). The anti-cyclonic circulation types accompanied by high air temperatures bring warm and sunny weather from the south, which are responsible for intensive ablation, especially during late winter in the southeastern Baltic Region.

The NAO and AO phases also influence the snow cover formation processes (Stankunavicius 2004, Falarz 2007, Gečaitė and Rimkus 2010, Klavins and Rodinov 2010). The impact of the NAO and AO on the snow cover in Lithuania is strongest in January and February. Positive phases of the NAO and AO are associated with decreases in snow cover parameters. The same relationship is seen in most of eastern Europe (Bednorz 2002, 2009). During periods of high NAO and AO values, zonal circulations are more intense and the strongest influence of warm marine air masses falls on the western part of Lithuania (Bartkevičienė 2003). In such cases, there are greater territorial contrasts. During weak zonal circulations (low index values) and reduced impact of the warm sea, there is more evenly distributed snow cover over the territory of Lithuania (Gečaitė and Rimkus 2010). Many studies indicate that the NAO/AO–snow mechanism exists (Bartolini *et al*. 2010, Kim *et al*. 2013). The investigation results show that the Arctic Oscillation is the main driver for winter snow parameters in central Europe and investigations suggest that the AO phase may depend on the extent of the snow cover in Siberia in October, which creates a feedback mechanism during winter and influences the winter snow cover regime in this region (Saito and Entekhabi 2001, Cohen *et al*. 2007, Allen and Zender 2011).

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